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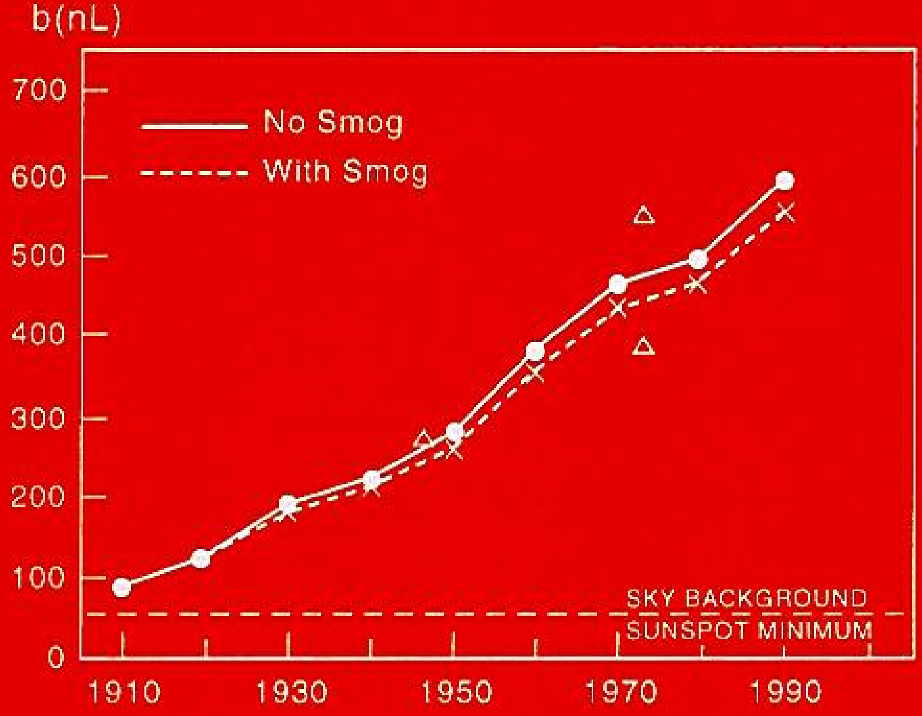

MEASURING AND MODELLING LIGHT POLLUTION

Edited by P. Cinzano

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PREFACE

The loss of a sky free from light pollution and radio interference is no less an environmental and cultural loss than the loss of clean air, forests, or diversity of species. The capabilities of optical observatories are continually eroded by urban growth and its baneful accompanying sky illumination. From even the most remote locations radio astronomers cannot escape radio interference because it increasingly originates from orbiting satellites. Sadly, a minority of the children of Europe and North America grow up knowing the Milky Way and meteors. As the general public and the astronomical community become bathed in this electromagnetic fog, these children are now becoming the legislators and business leaders upon whom the science of astronomy relies for its support. Action must be taken, and quickly.

This pioneering special issue is an important tool with which astronomers and other concerned professionals can learn more about these issues and get involved in the various efforts to improve the situation. I salute the Italian astronomers, both amateur and professional, who have done excellent work to characterize and reduce light pollution. I also invite them to become active at the international level through organizations such as the International Dark-Sky Association (www.darksky.org) and the International Astronomical Union (especially Commission 50). The current IAU effort is centered on Symposium No. 196, "Preserving the Astronomical Sky," to be held in Vienna in July 1999 (full information at the above Web address). This meeting will discuss all of the above issues in detail, as well as make resolutions for consideration by the UN Committee for the Peaceful Uses of Outer Space. For example, might not the dark night sky be declared a World Heritage Site?

The battles are tough, but not hopeless. One only needs to look at the history of the past decade to see that amazing things can happen in a relatively short time. Please join the authors of this volume in preserving for the future our common heritage of the sky.

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FOREWORD

There has been an increasing interest during the last years towards the effects caused by the light pollution not only for the limitations imposed to ground based telescopes but also for the loss of what has been defined a “world heritage”.

The pollution does not concern only the visible light, but extends to a large fraction of the electromagnetic domain reaching the surface of the Earth. The pollution, for instance, in the radio wavelength is such that radioastronomers are considering to place their instrumentation on the dark side of the Moon. The Commission 50 (The identification and protection of existing and potential astronomical sites) of the International Astronomical Union, estabilished in 1973, has played an important role in developing the interest about the protection of astronomical sites.

Nowadays the study of the phenomena related to the light pollution is so broad, since it concerns astronomy, botany, biology, psicology and other sciences, that it constitutes a new interdisciplinary field of research, which deserves to be more and more developed.

Dr. Pierantonio Cinzano, who is the editor of the present volume, is one of the pioneers in the field. In addition to the several papers on the subject he has recently published a textbook, now being traslated into English, where the various aspects of the light pollution are rigorously treated.

The articles collected in this book represent the contribution of several scientists which are very active in the field of research on light pollution. It will certainly contribute to stimulate further studies and to draw the attention toward a problem endangering the relationship of the man with the cosmos.

Francesco Bertola
Professor of Astrophysics
University of Padova

INTRODUCTION

It is a pleasure for me to introduce the reader to a book specifically devoted to the research on light pollution. The aim of this book is to support the research in this field giving to the researchers the possibility to publish together their works on the argument. We thanks the Italian Astronomical Society for the sensivity demonstrated accepting my proposal. From early '80, this Society was in first position in the battle against light pollution in Italy preparing, through its *Commission for the study of light pollution*, a Bill which was presented to the Italian parliament, where it is under discussion, and participating to the preparation of a national technical standard.

Many arguments are discussed in this book, ranging from the effects of light pollution on plants to the hazard to astronomy from space debris, from the radio pollution to the effect of air pollution on the propagation of light pollution, from the growth of the sky glow to its colors. Many measurements, computations and maps of sky brightness, sky luminance, magnitude loss and upward flux are presented. The connection between sky brightness, upward fluxes and particular kinds of fixtures is also discussed in this book but conclusions are not always in agreement.

The issue contains a non negligible contribution from Italian researchers. I think that I am not wrong identifying in the Asiago Autumn Rendezvous, organized by the University of Padova and the Astronomical Observatory of Padova-Asiago the 5th and 6th October 1995, the first seed for an Italian research on light pollution. The first day of this international meeting, organized by F. Bertola and by me, with the presence of D. Crawford and F. J. Diaz Castro, was devoted to discuss measurements of Light Pollution. I think it was the first time from the epoch of Bertiau's studies that a scientific discussion on the behaviour of light pollution was done in Italy among many researchers.

What make me happy is that a number of students show interest for this argument. In the last two years 2 degree thesis about light pollution were discussed at University of Padova, another will be discussed soon at University of Milan. They join to the thesis already discussed at the University of Catania some years ago.

Another appreciable thing is the large interdisciplinarity of people involved rising from astronomy to natural sciences, from biology to environmental physic and lighting engineering.

I hope that a better knowledge of light pollution will help a better control of it.

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LIGHT POLLUTION, AN ENVIRONMENTAL PROBLEM FOR ASTRONOMY AND FOR MANKIND

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ABSTRACT. Astronomy is suffering from rapidly growing environmental problems. One of these is light pollution. Urban sky glow is taking away the prime view of the stars and the universe that our ancestors had. A combination of population growth and the growth of outdoor lighting are the culprits. The main problem is that so much of that outdoor lighting is of low quality. Such lighting has many obtrusive effects, with the urban sky glow being one of them. Yet the our view of stars and universe is an important part of the nighttime environment, not only to astronomy but to the general public.

To preserve dark skies, astronomy need not push for the use of no lighting, but we must do all we can to insure that only good quality outdoor night lighting is used everywhere. With good outdoor lighting, we all win. We help preserve the dark skies, we see better (and are safer and more secure at night), we have a more pleasant and comfortable nighttime environment, and we save a great deal of energy and money doing so. Neither astronomers nor the public, anywhere, need any of the adverse environmental effects of poor lighting. Astronomy has a strong case in that all we need to do to preserve dark skies also improves the quality of lighting.

The paper summarizes the issues, reviews the problems, shows that solutions do exist, and offers guidance for implementing these solutions. These solutions work. Lack of awareness and apathy are the main problems we face. There is a slowly growing awareness of the problems and of the solutions, but much more educational outreach is needed. Action is called for!

Help and resources are available from the International Dark-Sky Association, a membership based non-profit organization with members now in close to 70 countries. IDA has produced many information sheets discussing the issues, as well as slide sets and other materials. Its Web page (www.darksky.org) contains much valuable information.

1. Introduction

Astronomy today is suffering greatly from the adverse effects of outdoor nighttime lighting. Such lighting has produced a veil over all of our cities, everywhere, and is removing our view of the stars and the Milky Way, not just for astronomers but for the public as well.

Most people are growing up unable to see the stars that their grandparents knew so well. They see the night sky only in pictures or at a planetarium. Indeed, many children may now say, after viewing the night sky in a rural area for the first time, that "It looks just like in the planetarium".

Light pollution is not a matter of life and death (at least in most cases). Yet it is important nonetheless, profoundly so. We human beings lose something of ourselves when we can no longer look up and see our place in the universe. It is like never again hearing the laughter of children; we give up a part of what we are.

For science, the impact has been even more tangible. Astronomers require observations of extremely faint objects that can be made with only the large telescopes at sites free of air pollution and urban sky glow. For example, astronomers interested in how the universe was formed must study the light of galaxies at incredibly vast distances from Earth. Yet after traveling a distance of countless light years, the light from these galaxies can be lost at the end of its journey in the glare of our own sky.

Such a loss might have to be accepted if light pollution were the inevitable price of progress. But it is not. Most sky glow is unnecessary. The combination of population growth and the attendant residential and commercial developments over the past years coupled with the growth in lighting technology has lead to a greatly increased growth in the use of outdoor lighting. This growth in usage was particularly apparent in the age of relatively cheap electrical energy. The main design approach in those days seemed to be "the more the better".

Some new lighting installations, well designed and installed, offer excellent visibility at night, at reasonable lighting levels, and also provide excellent ambiance for their settings. Many do not, however, and as a result, produce glare, overlighting, light trespass, and add greatly to the urban sky glow over our cities. An important additional negative is the energy waste due to the poor lighting.

In this present paper, I discuss these problems of light pollution in some detail, covering not only the sky glow issue that affects astronomy but all of the problems of obtrusive outdoor lighting. In attempting to solve the problem for astronomy, our strongest ally is the fact that all things done to improve the quality of our outdoor lighting and to minimize the non-astronomy problems also helps with the sky glow impact on astronomy. After all, who can be against good lighting? The lighting industry and the environmentalists can be and should be strong allies in the cause.

In the remaining sections of the paper I will discuss how the sky glow problem arises, the loss of value to astronomy due to the problem, what to do about it (in a general way), why we have night lighting at all, the problems of bad night lighting, the keys to good lighting, and then go into detail about the solutions that are needed and why they work. After that, I discuss some of the issues of outdoor lighting, such as lighting levels, glare, energy savings, advise on how to implement the solutions, give a bit of important information on the eye relative to night vision, and go into some detail about roadway lighting and security lighting. I discuss two of the international organizations that are allies for anyone interested in helping solve the problem of light pollution, and include as an appendix an extensive glossary of basic terms and definitions as well as a listing of the various units involved in lighting and photometry. Finally, a few basic references are given; they should be a guide to additional ones in the literature.

2. How Artificial Sky Glow Arises

The Earth's atmosphere causes the light coming from sources in an urban area to scatter, creating the halo of light visible over the city even from great distance. Even single bright sources in a dark local can be a source of local sky glow.

The light emitted directly into the sky and that reflected from the ground or buildings or other objects is then scattered by molecules and aerosols (solid or liquid particles) present in the air, of various amounts. Both scatter light differently, and both also absorb light. Allowance must be made for all such details in studies of light scattering.

Taking all these factors into consideration makes for a complicated problem. Several studies have been made of the issue, notably by Dr. Roy Garstang, of the University of Colorado. He showed that an empirically derived relation published by Dr. Merle Walker, of the University of California, is a good approximation for many applications. Walker's measurements led to a relation of the form $\Delta I = 0.01\ P\ r^{-2.5}$, where ΔI is the increase in sky glow level at a vertical angle of 45°towards the city; P is the population of the city; r is the distance from the city to the observing site, in kilometers; and 0.01 is a constant typical for most cities with average mixture of outdoor lighting. A ΔI value of 0.2 means an increase of 20 percent over the natural sky background level. The equation seems to fit best to situations where the average lumens per person is between 500 and 1000. Garstang discusses the scattering problems in detail and investigates many of the relevant factors. Let us just here note a few calculated values, as examples of its use.

For a city with a population of 500,000 at a distance of 60 km from the observing site, the sky glow increase would be 18 percent. If the town grows to be one million in population, the sky glow would double. If the city were half the size but at half the distance, then the increase would be about 50 percent. For a town of 5,000 at a distance of only 16 km, the increase in sky glow would be about 5 percent. To show the powerful influence of distance on the sky glow increase, a city at half the distance has six times the effect, and one at a tenth the distance has 316 times the effect.

Some important results derived from these models are:

1. From an observing site, there is a rapid increase in sky glow brightness the closer one is to the source (the city), and sky brightness falls off rapidly the further one is from the source.
2. The use of full cutoff lighting fixtures can help greatly in minimizing the adverse impact at observing sites well away from the city, as the low angle light (somewhat above and below the horizontal direction) strongly affects the sky glow at a distant site. The light at higher angles (more directly up going light) is much more of a problem in creating the sky glow directly above the city.
3. Air quality is an important issue too, especially for sites close to the city. For ones further away, the absorption of light due to the smog or haze actually decreases the sky glow at the observing site. It increases the sky glow above the city, of course.
4. Reflectivity of the ground and other reflective sources is an important issue also, as the high reflectivity causes more of the bounce light to get into the sky. In calculations of waste light and energy waste one should use the average reflectivity that best fits the conditions of the ground and other surfaces at the site. In most calculations, the average reflectivity is about 15 to 18 percent, but it depends on the kind of reflecting surfaces involved. It is much higher if the ground is snow covered, of course, and lower if the ground is very dark.
5. It is likely that larger cities emit more light per person than do the smaller ones, at least on the average. There is more advertising, more major sports parks, and more major highway lighting. The constant in the equation depends a great deal on the

Loss of Value for a 4-meter Aperture Telescope Due to Increased Urban Sky Glow

X	Equivalent Aperture In Meters	Equivalent Aperture In Inches	Percent of Original Value
1.00	4.00	157	100%
1.10	3.81	150	88
1.20	3.65	144	78
1.25	3.58	141	74
1.50	3.27	129	58
2.00	2.83	111	39
3.00	2.31	91	23
4.00	1.79	70	11

mix of lighting in the city, both usage and quality.

6. There is a good fit between observations and Garstang's models.
7. In a study of one typical city, Garstang estimated that about 40 percent of the sky glow impact was coming from "roadway lighting".

It is important to recognize that the solutions being promoted by astronomers and lighting engineers really work. Quality lighting does help a lot with the sky glow issues. For example, the city of Tucson has grown greatly from the time the first outdoor lighting control ordinances went into effect in 1970. It is now a city of close to 800,000 people. Yet the sky glow at the observatories about 70 km from the city have not increased over that period of great population growth. And in Tucson itself, a large city, one can still see the Milky Way on most nights when the Moon is not in the sky, not as well as at truly dark sites, but much better than in most cities of much less population.

3. Loss of Value: Sky glow effects on existing telescopes

There is a loss of effective telescope aperture and value due to the increasing urban sky glow. Many existing installations have already suffered such a loss. We give In the table below the calculated loss of value for a 4 meter aperture telescope. We define X to be the increased sky glow level above the natural background, where 1.0 denotes the natural background level, without any man-made contribution. A value of 1.2 means a 20 percent increase above the natural background, 2.0 is double the natural background, etc. We also define the equivalent aperture as $(aperture\quad squared/X)^{1/2}$ and assume that the value of the facility scales as $(aperture/4)^{2.7}$.

Clearly, the economic loss to astronomy and to observatories due to any significant amount of urban sky is very large. It is a present and potential problem.

4. What To Do?

Lack of awareness, rather than resistance, is usually the biggest problem in controlling light pollution. After all, it costs money to light pollute. Unlike the case with most other forms of pollution, simple solutions do exist. Moreover, everyone benefits from such solutions (except perhaps for the salesman for a company that only makes poor lighting fixtures). Most people are not yet aware of even the existence of light pollution, as it has crept up on them slowly, like a cancer. They are not aware of the expense, the waste, and the harm associated with poor quality lighting. They put up with the problems, not knowing that there is a better way. There is a better way.

Educating the public, governmental officials, even astronomers and lighting professionals has been the main thrust of most efforts to control light pollution, including those by the International Dark-Sky Association. These efforts have helped a lot. Most technical committees in the CIE and the IESNA have been addressing these issues and the upcoming standards, recommended practices, and design guides are reflecting these concerns. As they are issued and put into practice, we will expect to see them implemented on a wide ranging front, albeit slowly. It takes a great deal of effort and time to educate anyone, even though most all of the solutions are really just common sense. It is critical that astronomers and environmentalists do all they can to help promote quality lighting and the upcoming, much improved standards and recommended practices. We should do all we can to get such standards implemented in our own communities, regions, and countries. We can all win; we must do all we can to insure that just that happens.

5. Why Night Lighting?

The purpose of nighttime lighting is to help us see better at night. Seems simple, but it is a goal often forgotten in the rush to light up everything in an effort to turn the night into day. Certainly, in this day and age, we have greatly extended our “day”, enjoying the opportunity to shop, play sports, travel safely, and be more productive over a wider range of hours than those when the Sun is up. Advances in lighting technology have allowed mankind to put much more artificial light into the environment, some of it adding to our ability to see better at night and do the many things that we want. Unfortunately, some of it also doing little but adding glare, offending neighbors, and lighting up the night sky.

6. GLUT (Glare, Light Trespass, Uplight, Too Much Light)

These are four negatives often found with outdoor lighting. None help with visibility. All are a form of waste and of adverse impacts on the outdoor environment. They make no economic sense.

Glare has been defined as follows: The sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss of visual performance and visibility. It stands to reason then that good outdoor lighting design should minimize glare. Glare never helps.

Light trespass is light that is distributed where or when it is not wanted or needed. Street lighting, for example, should light streets and not the interior of houses nor rooftops. Light trespass occurs whenever the light shines beyond the intended target and onto adjacent properties.

Uplight is truly wasted light. Light that goes directly up into the night sky is lost into space and serves no useful purpose. It is the source of much of our urban sky glow, the bane of astronomers and anyone wishing to enjoy the beauty of the night sky. Uplight often results from the same sort of bad fixtures that produce glare and light trespass.

Too much light results when light levels exceed that needed for the task. Too much light often results from the myth that "more is better", or from businesses trying to outshine their competitors. It is a philosophy that wastes a great deal of energy.

All of these GLUT factors waste energy. And energy costs money. The amount involved is significant, because the operating cost of a light fixture throughout its lifetime is usually much greater than the initial cost of the lighting fixture or lamp. Even where energy is relatively cheap, a KWH of wasted energy produces unnecessary environmental pollution due to the production of that energy, regardless of its cost.

7. A Short List of the Keys to Good Lighting

Use the "correct" lighting level, not too little, not too much.
Eliminate glare.
Minimize light trespass, or obtrusive lighting.
Minimize energy waste.
Minimize direct up-going light, a major cause of urban sky glow.

These lead to the following recommendations:
Don't light it if not needed.
Turn the lights off when not needed.
Eliminate light above the 90°plane.
Reduce the candelas at high vertical angles (70°to 90°).
Eliminate light trespass with proper luminaire and optics selection.
Conceal lamp source and bright reflector sections from direct view.

With all these, we will have maximized the advantages of quality outdoor lighting for any installation and minimized all the adverse effects of poor lighting, including that of urban sky glow.

8. Solutions to the Problem, in Detail

What can be done to minimize the adverse impacts of light pollution, and in a way that does not compromise the effective and efficient use of nighttime outdoor lighting? Turning off all the lights might cure the problem for astronomy, but it is not a viable option. I give in the next paragraphs the American Astronomical Society's position on the problem. I will then discuss the various solutions in more detail in the remainder of this section of the paper.

8.0.1. The American Astronomical Society's Position on the Light Pollution Problem

This is a short summary of the AAS position on the light pollution issue. It was prepared by the Society's Committee on Light Pollution, Radio Interference, and Space Debris, and it has been endorsed by the Society's Board of Directors.

A. Astronomy

1. There are very few prime ground-based optical/infrared observing sites.
2. They need protection from light pollution.
3. Ground-based astronomy is not dead or dying due to space astronomy or other techniques, but it is more vital than ever.
4. Astronomy is important to the USA and to the public.

B. Light Pollution

1. There is a serious problem with light pollution.
2. However, there are solutions to the problem.
3. These solutions do work. With them, ground-based optical astronomy will have a viable and exciting future.

C. The Solutions

1. Use the right amount of light for the task, not overkill. "The More the Better" is bad lighting design.
2. Remove the non-visible ultraviolet and infrared "light", if any, by filters or other techniques. It is wasted energy.
3. Control the emitted light, by shielding, placement, and other techniques. Use well designed task lighting so as to minimize wasted light, light trespass, and light pollution.
4. Take advantage of lighting controls, such as timers and dimmers. The second half of the night can be darker than the first half and not compromise efficient living.
5. Consider also the effects of air pollution, ground reflection, etc as items that can increase the sky glow.
6. Avoid growth nearest the prime observatories, and use more rigid controls near the observatories.
7. Use monochromatic light sources near these observatories whenever possible. Presently, that means low pressure sodium (LPS) fixtures.

D. Summary

1. All of the above says, really: "Use the best possible professional lighting design and installation for the task, including all relevant factors, of which astronomy is one."
2. Most all of the solutions needed for protecting astronomy have positive side benefits of maximizing the energy savings and improving the efficacy of the lighting design.

No single solution alone will solve the problems. All are required to minimize the adverse impacts on astronomy and on the environment.

I will now expand on some of these solutions.

1. Use the right amount of light for the task. There is no question that many lighting "designs" have been installed with the idea that if a certain amount of light is OK, then more light will be better. Most lighting design professionals do not have that approach, but in the past, as it is today, a lot of lighting is installed without be benefit of any design. It is just purchased and installed without any thought of its adverse impacts. Good lighting should produce the right amount of light for the task. The only question is what that amount is. Most national and international lighting organizations have produced recommendations and standards for such lighting levels, and they should be used until newly revised recommendations are available, ones based on additional research and experience. Much more research is needed to advance the state of the art, and while some of that is underway, a great deal

is lacking. In one recent review of future needs, both "more research" and "better dissemination of current and future research results" ranked very high. The lighting community is currently active in studying "visibility" as a standard for the future with respect to designing and evaluating lighting installations. This method has much to recommend it, for visibility is really the task for so much of our outdoor lighting. When these new standards are well understood and in place, we can expect that future lighting levels will more closely relate to actual needs. Astronomy will always benefit from additional research into lighting issues. We need to encourage strongly all those involved in such research efforts.

2. Remove the non-visible "light". Any light sources that emit any significant amount of such energy are not cost effective. For example, the mercury vapor light so common in outdoor lighting emits a great deal of ultraviolet energy, of no use for visual tasks. It is just wasted energy. More efficient light sources should be used for almost all applications. In addition, ultraviolet light scatters much more than does longer wavelength light, and so it is more of a problem to astronomy. Such wasted "light" should be eliminated by the choice of a more efficient light source, or by filtering out the offending energy.
3. Control the emitted light by shielding, placement, etc. Shine the light only where it is needed. In most cases, that means downwards. Hence the strong emphasis on the use of full cutoff lighting fixtures, ones that avoid any direct up going light and also greatly minimize glare, spill light, and light trespass.
4. Take advantage of light controls, such as timers and dimmers. As with the rest of the items, this one is rather obvious and offers obvious benefits. Only use light when you need it, and if less will serve, dim it down. Why do parking lots need to be lit all night when no one is there?
5. Consider also the effects of air pollution, ground reflection, etc. Signs and billboards are one place where this consideration can be applied, for example, by using light colored lettering on darker backgrounds. Contrast is good, and sky glow minimized.
6. Use low pressure sodium whenever possible. Since LPS is essentially a monochromatic light source, it can be filtered out by astronomers rather well for most research applications. Hence the sky remains dark, while the ground is well lit. One hears many objections to the use of LPS as a lighting source. Most of these are not well thought out. The lack of color is the item most often mentioned. However, with creative design, this is no problem (and often no problem anyway). There is even a new automobile sales lot lit with LPS in the Tucson area. No problem. The designer added about 10 percent white light (metal halide or fluorescent lamps) and color rendering is near perfect. No one has ever brought a car back the next day because it had a different color than when they bought it the night before. Two other factors are also important to consider. First, in almost all areas where LPS is used, there are also other light sources being used. Only a few of these nearby are enough to offer adequate color rendering to the scene. Second, at low lighting levels (scotopic), the eye is not seeing color anyway, as the rods in the eye are not color sensitive. While the Purkinje effect also holds for these lighting levels, LPS is still a very viable solution for most applications. This issue of color sensitivity shifts in the eye at lower lighting levels is another topic now much under discussion. One of

the items being pushed currently is the use of whiter light sources at the low light levels often encountered in outdoor lighting. While there is some validity to these arguments, such decisions must be carefully investigated, both in the area of the eye efficiency and in the area of life cycle costs of proposed installations.

9. Lighting Levels

How we perceive a visual object has to do with its brightness (luminance), its contrast, its size, and how long we have to observe it. All of these factors are interrelated. To improve the visibility of an object (a sign, for example), we can use the following options:

1. Increase the luminance (lighten up on the color, or add more light).
2. Increase contrast (change the foreground luminance vs. the background luminance).
3. Increase the size (make the sign or lettering larger).
4. Increase the length of time one views the object.

It is important to remember that using a large quantity of light does not guarantee good visibility. In fact, over-lighting is often the cause of glare and other problems that hamper good visibility. The eye can see very well over a wide range of lighting levels, from fainter than moonlight to bright sunlight (over a range in brightness of 10^7, in fact). While the eye is very adaptable, it can adapt to only one light level at a time, and it takes some time for it to adjust (transient adaptation). If there are no bright sources nearby to cause the eye a problem, we see very well in a night scene illuminated only by moonlight, as any amateur astronomer knows well. But if a bright flashlight is turned on, one loses that adaptation and sees only what is illuminated by the flashlight. When the eye's nighttime view includes a range of light intensities, it adjusts to the brightest level and the other areas look dark. So a good lighting installation will have:

1. Illumination levels appropriate for the task, not overkill.
2. Reasonably uniform illumination levels (but with adequate contrast).
3. No glare sources in the field of view.

One of the keys to good lighting is to use transition lighting. By that, I mean avoiding the situation where immediately adjacent properties have greatly different lighting levels. The one with the lower lighting levels may be perfectly well lit, according to standards, but it will look dim compared to the overlit property. One might even say that this fact is one of the main reasons for over lighting: be sure and light up more than your competitor, no matter what rational standards for task lighting say. This type of overkill leads to ratcheting up lighting levels to far beyond any reasonable level. One hears justifications of safety and security, but they are false justifications as recommendations for just such goals have been far exceeded.

Any lighting designer should carefully analyze the lighting task, including all relevant factors. This then leads to a lighting solution that allows adequate visibility for the task and enhances the environment as well. Choosing the lighting level is one of the key elements in this design process. Some tasks need very little light, while others require more. Using only the amount of light necessary saves energy, decreases sky glow, minimizes light trespass, and avoids escalation of lighting levels in the surrounding neighborhoods. It does a good job of enhancing visibility, and sets a good example of environmentally friendly lighting.

Most tasks that require lighting have been investigated by the CIE and the IESNA, and they have published recommendations for light levels for those tasks. These are guidelines and should be adjusted for specific site conditions. It is important to understand that these recommendations have been reached by consensus among technical committee members based both on research and on more subjective factors.

10. Glare

There are many good discussions of glare in the literature. I include only a short discussion of the issue here. Interested readers are urged to investigate the topic further via some of the papers referenced in the References.

Glare, as it affects human vision, is commonly divided into two components, disability glare and discomfort glare. They are not completely separate, but they can be looked at separately. Disability glare, or veiling luminance, is glare that compromises visual performance, while discomfort glare does not necessarily do so.

Stray light is produced in the eye by sources of different contrast within the field of view, and must be taken into account in any quality lighting design. Such stray light produces a veiling luminance (L_v) which is superimposed upon the retinal image of the object being viewed. This alters the apparent brightness of the object and the background against which it is being viewed, thereby impairing the ability to perform visual tasks. Veiling luminance can not be completely eliminated, but it can be greatly reduced by careful, quality lighting design.

The L_v of a roadway lighting system can be calculated from the observer's position by the following empirically formula, calculating the L_v for each luminaire separately and summing the individual values: $L_v = 10E_v/(\theta^2 + 1.5\theta)$, where E_v is the vertical illuminance (lux) in the plane of the pupil of the observer's eye, θ is the angle between the observer's line of sight and direction to the luminaire, in degrees. L_v is in cd/m^2. Tables are given in the various recommended practices for limiting values of L_v.

Discomfort glare and disability glare are related to the light flux produced, source size, displacement angle of the source from the direction of view, illuminance at the eye, adaptation level, surrounding luminance, exposure time, motion, and the observer's age and condition of the eye.

Both the CIE and the IESNA have active technical committees and individuals working on the various aspects of glare, a most important factor in vision at night. Glare never helps visibility, and quality lighting designs must always minimize the adverse impact of glare.

11. Energy Savings

Certainly this topic is one of interest to everyone, and it is one of the big pluses in our efforts to educate people about the advantages of quality lighting. While it is possible to do many calculations relative to the issue and to talk about it at great length, I will discuss it here mainly by extracting information from two documents.

The booklet produced by a group in Vermont USA has a very good section on energy savings. They note that most past efforts to conserve energy for exterior lighting have focused on the use of energy efficient lamps. Using such lamps could in principle conserve a lot of energy, if one lights to the same levels as the energy inefficient installations. However, many who have replaced older lamps with newer, more efficient lamps have done so at the same wattage levels, not at the same lumen levels, in the mistaken belief that "the more light the better". Because electricity has traditionally been inexpensive, this was an easy thing to do. The result has been a ratcheting up of lighting levels, and much more glare, light trespass, urban sky glow, and energy waste. In most cases, accidents have not gone down, nor has safety and security been improved. The lighting level before the change was adequate for those goals.

The report recommends:

1. Use appropriate light levels. A well designed installation uses only the amount of light needed for the task and will eliminate overlighting.
2. Reduce glare. Use the proper fixtures to insure improved visibility.
3. Reduce wasted light. Light that spills from fixtures directly up into the sky or toward a neighbor's window is wasted light energy. Full cutoff fixtures avoid these problems.

The study panel estimated the amount of energy that could be saved in Vermont. In the year 2000, the total electricity demand in Vermont is expected to be 21 trillion BTUs per year, costing 69 million dollars. Standard estimates hold that 25 percent of all electrical usage is for lighting and that 2.5 percent is used for outdoor lighting. That means that in the year 2000 Vermont will be using 0.13 trillion BTU's per year, costing 3.6 million dollars. If 30 percent of this is wasted energy (perhaps a conservative estimate), then over one million dollars a year could be saved. And that is just in the state of Vermont, a rather small state by population standards.

They note that every installation is unique, however. Each user must balance all the variables according to the needs and priorities. It is important that any proposed lighting installation be subject to a life cycle cost analysis and that dollar costs take into account the quality of light provided and its impact on the surrounding areas.

To supplement their discussion, I will give here a few facts about the energy efficiency of several different lamps used commonly for outdoor lighting installations. I choose lamps that offer about the same amount of light output, one at the levels common for the lighting of major streets and one at a level common for residential streets or even for some home lighting applications.

The circuit wattage includes both the lamp wattage and the ballast losses. Mean lumens per watt is a measure of the relative efficiency of the lamp output, as is the annual KWH usage, of course. Note that these efficiency figures are for the lamps and ballast only, and do not include fixture efficiencies or any other items. These later values vary greatly with the application and with the specific installation and should be included in any full examination of costings. Life cycle costing involves additional items as well.

12. Implementing the Solutions

It is clear that solutions do exist, and that they work. The key is to build awareness of the solutions (and of the problem) and implement their use.

Table of Relative Lamp and Circuit Efficiencies:

Mean lumens in the range of 25,000 to 33,000:

Lamp type	LPS	HPS	MH	Mercury
Lamp wattage	180	250	400	700
Circuit wattage	220	294	456	765
Mean lumens/watt	150	87	63	39
Annual KWH usage	902	1205	1870	3137

Mean lumens in the range of 5000 to 7000:

Lamp wattage	35	70	100	175
Circuit wattage	60	88	115	205
Mean lumens/watt	80	64	56	35
Annual KWH usage	246	361	472	841

Even though the educational efforts have been underway for only a limited time, there has been a lot of activity and progress is being made. Examples of such progress are noted in a few places in this article and many are given on the International Dark-Sky Association's web page, at www.darksky.org.

Here are a few suggestions on how to build awareness and encourage implementation.

1. First, educate yourself about the problem and about the solutions. Resources for this exist, and can also be used to educate others. The International Dark-Sky Association has many such resources available. Most people you will be talking to have little or no information on the issues, and you will become their local expert in many cases.
2. Contact staff in cities and counties to make them aware of the problem and the fact that solutions exist. Show them what is being done elsewhere to combat the problems. Give them literature, including copies of outdoor lighting control ordinances in other cities. This approach has been successful. Many ordinances are now in place. (The IDA Web site lists many such locales.) The number is growing rapidly. Many more people are aware of the issues and that something can be done.
3. Work at educating everyone, the public, community leaders, neighborhood groups, environmentalists, professional astronomers and their organizations, amateur astronomers and their organizations, lighting engineers and designers, electrical utility companies, the media, everyone.
4. Action is called for, and now, before things get any worse. Get involved!

13. The Eye

The eye functions somewhat like a camera, in that it has a lens, and iris, and photosensors. There are two types of photosensors, located at the back of the eye in the retina, which acts rather like the film in the camera. Light falling on these sensors activates chemical reactions and sends messages to the brain, which interprets them as images of the visual scene around us.

These two types of photosensors are called rods and cones. The cones are located mostly in the very center of the eye (the fovea), and send very detailed, sharp images to the brain. They perceive color well but are not as sensitive to light as are the rods. The rods are located mostly away from the center of the eye and are more sensitive to light than are the cones. They have no color sensitivity. They are very sensitive to motion, but not to details. We see details by looking directly at an object, such as print on a page, but we can and do see motion very well away from the center of view. Since the rods are more sensitive to light at low levels than are the cones, we see better at low levels by using peripheral vision (looking a bit away from what we are trying to see) than we do by looking directly at the object we are trying to detect. This fact is well known by all astronomers, of course.

At night, at very low light levels, we see with the rods only and our color sensitivity is non existent. We see mostly by distinguishing light from dark and by detecting motion. At the level of strong moonlight, vision with the cones has come into play as well, and some colors can just be detected, though color vision is not good. At higher lighting levels, the cones are fully in operation and we see color well and a great deal of detail in the image the eye is detecting. We call vision at the lowest lighting levels "scotopic", at the high lighting levels "photopic", and the region in between "mesopic" (where both rods and cones are in action).

The iris in the eye stops down under high lighting levels and opens up in low lighting levels, just like the iris in a camera does, reducing the amount of light entering the eye. If we have too much glare (and it doesn't take much) in the field of view when the overall lighting level is low, the iris stops down to cut the glare, and so we see less well. In addition, the fluid in the eye, and even the impurities in the lens, can cause scattering of the incoming light, giving a veiling luminance in the presence of glare. In fact, glare is often discussed and quantified by the term veiling luminance. Such scattering in the eye increases with age, and the older eye is more sensitive to glare than is the young eye.

The eye also adapts very well to changing levels of light, and we can see remarkably well over a very wide range of lighting levels. This adaptation involves chemical changes in the retina as well as changes in the size of the iris. These changes are not immediate, and so when going from a brightly lit scene to a dark one, the eye takes a while to adapt. This is called "transient adaptation". It also occurs on going from a dark scene to a brighter one, but the eye does adapt quicker in this case. To achieve a fully dark adapted eye can take as long as a half an hour.

It is critical to understand and allow for these properties of the eye and of vision in the successful design of nighttime lighting installations. Not to do so is to compromise visibility.

14. Roadway Lighting

Roadway lighting as discussed in many applications includes not only roadways (streets and highways) but parking lots, walkways, bikeways, and other such uses. In the discussion below, taken mostly from the IESNA Roadway Lighting Standard Practice, one should remember that it is not just streets and highways, but that these other applications of "roadway" lighting that are included as well.

RP-8, the Recommended Practice for Roadway Lighting, produced by the IESNA, lists the following as the purpose of roadway lighting: *To produce quick, accurate, and comfortable seeing at night. Every designer should provide for those inherent qualities required by the roadway user, making the streets and highways as useful during the hours of darkness as well as during the daytime. The proper use of roadway lighting as an operative tool provides economic and social benefits to the public, including:*

1. *Reduction in night accidents, attendant human misery, and economic loss.*
2. *Facilitation of traffic flow*
3. *Aid to police protection*
4. *Promotion of business and industries during the night hours*
5. *Inspiration for community spirit and growth.*

One would think that items 1 and 2 are the main drivers and reason for roadway lighting, the other three being added benefits. Few if any communities would light streets solely for items 3, 4, and 5.

Darkness brings increased hazards to users of streets and highways because it reduces the distance they can see. The fatal accident rate at night is about three times greater than in the daytime, based on proportional vehicle kilometers of travel. There are additional factors interacting at night with the reduced visibility that help account for this higher nighttime rate. They include glare from the fixed lighting system and from the extraneous off-roadway lighting, defective, inadequate, or improperly maintained or used vehicle lighting, driver fatigue, increased use of alcohol and other drugs, and declining visual capability (perception, adaptation, accommodation, and glare tolerance) "particularly for the older driver" at the lower lighting levels available at night.

There are also energy management implications, and the designer is urged to utilize efficient luminaires and lamps, a good maintenance program, and appropriate mounting heights and luminaire positioning.

The recommended practice is given presently in terms of either illuminance or luminance, and the new recommended practice now under final discussion (summer of 1998) will include these and will add "small target visibility" as an additional method. This latter method will change many of the old rules of thumbs about roadway lighting, and will probably have the net result of lowering some of the recommended lighting levels, emphasizing even more the impact of veiling luminance (glare), and decreasing the emphasis on uniformity of the roadway lighting.

Some of the important considerations in roadway lighting design include:

1. Quality. In this sense, it means the relative ability of the available light to provide the necessary contrast differences so that people can make quick, accurate, and comfortable detection and recognition of the cues required for the lighting task.
2. It must be recognized that changes to optimize one factor may adversely affect another and the total quality might well be adversely affected.
3. Key items to consider include:
   a) Uniformity
   b) Luminaire mounting height
   c) Luminaire spacing
   d) Luminaire selection
   e) Lighting system depreciation
   f) Veiling luminance (glare)

g) Traffic conflict areas (intersections, crosswalks, etc)
h) Roadside areas (walkways, houses, etc)
i) Lighting termination (where the road lighting ends)
j) Partial lighting and multi-level lighting
k) And so on.

RP-8 gives a detailed discussion of all of these issues, and many examples of How To, including how to calculate illuminance and luminance designs meeting the IESNA recommendations given in the Standard Practice.

I must add an additional item to the list of criteria for quality lighting: Don't over light. Since there will always be dark areas at night, it is essential to remember transient adaptation issues and allow for transition from such dark areas to areas that are lighted. This should occur in stages, and the process is discussed in depth in other IESNA documents, such as the upcoming RP-33, on Outdoor Environmental Lighting. Continuing to ratchet up lighting levels beyond what is needed is not a good design process. Use IESNA and CIE recommended lighting levels. Overkill never helps, it usually just adds glare and it always wastes energy.

15. Pole Spacing and Other Geometric Considerations

There are quite a number of geometric considerations relative to outdoor lighting. This section will discuss a number of them, especially relative to their impact on light pollution considerations.

Consider the light coming from a lighting source (or fixture), such as a street light or a parking lot light. The down going light falls on a surface such as the street pavement. Assume a flat surface under the light and over the area being lighted by the light output from the fixture. We will consider the geometry of a light beam that hits the surface some distance away from the pole supporting the light source, or, more exactly, from the point directly below the light source. The following definition and lighting *laws* apply:
H = Mounting height of the light = the distance of the light above the surface.
D = the distance from the light source to where the light hits the surface.
θ = the angle between the vertical and the direction in question, that is, between the H and D lines. For example, 0°is straight down and 90°is horizontal.
X = the distance between the spot directly beneath the light source and the point where the light hits the surface.
Note that X = H $tan\theta$, D = H/$cos\theta$, $sin\theta$ = X/D, $cos\theta$ = H/D, and $tan\theta$ = X/H.

The **Inverse Square Law** states that the illumination E at a point on a surface varies directly with the luminous intensity I and inversely as the square of the distance D between the source and the point in question. If the surface is normal to the direction of the incident light, then $E = I/D^2$. The light is getting spread out over a larger area as it gets further from the source.

The **Cosine Law** states that the illuminance on any surface varies as the cosine of the angle of incidence. The light is falling on a larger area than if it hit perpendicular to the surface. It can be combined with the inverse square law to become $E = Icosq/D^2$.

Table

Angle θ	X	D	D^2	$1/D^2$	PS (ft) If MH = 30 ft	PS/MH
45°	1.00	1.41	2.0	0.50	60	2.0
60	1.73	2.00	4.0	0.25	104	3.5
65	2.14	2.37	5.6	0.18	128	4.3
66	2.25	2.46	6.0	0.16	136	4.5
70	2.75	2.92	8.5	0.12	170	5.7
71	2.90	3.07	9.4	0.11	174	5.8
71.6	3.00	3.17	10	0.10	180	6.0
75.1	3.75	3.89	15	0.07	224	7.5
80	5.67	5.76	33	0.03	340	11
80.5	6.00	6.06	37	0.03	360	12
82.9	8.00	8.09	65	0.02	480	16
84.3	10.00	10.00	100	0.01	600	20
85	11.43	11.47	132	0.01	680	23
87.5	22.90	22.93	526	0.00	1370	46

The **Cosine Cubed Law** arises from substituting $H/cos\theta$ for D to get $E = Icos^3\theta/H^2$.

Let us now consider the issue of pole spacing relative to any lighting design. The angles and distances that we illustrate in the table below could refer to either the cutoff angle (no light at all emitted at an angle above the angle in the table) or to the angle of maximum candlepower output of the luminaire, or even to any angle under investigation. The optimum pole spacing is sometimes considered to be the distance at which the maximum candlepower output from two luminaires meet on the ground between the poles. Other scenarios are possible, of course, and more likely to be seen in practice. The rows in the table have been calculated with either the angle or the value of X as the dependent variable, and the calculated values have been rounded off in most cases. The mounting height of the lighting luminaire above the ground, the horizontal spacing of one pole to the next, and the cutoff angle of the luminaire are all important issues in outdoor lighting design, just as is the choice of the luminaire, the lamp type, and the wattage of the lamp. The luminaire optics control the distribution of the light output, for example, as a function of the angle. Higher poles often mean the need for less poles, but increase the lamp wattage needed. Lower poles coupled with poor luminaire optical control can mean a lot of glare. And so forth. A careful investigation of all relevant factors is needed for any good design. The table offers insight to just the pole spacing issue. It relates some of the geometry of pole spacing relative to cutoff angles.

At high cutoff angles, the X and D dimensions really stretch out, and the $1/D^2$ values show that there is little light left to light up anything. There is no excuse to have cutoff values of even 80°much less no cutoff values at all. Any higher angles do not add anything to the effective light distribution, but they still do produce significant glare.

In fact, a cutoff angle of about 75°or less appears to make very good sense. This still allows sufficient overlap of the beams from two adjacent fixtures. The key to designing a "good" lighting fixture is to get the maximum light output at an angle of say 65°to 70°, thus getting a good light throw out away from under the lighting fixture (avoiding a "hot spot" under the fixture) while at the same time getting a sharp cutoff at an angle of 75°. The result is a uniform distribution of light on the ground out to a distance of at least six mounting heights from the pole, minimum glare, and no direct uplight.

16. Security and Outdoor Lighting

Certainly, safety and security are major topics discussed in any decision to install or upgrade outdoor lighting. It is an issue in all outdoor lighting and especially in that labeled security lighting - lighting installed to enhance the protection of people or property. Unfortunately, security lighting is often a significant source of glare, light trespass, and overlighting.

It is widely accepted in the lighting and in the security communities that lighting in itself does not prevent crime, but that it does increase the perception of safety and security in most people's minds. All types of crime occur at all hours of the day and night. Despite the widespread and increasing use of security lighting, there is little definite evidence that such lighting has been a detriment to crime. Clearly, the usage of outdoor lighting has increased greatly over the last decades, but so has the fear of crime and perhaps even the level of crime. Lighting appears to have done little or nothing to help. A cynic might even say that the increase in lighting levels correlates well with the increase in the crime levels.

It is my firm belief that quality lighting can and does help, but that poor lighting makes the criminal's job easier and does little or nothing to help with the safety and security problems. In addition, security lighting is only one component of a well planned security system. Gates, locks, detection devices, guards, and many other items are part of an effective security system.

The Vermont report discussed earlier includes several paragraphs that I quote here:

Crime is a complex social issue that includes many community factors. For a crime to occur, there must be three criminal opportunity elements: a suitable target, a motivated offender, and the absence of a witness. Lighting can play a direct role in discouraging crime by increasing the "witness potential". The perception of visibility and the increased chance of being identified may make the criminal less motivated.

The goal of security lighting then is to increase the potential of a criminal being seen and identified. Security lighting should therefore be designed to produce good visibility. Lights that are too bright or too glaring can prevent good visibility.

If a facility is located at a remote site where there is no guard nor neighbors, surveillance cannot take place and security lighting will not be effective. It is better then to have an alarm system rather than lighting. There are applications where the "no lighting at all" approach has proven to be very effective with regard to vandalism and crime.

Another way that quality lighting helps is that it can play an important part in raising the comfort level of people at night, for those using streets, parking lots, and shopping areas. The more people in an area, the safer it usually is. A study of crime levels at convenience markets in Tucson showed that there was a strong positive correlation between the quality of lighting, the number of people using the facility, and the lack of crime at the facility. Quality lighting does have value.

We must light our public and private areas in an inviting manner. Harsh and glaring lights discourage public use. Overlit streets have become associated with high crime areas. Lighting should be comfortable and attractive.

17. The CIE - Commission Internationale de l'Eclairage (The International Commission on Illumination)

The CIE is an international organization whose goals are:

1. To provide a forum for the discussion of matters relating to science, technology, and art in the fields of light and lighting, and for interchange of information among countries.
2. To develop basic standards and procedures of metrology.
3. To provide guidance in the application of principles and procedures in the development of international and national standards.
4. To prepare and publish reports, reviews, recommendations, and standards.
5. To maintain liaison and technical interaction with other international organizations.

There are approximately 35 countries who are members of the CIE, participating in activities through a National Committee whose members contribute their time and talent. Persons from countries where a National Committee has not been formed may join the CIE as Individual Members. For example, the United States National Committee of the CIE (USNC/CIE) has approximately 315 members, representing a wide spectrum of professional interests in all aspects of lighting. The CIE was formed in 1913, and throughout the years has been recognized as the source for internationally agreed upon information on subject matters relating to light and lighting.

There are seven divisions in the CIE, and over 100 Technical Committees. Through the work of these committees and divisions, the CIE develops international agreements on reports, recommendations, and standards for many areas of lighting research and practice. The CIE also maintains formal contact with other international organizations, including the International Astronomical Union.

The current CIE Divisions are:

Div 1: Vision and Colour.
Div 2: Measurement of Light and Radiation.
Div 3: Interior Environment and Lighting Design.
Div 4: Lighting and Signaling for Transport.
Div 5: Exterior and Other Lighting Applications.
Div 6: Photobiology and Photochemistry.
Div 7: General Aspects of Lighting.

Division 4 studies lighting and visual signaling such as road and vehicle lighting, signing, and so forth. Division 5 studies procedures and prepares guides for the design of lighting for exterior working areas, security lighting, floodlighting, pedestrian and other urban areas, and sports and recreational lighting. Division 7 studies and evaluates activities in terminology, education, economics of lighting, and provides information on the development of light sources.

A plenary session of the CIE is held every four years, in one of the member countries. The one in 1991 was held in Melbourne Australia, the one in 1995 in New Delhi India, and the one in 1999 is scheduled for Warsaw Poland. At these meetings, papers are given and most of the Technical Committees hold meetings. These TC's also hold other meetings in the intervals between the plenary sessions. They produce a number of publications as a result of their work, all available from the CIE.

The TC's come and go, depending on the need and on the level of activity of the members. Many of these TC's are of interest for those involved in outdoor lighting and light pollution issues. I list a few of them here:
TC 1-18 Disability Glare
TC 1-23 Photometry of Street Lighting Luminaires
TC 4-03 Urban Lighting
TC 4-21 Interference of Light with Astronomical Observations
TC 5-04 Glare in Outdoor Areas
TC 5-06 Decorative Lighting for Exterior
TC 5-10 Exterior Security Lighting
TC 5-12 Obtrusive Lighting
TC 7-05 Lighting Education
TC 7-07 Light Sources

The CIE address is: Central Bureau of the CIE, Kegelgasse 27, Vienna, Austria A-1030 Their email is: ciecb@ping.at

18. The International Dark-Sky Association (IDA)

IDA is a non-profit organization, incorporated in 1988, whose goals are to preserve and restore the pristine dark skies that most of our ancestors had while at the same time maximizing the quality and efficiency of nighttime outdoor lighting. IDA is a membership based organization, and these members are doing a lot to educate their neighbors and their communities about these goals. As of May 1998, IDA had close to 2500 members, from all of the states in the United States and from 68 other countries. About ten percent of these were organizational members, the remainder individuals, including astronomers, both amateur and professional, lighting engineers and designers, environmentalists, and concerned members of the public.

Lots of useful information is available on the IDA Web site, at www.darksky.org. It also lists many of the other resources that IDA has available to help those involved in the cause. There is a regular newsletter, and many information sheets, images, slides, and several videos. More resources are being added regularly. IDA can supply sample outdoor lighting control ordinances, and lists of communities that have adopted such lighting controls. There are formal IDA Sections and Affiliates in many locations, groups that can act as local centers of information and resources and activities. Naturally, the web site also includes membership forms, and I urge everyone to join. Dark skies need your help.

We estimate that only about 1 percent of those astronomers adversely affected, professionals and amateurs, are currently IDA members. As Dan Green of the Smithsonian

Astrophysical Observatory, said in a recent issue of Sky&Telescope (May 1998): *Where are all the astronomers? If astronomers don't care about dark skies, who will!*

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19. Summary

Have you looked up at night lately in any of the world's cities? Or most anywhere? The prime view of the stars and the universe that our ancestors had is gone. It has been stolen away by the growth of so much bad outdoor lighting in our urban environment. Yet mankind's view of stars should be, must be, an important part of the nighttime environment, not only to astronomy but to the general public.

Quality outdoor lighting is the key to bringing back the night. With such lighting, we all win. We help preserve the dark skies, we see better (and are safer and more secure at night), we have a more pleasant and comfortable nighttime environment, and we save a great deal of energy and money doing so. Neither astronomers nor the public, anywhere, need any of the adverse environmental effects of poor lighting.

The present paper has reviewed the issues and the problems, and it has gone into detail about the solutions and what we must do to implement them. The key is to build awareness everywhere about the problems and the solutions, and to urge action in attacking the problems. Key elements in the solutions include: limiting direct uplight by the use of quality lighting fixtures and designs, don't overlight, switch off lights when not needed, and take responsibility for insuring that only quality lighting is used.

The International Astronomical Union (IAU) and the International Commission on Illumination (CIE), as well as many national and local organizations, have become active in the educational and implementation efforts. Laws have been passed in many locations to control the spread of obtrusive lighting. The pace is accelerating, and we must encourage it.

Help is available from the International Dark-Sky Association, a non-profit organization. IDA is a membership based organization with members now in close to 70 countries. IDA has produced many information sheets discussing the issues, as well as slide sets, videos, and other resources. Check out IDA's Web page on the Internet: http://www.darksky.org

There is a slowly growing awareness of the problems, and of the solutions, but much more educational outreach is needed. It is clear that there is a worldwide problem with light pollution, and it is still getting worse most everywhere. However, there are solutions, and they work. They also improve the quality of our nighttime lighting, and they help us save a great deal of energy and money. Lack of awareness and apathy are the main problems.

20. Appendix One: Summary of Radiant and Lighting Units

This appendix is partially extracted from a paper by the author given at a conference organized by Commission 50 of the IAU (International Astronomical Union) and Technical Commission TC 4-21 of the CIE (Commission Internationale de l'Eclairage), in The Hague, Netherlands, in 1994. A summary of this paper has been published in The Observatory, 117, 14-18, 1997. The reader should see this publication for more details and discussion of units. Other references relative to units and terminology are given in the References.

Some of the relations between the units are given in the table. A few others are:
1 fc = 10.76 lux.
1 cd/m^2 = 0.2919 footlambert = 3.1416 apostilb = 0.3142 millilambert
= 10^{-4} stilb = 0.0929 cd/ft^2 = 6.45 $10^{-4} cd/in^2$
1 nit = 1 cd/m^2 = 1 $lm/m^2 sr$ = 1 lux/sr
1 radian = 57.29578 degrees
1 meter (m) = 3.282 ft
1 joule = 1 watt sec = 10^7 erg 1 kw-hr = 3.6 10^6 joule
1 nm = 10^{-9} m = 10 Angstroms = 10^{-3} microns (micrometer)

A few notes about the eye's sensitivity: The eye can see over a range of 10^7 in brightness (luminance), when well adapted. The minimum perceptible light level the eye can see is about 5 $10^{-6} cd/m^2$. Rods and cones in the eye have different sensitivities. We use the term scotopic to refer to vision with the rods and photopic to vision with the cones. Cones have three different sensitivity bands: B at about 450 nm, G at about 550 nm, and R at about 580 nm, with the overall maximum sensitivity at about 555 nm. Rods have their maximum sensitivity at about 507 nm. People vary greatly in their luminous efficiency.

While color is a complex issue, we can usually assume the following:
Red $>$ 610 nm approximately
Orange 590 to 610 nm
Yellow 570 to 590 nm
Green 500 to 570 nm
Blue 440 to 500 nm
Violet $<$ 440 nm
Infrared is beyond the red ($>$ 770 nm) where the eye is not sensitive.
Ultraviolet is beyond the violet ($<$ 380 nm) where the eye is not sensitive.

The relation of these lighting units to some photometry units used in astronomy are also discussed in the paper referenced above. A few of these are extracted here.

1 footcandle (fc) = 1 lm/ft^2 = 10.76 lux = 4.2 10^6 stars of $m_V = 0$.
1 nanoLambert (nL) = 3.18 $10^{-6} cd/m^2$ = 4.6 10^{-4} stars of $m_V = 0$ per sq degree =

Table: Definitions and Units

Item	Symbol	Defined	Unit
Radiant energy (quantity)	Q_e		**joule**, KWH, erg
Radiant flux (power)	$F_e = \Phi_e$	dQ_e/dt	**watt**, joule/sec, erg/sec
Spectral radiant flux	$F_{e,\lambda}$	$dF_e/d\lambda$	**watts/nm**
Radiant flux at a surface Incident E = Irradiance (E) Emitted E = Exitance (M)	E_e	dF_e/dA	**watt/m²**
Radiant intensity	I_e	$dF_e/d\omega$	**watt/sr**
Radiance	L_e	$dF_e^2/d\omega\ dA \cos\theta$ $= dI_e/dA \cos\theta$	**watt/sr m²**
Quantity of light	Q_v		**lumen sec** (= talbot)
Luminous flux	$F_v = \Phi_v$	dQ_v/dt	**lumen** (lum)
Illuminance = Areal density of luminous flux incident at a point on the surface	E_v	dF_v/dA	**lux** (= lum/m²) (phot = lum/cm² = 10^4 lux) fc (= lum/ft²)
Luminous intensity	I_v	$dF_v/d\omega$	**candela** (cd) (= lum/sr)
Luminance	L_v	$dI_v/dA \cos\theta$, or $d^2F_v/d\omega\ dA \cos\theta$	**cd/m²** (= nit) cd/cm² (= stilb = 10^4 nit) cd/ft² or cd/in² cd/π cm² (= lambert) cd/π ft² (= ft lambert) cd/π m² (= apostilb)
Luminous efficacy	K	F_v/F_e	lumens/watt
Luminous efficiency		K_λ/K_λ(max)	

Notes to the table:

Units given in bold face are the preferred units to use.
Some of the other units are rarely seen, but given here for completeness.
The subscript "e" denotes radiant quantities and "v" lighting quantities.
For example, the relation between the fluxes are $F_v = K_m \int F_{e,\lambda} V(\lambda)\, d\lambda$
where K_m is the maximum spectral luminous efficacy in lm/watt
and $V(\lambda)$ is the spectral luminous efficiency function.
"A" is the symbol for area. "m" for meter. "fc" for footcandle.
"ω" is the symbol for solid angle. The unit is the steradian (sr).
"θ" is the angle between the line of sight and the normal to the surface.
When it is clear if it is radiant energy or light, the subscript can be dropped.

$$26.33\ mag/arcsec^2 = 1.31\ 10^6\ photons(555nm)sec^{-1}cm^{-2}sr^{-1}$$

A few "brightness" values (illuminance and stellar magnitudes):
The Sun: = -26.7 mag = 1.2 10^5 lux
Sunlight on the ground on a clear day, 10^5 lux; and on a cloudy day, 10^5 lux.
Average street lighting levels, 3 lux to 10 lux approximately.
Moonlight on the ground, 0.1 lux approximately (0.01 fc), with full moonlight a bit more.
60 W incandescent lamp at 1 km = -3.6 mag = 6.4 10^{-5} lux
Sirius (brightest star) = -1.5 mag = 9 10^{-6} lux

Table of Luminance Values

Source Luminance	cd/m^2	nL	$mag/arcsec^2$
Sun's surface	$1.6\ 10^9$	$6\ 10^{14}$	
750 W tungsten filament	$2\ 10^7$		
Mercury lamp	$1.5\ 10^6$		
60 W frosted incandescent bulb	$1.2\ 10^5$		
Fluorescent lamp	$1\ 10^4$		
A candle	$1\ 10^4$		
Full Moon surface	2500		
Typical clear daytime sky	3000	$5\ 10^8$	
Overcast daytime sky	300		
Zenith at sunset	100	$3\ 10^7$	
Typical sky in a big city	3	$1\ 10^6$	11.3
"Twilight"	3		
Lower limit of photopic vision	3		
Zenith at Civil Twilight	$3\ 10^{-1}$	$1\ 10^5$	
Typical sky at Full Moon	$3\ 10^{-2}$		16.8
Upper limit of scotopic vision	$3\ 10^{-2}$		
Sky with 10 day Moon	$5\ 10^{-3}$	1500	18.5
Zenith for an avg dark sky site	$6\ 10^{-4}$	180	20.7
Zenith for a good dark sky site	$4\ 10^{-4}$	120	21.1
Darkest sky ever observed	$2\ 10^{-4}$	54	22.0
For comparison	$3.2\ 10^{-6}$	1	26.33

A table extracted from the paper referenced above is included here (with some additions) to show some representative luminance values:

And a few relationships between the various units:
Night sky at the zenith: 400 10th mag stars/sq degree = 30 10^{-5} cd/m^2
m_V = 0 stars per sq degree, outside the atmosphere = 0.820 10^{-6} cd/m^2
m_V = 0 star, outside the atmosphere = 2.43 10^{-6} lux.
m_V = -14.0 - 2.5 log(I), for I in lux, or -16.6 for I in fc.

And finally, a few other bits of useful data, relative to lighting and the visual spectrum:
Mercury emission lines in the spectrum: 365.0, 404.7, 435.8. 546.1, 577.0, 579.1 nm.
Sodium resonance lines: 588.997 and 589.594 nm.
Hydrogen Balmer lines: 656.3, 486.1, 434.0, 410.2 nm.
H and K lines: 396.8 and 393.3 nm.
OII 372.7; OIII 495.9 and 500.7; NI 654.8 and 658.4; OI 557.7, 630.0, and 636.4 nm.

21. Appendix Two: Glossary of Basic Terms and Definitions:

A great deal of understanding can be obtained by just understanding the terminology of the subject. I therefore include here a rather comprehensive glossary of many of the definitions, basic terms, and words used in the lighting community. Some common terms which are rather obvious have been omitted (such as time clock, or lighting pole). I have also not included here any terms relating primarily to color nor to interior lighting. For further information and precise definitions, see discussions in standard dictionaries, encyclopedias, the various CIE and IESNA documents, and other lighting industry books and articles.

Glossary

Accent lighting: Lighting used to emphasize or draw attention to a special object or building.

Adaptation: The process by which the eye becomes accustomed to more or less light than it was exposed to during an immediately preceding period. It becomes more or less sensitive to light.

Ambient light: The general overall level of lighting in an area.

Angstrom: A unit of wavelength often used in astronomy, equal to 10^{-10} meter or 0.1 nanometer.

Baffle: An opaque or translucent element to shield a light source from direct view.

Ballast: A device used with a discharge lamp to obtain the necessary voltage, current, and/or wave form for starting and operating the lamp.

Beam spread: The angle between the two directions in the plane in which the intensity of is equal to a given percentage (usually 10 percent) of the maximum beam intensity.

Bollard: A luminaire having the appearance of a short, thick post, used for walkway and grounds lighting. The optical components are usually top mounted.

Brightness: Strength of the sensation which results from viewing surfaces from which the light comes to the eye.

Bulb or lamp: The source of electric light. Distinguish from the whole assembly (see luminaire).

Candela (cd): Unit of luminous intensity. One candela is one lumen per steradian. Formerly called the candle.

Candlepower distribution curve: A plot of the variation in luminous intensity of a lamp or luminaire.

Candlepower: Luminous intensity expressed in candelas.

CIE: Commission Internationale de l'Eclairage. The International Lighting Commission.

Coefficient of Utilization (CU): Ratio of luminous flux (lumens) from a luminaire received on the "work-plane" [the area where the light is needed] to the lumens emitted by the luminaire.

Color rendering: Effect of a light source on the color appearance of objects in comparison with their color appearance under normal daylighting.

Cones and rods: Retinal receptors. Cones dominate the response when the luminance level is high, and provide color perception. Rods dominate at low luminance levels.

No rods are found in the central part of the fovea. Rods have no color perception ability.

Conspicuity: The capacity of a signal to stand out in relation to its background so as to be readily discovered by the eye (as in lettering on a sign, for example).

Cosine law: Illuminance on an surface varies as the cosine of the angle of incidence of the light. The inverse square law and the cosine law can combined: $E = (Icos\theta)/d^2$.

Curfew: The time after which stricter requirements for the control of obtrusive lighting apply; often a requirement imposed in outdoor lighting control ordinances.

Cut off angle, of a luminaire: The vertical angle, measured up from the nadir (=straight down), between the vertical axis and the first line of sight at which the bare source (the bulb or lamp) is not visible.

Cutoff fixture: A fixture that provides a cutoff (shielding) of the emitted light. In roadway lighting, it is more precisely defined as when the candlepower per 1000 lamp lumens does not numerically exceed 25 (2.5 percent) lumens at a vertical angle of 90 degrees above the nadir and 100 (10 percent) lumens at a vertical angle 80 degrees above the nadir. This applies to any lateral angle around the luminaire. See also full cutoff fixture and semi-cutoff fixture.

Dark adaptation: The process by which the eye becomes adapted to a luminance less than about 0.034 candela per square meter (0.01 footlambert).

Diffuse reflection: Reflection where the incident flux is redirected over a range of angles.

Disability glare: Glare resulting in reduced visual performance and visibility. It is often accompanied by discomfort.

Discomfort glare: Glare that produces discomfort, but not necessarily diminishing visual performance.

Efficacy: The ability of a lighting system to produce the desired result.

Efficiency: A measure of the effective or useful output of a system compared to the input of the system.

Electromagnetic (EM) spectrum: The distribution of energy emitted by a radiant source, arranged in order of wavelength or frequency. Includes gamma ray, X-ray, ultraviolet (UV), visual, infrared (IR), millimeter, and radio regions.

Energy (radiant energy): Unit is joule, erg, or KWH.

Fixture: The assembly that holds the lamp in a lighting system. It includes the elements designed to give light output control, such as a reflector (mirror) or refractor (lens), the ballast, housing, and the attachment parts. See also Luminaire.

Floodlight: A fixture designed to "flood" a well defined area with light.

Flux (radiant flux): The power emitted, transmitted, or received in the form of radiation. Unit is the watt. Radiant flux is at all wavelengths. Luminous flux is the flux at just the (optical) wavelengths at which the eye is sensitive, with the unit of lumen.

Footcandle: The English unit of illuminance. It is the illuminance produced per square foot on a surface by a source of one candela. One footcandle is approximately 10 lux.

Footlambert: The average luminance of a surface emitting or reflecting light at a rate of one lumen per square foot.

Fovea: The small region in the center of the retina (subtending an angle of about 2 degrees) which contains cones but no rods. It forms the site of the most distinct vision.

Full cutoff fixture: A fixture that allows no emission above a horizontal plane through the fixture. In roadway lighting, it is more precisely defined as when the candlepower per 1000 lamp lumens does not numerically exceed 0 (0 percent) lumens at a vertical angle of 90 degrees above the nadir. This applies to any lateral angle around the luminaire.

Glare: Intense and blinding light. Never helps visibility. It is the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility. The magnitude of glare depends on such factors as the size, position, luminance of the source, and of the luminance level to which the eyes are adapted.

High intensity discharge (HID) lamp: In a discharge lamp, the emitted energy (light) is produced by the passage of an electric current through a gas. HID lamps include mercury (Hg), metal halide (MH), and high pressure sodium (HPS). Other discharge lamps are low pressure sodium (LPS) and fluorescent. Some such lamps have internal coatings to convert some of the ultraviolet energy emitted by the gas discharge into visual output.

High mast lighting: Illumination of a large area by means of a group of luminaires which are mounted at the top of a high mast, generally higher than 20m (65 ft).

High Pressure Sodium (HPS) lamp: HID lamp where radiation is produced from sodium vapor at relatively high partial pressures (100 torr).

Illuminance: The luminous flux per unit area incident on a surface. Unit is the lux or the footcandle. It is the amount of light falling on a surface, the density of luminous flux. One lux is one lumen per square meter. One footcandle is one lumen per square foot.

Illuminate: To give light to, to supply light.

Illumination: Lighting up something. Not to be used to denote Illuminance, a technical term.

Illuminating Engineering Society of North America (IES or IESNA): the professional society of lighting engineers and others professionally involved in lighting in North America.

Incandescent lamp: Light is produced by a filament heated to a high temperature by electric current.

Infrared radiation: EM radiation just to the long wavelength side of the visual.

Intensity: The degree or amount of energy or light. See luminous intensity.

International Dark-Sky Association (IDA, Inc.): A non-profit organization whose goals are to build awareness of the value of dark skies and of the need for quality lighting.

Inverse square law: Illuminance at a point varies directly with the intensity of a point source and inversely as the square of the distance to the source. $E = I/d^2$.

Isocandela line; A line plotted to show directions in space about a source of light in which the intensity is the same. A series of such lines is called an isocandela diagram.

Isolux (or isofootcandle) line: A line plotted to show all the points on a surface where the illuminance is the same. A series of such lines is called an isolux diagram.

KWH: Kilowatt-hour. Unit of energy equal to the work done by one kilowatt (1000 watts) of power acting for one hour. Energy is capacity to do work. Power is rate of use of energy.

Lambert's cosine law: The luminous intensity in any direction from an element of a perfectly diffusing surface varies as the cosine of the angle between that direction and the perpendicular to the surface element. A Lambertian surface is a surface that emits or reflects light in accordance with Lambert's cosine law. It has the same luminance no matter what the viewing angle.

Lamp: Generic term for a man-made light source.

Light: Radiant energy (electromagnetic energy) that is capable of exciting the retina and producing a visual sensation. Wavelengths of approximately 380 nm to 770 nm.

Light pollution: Any adverse effect of manmade light. Often used to denote Urban Sky Glow.

Light trespass: Light falling where it is not wanted or needed. Obtrusive light.

Low Pressure Sodium (LPS) lamp: A discharge lamp where the light is produced by radiation from sodium vapor at a relatively low partial pressure (about 0.001 torr). LPS is a "tube source". It is essentially a monochromatic light.

Lumen: Unit of luminous flux; the flux emitted within a unit solid angle by a point source with a uniform luminous intensity of one candela. A source emitting a luminous intensity of 1 cd uniformly in all directions will have a luminous flux of 1 lumen on a unit area of the sphere about it (the area of the sphere is 4 π square units). An isotropic source of luminous intensity of 1 cd will produce a total luminous flux of 4 π lumens.

Lumen depreciation factor: Light loss of a luminaire with time due to the lamp decreasing in efficiency, dirt accumulation, and any other factors that lower the effective output with time.

Luminaire: The complete lighting unit, including the lamp, the fixture, and other parts.

Luminance: At a point and in a given direction, the quotient of luminous intensity in the given direction produced by an element of the surface surrounding the point by the area of the projection of the element on a plane perpendicular to the given direction. It is sort of the brightness we see, the visual effect of illuminance. For reflected light, luminance depends on the amount of illuminance, on the reflective properties of the surface, and the projected area of the surface on the plane perpendicular to the direction of view. Unit: candela per square meter or candela per square foot.

Luminous contrast: The relationship between the luminances of an object and its immediate surrounds. It is equal to $(L_s - L_o)/L_s$.

Luminous efficacy: The total luminous flux emitted by a lamp divided by the total lamp power input. Unit: lumens per watt.

Luminous flux: The radiant flux at only the (optical) wavelengths at which the eye is sensitive. The unit is the lumen. Unless so noted, it will be for the eye's photopic response function.

Luminous intensity: The luminous flux per unit solid angle in a given direction. The unit is candela (cd) or lumens per steradian (lm/sr). It is the "force" generating the luminous flux. It compares to radiant intensity, but holds only for the wavelengths to which the eye is sensitive.

Lux: One lumen per sq meter. Unit of illuminance. It is the luminous flux per unit area.

Mercury lamp: An HID lamp where the light is produced by radiation from mercury vapor.

Mesopic vision: Vision with fully adapted eyes at luminance conditions between those of photopic and scotopic vision, that is at luminance levels between about 3.4 and 0.034 cd/m^2.

Metal halide lamp: An HID lamp where the light is produced by radiation from metal halide vapors.

Mounting height: The height of the fixture or lamp above the ground.

Nadir: Directly down towards the ground. Opposite to the zenith, which is straight up.

Nanometer (nm): 10^{-9} meter. Often used as the unit for wavelength in the EM spectrum.

Nuisance glare: Glare of such a level to cause complaints.

Obtrusive light: Unwanted spill light which, because of quantitative, directional, or spectral attributes in a given context, gives rise to annoyance, discomfort, distraction, or a reduction in the ability to see essential information. Light trespass is often used as a synonym.

Overhang: The distance between a vertical line passing through the luminaire on a pole and the curb or edge of a roadway.

Photometry: The quantitative measurement of light level and distribution.

Photopic vision: Vision at high light levels, essentially or exclusively with the cones, at luminances above about 3.4 cd/m^2.

Point source: A source of radiation whose dimensions are sufficiently small compared with the distance between the source and the irradiated surface so that these dimensions can be neglected in calculations and measurements.

Pole spacing: The distance from one pole supporting a light fixture to the next one.

Purkinje effect: In passing from photopic to scotopic vision, the wavelength of maximum spectral luminous efficiency shifts, the eye becoming more blue sensitive. Hence the perceived brightness of a red light decreases with respect to that of a blue light.

Quality of light: A subjective ratio of the pluses to the minuses of any lighting installation. The pluses enhance visibility, visual performance, visual comfort, safety, security, and esthetics, minimizing glare, light trespass, urban sky glow, and energy waste.

Reflectance: The ratio of the reflected flux to the incident flux. It depends on the geometry and on the character of the reflecting surface. Albedo refers to the reflectance of the ground.

Reflector: Controlling light output by means of reflection (mirror).

Refractor: Controlling light output by means of refraction (lens).

Reference direction: The direction of the maximum luminous intensity from a luminaire, or, where there is no unique maximum, the direction of the center of the light beam.

Retina: The inner most coat lining the interior of the eye, containing the photoreceptive cells (rods and cones) sensitive to light.

Scotopic vision: Vision at low light levels, essentially or exclusively by the rods, at light levels below a luminance of about 0.034 cd/m^2.

Semi-cutoff fixture: One that provides some cutoff, but less than a full cutoff or a cutoff fixture. In roadway lighting, it is defined more precisely as when the candlepower per 1000 lamp lumens does not numerically exceed 50 (5 percent) at a vertical angle of 90 degrees above the nadir and 200 (20 percent) at a vertical angle of 80 degrees above the nadir. This applies to any lateral angle around the luminaire.

Sky glow: The brightening of the night sky that results from the scattering of radiation by the constituents of the atmosphere (gaseous, molecules, aerosols, and particulate matter) in the direction of observation. There is both a natural sky glow attributable to radiation from celestial sources and luminescent processes in the Earth's atmosphere and an artificial sky glow which is attributable to man-made sources of radiation, including that which is emitted directly upward and radiation that is reflected from the ground and other surfaces. The artificial sky glow is often called Urban Sky Glow.

Solid angle: A measure of that portion of space about a point bounded by a conic surface whose vertex is at the point. Defined as the ratio of intercepted surface area of a sphere centered on that point to the square of the sphere's radius. Unit, steradian. (sr).

Spectral luminous efficiency: The ratio of the luminous efficiency for a given wavelength to the value at the wavelength of maximum luminous efficacy. Dimensionless. Different values hold for photopic vision $[V(\lambda)]$ or scotopic vision $[V'(\lambda)]$, and likewise for mesopic ranges.

Specular reflection: Reflection where the incident flux is redirected at an angle equal to the angle of incidence but opposite to the incident angle in the vertical plane.

Spill light. Same as Stray Light. Light spilling outside the boundaries of the property on which the lighting installation is sited. Light straying from where it is needed or wanted. Often causes Light Trespass.

Spot light: A fixture designed to light only a small, well defined area.

Stray light: See Spill Light.

Task lighting: Lighting designed for a specific purpose or task, as opposed to ambient light. Lighting directed to a specific area to provide illumination for a visual task.

Threshold increment (TI): The measure of disability glare expressed as the percentage increase in contrast required between an object and its background for it to be seen equally well with a source of glare present. Higher values of TI correspond to greater disability glare.

Ultraviolet "light": The energy output by a source which is of shorter wavelengths than the eye can see. Some photographic films are sensitive to UV energy, as are many electronic detectors. "Black Light".

Upward light waste ratio (ULWR): The proportion of the flux of a luminaire that is emitted above the horizontal when the luminaire is mounted in its normal installed position.

Urban sky glow: The brightening of the night sky due to man-made lighting.

Veiling luminance: A luminance produced by bright sources in the field of view superimposed on the image in the eye reducing contrast and hence visibility.

Visibility: Being perceived by the eye. Seeing effectively. The main goal of night lighting.

Visual acuity: A measure of the ability to distinguish fine details. Quantitatively, it is the reciprocal of the minimum angular size in minutes of arc of the critical detail of an object that can just be seen.

Visual task: Usually denotes the details and objects that must be seen for the performance of a given activity, such as driving or walking or reading.

Zenith: Straight up. Directly overhead in the sky. Opposite direction to the nadir.

References

General sources, from a number of organizations:

International Dark-Sky Association (IDA) information sheets: There are currently about 140, on many topics relating to the issues. Write IDA, 3225 N. 1st Avenue, Tucson AZ 85719 for a list, or see the IDA Web site (www.darksky.org).

CIE documents contain much useful information; there are many such documents.

Illuminating Engineering Society of North America (IESNA) Handbook, 1993. An excellent basic reference to lighting, full of valuable information and discussions.

Illuminating Engineering Society of North America (IESNA), various Recommended Practices, Technical Memoranda, Design Guides, and other documents.

Some specific books and articles:

Allen. C. "Astrophysical Quantities", 3rd Edition, Athlone Press, Univ. of London.

Budding. E. Astronomical Photometry, Cambridge Press, 1993. A good recent discussion of the topic; gives references to earlier works.

Crawford, D.L. Publ. Astron. Soc. Pacific, 100, 887-895, 1988. A general review of astronomical photometry and its history.

Erhardt, Louis. "Radiation, Light, and Illumination", 1977.

Garstang, R. PASP 103, 1109, 1991; 101, 306, 1989; 98, 364, 1986; Ann. Rev. Astron. 27, 19, 1989. These discuss models of urban sky glow and atmospheric scattering.

Handbook of Optics, Optical. Soc. America,1978, Chapter One, by J.F. Snell, on Radiometry and Photometry.

Schaefer, B. Vistas in Astron. 36, 311, 1993. Many other references are given.

Sterken, C.,and Manfroid, J. 1992. Astronomical Photometry, Kluwer Academic Publishers.

van Bommel, W.J.M., and de Boer, J.V. 1980. "Road Lighting".

Walsh, J. "Photometry", 3rd Edition, 1958. Dover Publications.

A source specifically quoted in the text:

Outdoor Lighting Manual for Vermont Municipalities, 1996. Chittenden County Regional Planning Commission.

A list of references is given by Cinzano:

debora.pd.astro.it/cinzano/refer/index.htm

THE HAZARD TO ASTRONOMY FROM OPERATIONAL SATELLITES

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ABSTRACT. Operations in space are frequently regarded as not creating problems because of a presumed large volume dilution factor. That this is not the case is clear from the threat posed by space debris to operational space craft. However, the problems posed by space activity also impinge directly on astronomy through the crossing of fields under observation, optically and in the IR, by both bright satellites and debris. Telecommunications with operational satellites are having a grave, even potentially disastrous, effect on radio astronomy and the recent development of inter-satellite and satellite-to-ground communications using far red laser beams has the potential to bring the same threat now affecting radio astronomy to optical and IR astronomy.

1. Introduction

The science of astronomy is under significant threat from many activities of a civilised society. These activities produce unwanted degradation of observational astronomy - upon which the whole of astronomy depends for its primary data. Astronomy, unlike any other physical science - apart from seismology - is obliged to "share" its "laboratory" with the rest of mankind. The rest of mankind, being unaware they are in someone's laboratory, create mayhem. The consequences for astronomy of electromagnetic noise at all wavelengths is all too readily documented (Crawford 1989, McNally 1994, this volume, for example). This paper is designed to draw attention to another hazard consequent upon the activities of the rest of mankind - the consequences of the increasing population of operational satellites and associated large debris (non-operational satellites, fuel tanks, rocket motors, etc,.

2. Plate Trailing

Deep sky surveys have brought to light just how common plate trailing has become. The first Palomar Survey rejected plates which carried trails. Now, however, recent deep sky surveys accept plates which carry many trails. Analysis of the counts by Tritton and Norton (1995) of UK Schmidt Plates and analysis of recent SRC/ESO Survey Plates show that 50% of all the plates investigated carry at least one trail and 25% carry' multiple trails. In one instance a single $6^\circ \times 6^\circ$plate carried 13 trails. As the counts were carried out with only modest optical aid, there are likely to be fainter unnoticed trails.

Conventionally such trails are put down as "space debris trails". The nature of the debris is not determined.

The work of Tritton and Norton showed that a steep increase in debris trail rates occurred between 1983/84 and 1985/86. As no super break-up had occurred in that interval, enquiry showed that a filter change had occurred at that time. The data since 1985/86 to 1993/94 was treated as a homogenous sample to compare with the population of satellites for the same period. The data were normalised to the values for 1987/88 to create an appropriate index I_{trail} or $I_{satellite}$ - the values are given in Table I (see McNally & Rast 1998).

Tab. I

Year	Trails/60min exposure	no. of satellites in orbit	I_{trail}	$I_{satellite}$
1985	2.5	1500	1.1	0.9
1987	2.3	1624	1.0	1.0
1989	2.7	1749	1.2	1.1
1991	2.4	1916	1.0	1.2
1993	2.9	2084	1.3	1.3

The satellite numbers are taken from Fig.1-2, p.20 of Orbital Debris (National Research Council, 1995) and the trail data came from the UK Schmidt archive as determined by Tritton and Norton. The satellite index $I_{satellite}$ increases steadily while the I_{trail} increases rather jerkily. This is to be expected since the distribution of plate observation times will vary from year to year. However, it is clear that within such limits, the indices are rising in step. This would support the view that the debris responsible for "debris trailing" are satellites and no doubt large pieces of debris capable of reflecting significant amounts of sunlight. There seems to be no evidence that trail rates are influenced by major satellite break-ups. 20% of all the 8000 + catalogued space debris (McNally & Rast 1998) are at the limit of naked eye brightness. The double satellite TiPS (with an angular size of $\sim 7'$ in the sky) is again just on the edge of naked eye visibility.

Satellites (and their associated fuel tanks, etc.) double in number approximately every 15 years. Since a satellite must be illuminated by the Sun in order to reflect sufficient light to record a trail, trailing is going to be most frequent near twilight. Since Schmidt plates are exposed from shortly beyond twilight and through the hours of darkness, it follows that trailing will increase more slowly than the population of operational and non-operational satellites. But the launch rate of satellites is undergoing rapid acceleration with the development of multisatellite communications systems such as IRIDIUM and TELEDESIC. IRIDIUM is now operational and well on the way to an operational system of 66 satellites plus a number of backup satellites. Given that the operational lifetime of each component satellite is expected to be three years, it is clear that IRIDIUM will quickly generate many more satellites than the operational 66 + standbys. The early plans for TELEDESIC called for in excess of 800 operational satellites and clearly that system would lead to a virtual doubling of the current number of satellites very quickly. The revised plans stilI call for in excess of 200 operational satellites. Given that there is no reduction in the numbers of satellites being launched for other purposes, we may expect a significant increase over the next few years in the number of operational satellites - and a concomitant rise in the number of trails across astronomical fields under observation.

3. Consequences for Astronomy

The consequences for astronomy are only too clear. Few deep sky survey plates will be trail free and more plates will carry multiple trails. Photometric observations will increasingly be affected by trailing.

A plate is not necessarily ruined by carrying trails. The trails may not affect those areas of the plate of maximum interest. Nevertheless any trail degrades the plate. The prospect of an enhanced trail rate is not good news.

It is not only deep sky photographic surveys which are affected. One might expect considerable trailing for plate scales of $6° \times 6°$. However, photometric fields (with fields of 30" x 30") are also increasingly affected. There are examples where a piece of debris crossing a photometric field has been originally interpreted as the optical equivalent of an γ-ray burster. Because photometry is carried out on objects of all types from bright to exceedingly faint, it is clear that photometry must also be concerned with not only large space debris but with smaller and therefore fainter items of space debris. Photometric fields may be small but debris populations increase as the size of the debris decreases. The most sensitive photometric detectors are fitted with shutters designed to close if too bright an object is likely to enter the field. However, one might anticipate an unfortunate series of mishaps, which might allow damage to a sensitive detector as well as loss of observations.

4. Remedies

One might argue that there is an obvious remedy - to avoid trailing wait a decent interval following sunset and before sunrise, so that the amounts of light reflected by satellites will be negligible. This period is conventionally set at two hours, i.e. four hours out of any given night. This represents a very significant fraction of a night. For example, four hours is 40% of a 10 hour dark period. This is a serious inroad on observing time given that the deepest surveys and serious photometry must avoid the bright of the Moon. In other words the operational efficiency of a telescope is reduced and concomitantly the hourly cost of operation is increased, the more hours a telescope remains idle. That extra cost is a charge on the science of astronomy and not on the owners and operators of satellites. This is interference by one party on the legitimate activities of another. Remedy however is not simple.

Clearly if it is important to avoid trailing particular observations, then the hours of maximum trailing should be avoided. However, as McNally & Rast (1998) have shown, the orbits of over 8000 items of space debris are known and kept updated - the expected incidence of trailing can be predicted and observing programmes scheduled accordingly. The process may not be as extensive as including all 8000 odd catalogued space debris, but only that subsection deemed capable of affecting the planned observations. Such forward scheduling could reduce trailing in the post- and pre-twilight periods.

Satellites could also be made less reflective. This is an area which still requires investigation. Clearly poorly reflecting satellites will preclude optical detection of these satellites. Large debris from collisions will not necessarily retain the low reflection properties of their parent bodies but low reflection satellites would again help reduce the numbers of recorded debris trails.

This is an area where activity in one field has impact on activity in another. Exploitation of space is a legitimate activity. It is an area of activity of benefit to astronomer and non-astronomer alike. Astronomers as citizens benefit from first class, state of the art, communications facilities. Astronomers as astronomers benefit from access to space observatories. But space activity impacts astronomical observation - another legitimate activity. This is an area where close co-operation with the space agencies could be of great benefit to astronomy though at some expense to those agencies as well as astronomy.

5. A Space Nightmare

There is a further space problem which keeps recurring - the prospect of advertising from space. This is perhaps one of the most worrying problems for optical astronomy. The Moon rules out observation of the faintest celestial objects for about two weeks of each lunation. Space advertising would need to rival the full Moon in brightness in order to be readily observable. It is therefore reasonable to take as a guide that space advertising will need to provide a source at least as bright and extensive as the full Moon.

Solar reflectors have been proposed for such purposes - the Ring of Light, the Space Billboard are examples. The Star of Tolerance was somewhat different but was still proposed to be as bright as Jupiter and designed to create an artificial “double star”. So far, fortunately, no such project has been implemented.

Solar reflectors have limitations. They must be very large (km size) and they are limited by the amount of twilight they can reflect. Because they reflect sunlight, they will be twilight features. Why does this interfere with astronomy? It is likely that putative advertisers will want to raise the orbits of their reflectors to maximise contrast between sky and reflector so as to enhance their message. This will make more of the night unusable - unusable, not just the avoidance of trailing by debris. Several reflectors each as bright as a full Moon will pose a threat to a range of astronomical observations - not just faint objects. Such reflectors will be there every night not just the week either side of full Moon.

The Znamya project will test a 25 m solar reflector on Nov 09, 1998. This has a brightness of 5 - 10 full moons - well in excess of the brightnesses quoted in the previous paragraph. A 60/70 m reflector is expected to be launched in 2000 and a 200 m reflector having a brightness of 10 - 100 full moons will be launched further downstream. The earlier assumption of a brightness of 1 full Moon is soon to be surpassed by one or two orders of magnitude! The pressure to use such reflectors commercially will be very great - indeed astronomy’s nightmare scenario has been brought significantly closer.

The twilight limitations of the solar reflector are already recognised. There has been a proposal to use lasers to produce holographic images. Image brightness will depend on the power of the lasers used and that is, in part, a matter for willingness to spend. Advertising brighter than 10-100 full moons may therefore be a possibility *in dark sky time*. Were advertising from space to be acceptable, there is no doubt that advertising would eventually become an all night, all sky phenomenon. In that eventuality, observational astronomy from the ground (and perhaps from space) would be dead.

If observational astronomy is to survive as an effective tool for studying the Universe, there will have to be an unequivocal moratorium on space advertising. Such an International Agreement is not yet over the horizon despite its urgent need. The IAU is seeking World Heritage Status for the Night Sky. A view of the heavens is part of the heritage of mankind, an inspiration to enquire and a tool of considerable use. That heritage should be actively championed and protected - not just for the astronomers.

6. And Finally

Radio band width is in short supply. We all know the severe problems this causes observational radio astronomy. But now satellite engineers are discussing, and indeed ESA has implemented with SPOT-4, laser communication between satellites and with the ground. The lasers operate in the red - at approximately 8000 Å. The optical and infra-red spectrum are not regulated like the radio spectrum. If such laser communication systems become universal, will optical and infra-red astronomy soon be in the position of radio astronomy - grudgingly confined to narrow spectral regions? The radio astronomers were represented on the International Telecommunications Union from 1958. Perhaps it is time for optical and infrared astronomers to learn the lessons of radio astronomy and act now to ensure that laser beam communication does not affect sustained optical and infrared observations.

It is by recognising the multifaceted threat to astronomical observation that astronomy may be able to survive. It is not just light pollution, or pressure on radio bandwidth, that must be resisted - it is all forms of degradation of the conditions for high grade astronomical observation. At some times some frequencies may be under more threat than other frequencies. But astronomers should be aware that the forms of the threat can change on short timescales. The efforts focussed on combating particular threats should also allow for support for other differently beleaguered colleagues. There is a tremendous task to ensure proper public appreciation of astronomy's problems - a public often wonderfully sympathetic. We spend much effort explaining the power of astronomical objects - but we do not spend time explaining the inverse square law which makes those same powerful objects so difficult to detect.

We face a difficult task - but the consequences of ignoring that task are unthinkable for astronomy. We have to convince patrons and public alike of the threat to astronomy - and above all we have to convince our colleagues that the threat is real and unlikely to go away.

References

Crawford, D.L., Ed., 1991, *Light Pollution, Radio Interference and Space Debris*, IAU Colloquium 112, Astronomical Society of the Pacific, San Francisco.

McNally, D., Ed., 1994, *The Vanishing Universe*, Cambridge University Press, Cambridge.

McNally, D. & Rast R.H. 1998, Adv. Space Res., submitted.

National Research Council, 1995, *Orbital Debris - a technical assessment*, National Academy Press, Washington, DC.

Rast, R.H., 1998, private communication.

Tritton, S. and Norton, L. 1995, Private Communication of internal ROE report.

RADIO POLLUTION OF THE OH 1612-MHZ BAND

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ABSTRACT. The hydroxyl radical (OH) was the first interstellar molecule to be detected by radio telescopes and its spectral lines at 1.6 GHz have good regulatory protection. Despite this, astronomical research using the 1612-MHz line of OH is now compromised by interference from satellites which transmit on nearby frequencies. The nature of the science which can be done only at 1612 MHz is reviewed and the effects of interference from GLONASS are explained. The effects of the interference can be mitigated in some circumstances, with an associated loss in observing time or sensitivity. Attention is drawn to the large number of similar interference problems which could be caused by new generations of satellites, including Iridium.

1. Introduction

Radio astronomy is a young branch of astronomy, but one which has completely transformed our view of the Universe. The radio window is the only waveband apart from the optical which is accessible to ground-based instruments. The opening of this window gave us our first glimpse of phenomena which had been largely hidden to optical telescopes. The discovery of interstellar molecules, of pulsars, masers, radio galaxies, quasars and the cosmic microwave background radiation were all made during the pioneering days of radio astronomy. These discoveries were followed by revolutions in radio imaging, and by steady improvements in angular resolution and sensitivity (Kellerman 1997), which have allowed us to probe ever deeper into the universe. The technique of very-long-baseline interferometry (VLBI) offers the highest angular resolution which can be achieved in any branch of astronomy (now measured in microarcseconds). Yet now radio astronomy finds itself under threat from new technology on satellites.

Cosmic radio sources produce power levels at the Earth's surface which are extremely low and are easily masked by manmade signals (Thompson et al. 1991). Transmitters on satellites pose a particularly serious threat to radio astronomy because they lie in direct line-of sight of the radio telescope. Under these conditions not only intentional transmissions but also unwanted emissions can cause interference. Modern satellites employ techniques of wide-band digital modulation and beam-forming by active antennas which inevitably lead to unwanted emissions. When such satellites operate close to a frequency band used by radio astronomy then interference is almost inevitable. This paper describes interference from satellites into the radio astronomy band 1610.6–1613.8 MHz, which is used primarily for observations of the 1612.2-MHz spectral line of the hydroxyl (OH) radical. The problems encountered there are a warning of what may lie ahead in many other radio astronomy frequency bands.

2. Astronomy at 1612 MHz

OH 1612-MHz emission is characteristic of a special class of astronomical objects, the OH-IR sources. OH-IR sources are red giant stars which have evolved beyond the asymptotic giant branch and are losing mass at prodigious rates of up to 10^{-4} $M_{\odot}yr^{-1}$ (Habing 1996). The stars are usually long-period variables with periods of 1 to 6 years. The thick shell of circumstellar matter absorbs most of the starlight, which is re-emitted as infrared radiation, hence the name OH-IR sources. OH-IR sources are of great interest for theories of stellar evolution, and as a source of nuclear-processed material for the interstellar medium. Our Sun will one day pass through this phase, on its way to becoming a planetary nebula. About three thousand OH-IR sources are now known, as a result of 1612-MHz surveys of IRAS-selected targets and systematic surveys of the galactic plane and the galactic bulge.

Without the OH 1612-MHz line we would know very little about OH-IR sources. The 1612-MHz line is excited as a maser in the outer layers of the circumstellar envelope by an infrared pump, details of which have recently been confirmed by *ISO* (Sylvester et al. 1997). The shell of 1612-MHz maser emission can be directly observed using radio interferometers such as MERLIN (Booth et al. 1981). The angular sizes are typically one second of arc or less. The maser emission varies in synchronism with the varying infrared pump, but because of the light travel time across the shell we see a phase-lag between the blue-shifted and red-shifted emission. Measurement of this phase-lag together with an interferometer measurement of the OH shell diameter thus yields the distance to the star. This powerful technique is now being used at several radio observatories around the world. Regular monitoring over many years is required.

A typical 1612-MHz spectrum of an OH-IR source is shown in Figure 1. The spectrum is usually twin-peaked like this because the maser emission is beamed radially outwards from the star. We therefore see strongest emission from the very front and the very back of the OH shell. The stellar velocity is accurately defined by the midpoint of the two 1612-MHz peaks, and the separation between the two peaks gives twice the expansion velocity of the shell. Expansion proper motions have been directly measured using VLBI (Kemball 1992). The lower half of Figure 1 shows that the 1612-MHz emission is polarized. Linear and circular polarization have both been measured. Polarization imaging yields information on the circumstellar magnetic field (Szymczak & Cohen 1997).

OH-IR sources are one of the few stellar populations whose distribution and kinematics can be studied throughout the Galaxy. Lindqvist et al. (1992a, 1992b) have surveyed the galactic centre for OH-IR sources and determined accurate positions and radial velocities. Treating the OH-IR sources as test particles in the galactic potential they were able to deduce the existence of a central concentration of mass, possibly a 2×10^6 $M_{\odot}$ black hole.

Apart from the study of OH-IR sources, the 1612-MHz band is used for many other purposes. The 1612-MHz line is one of 4 transitions of OH in its rotational ground-state, and observations of the different line ratios are an essential diagnostic of the physical conditions in the molecular gas. The 1612-MHz line is studied in a wide range of objects including comets, star-forming regions, molecular clouds and outflows, and in external galaxies (where the red-shift may take the line out of the allocated band). Powerful OH

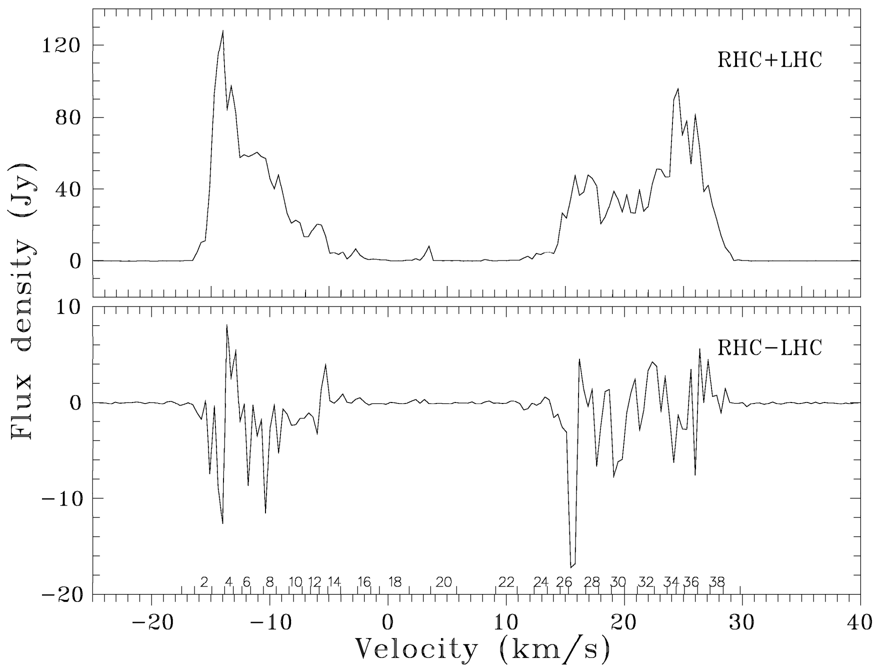

Fig. 1. OH 1612-MHz spectrum of VXSgr, taken with MERLIN on 23rd October 1993 and covering a bandwidth of 360 kHz with a resolution of 2 kHz (Syzmczak & Cohen 1997).

megamasers are perhaps the most spectacular objects observed at 1612-MHz.

Continuum observations are also made at 1612 MHz for various purposes. Nevertheless in what follows the effects of interference will be discussed only for the spectral line measurements for which the radio astronomy band is primarily intended.

3. Interference from GLONASS

The Russian global navigation satellite system GLONASS has caused worldwide interference to radio astronomy at 1612 MHz since it was first launched in 1982 (Ponsonby 1991). GLONASS uses a constellation of satellites in three orbital planes, with 8 orbital positions per plane. The orbital period is such that after 24 hours each satellite has completed exactly two and one-eighth orbits. The GLONASS satellites transmit one of their main navigation signals on 25 possible centre frequencies equally spaced from 1602.0 to 1615.5 MHz. Six of the frequency channels fall directly in the radio astronomy band 1610.6–1613.8 MHz.

The peak power flux density produced at the Earth's surface by a single GLONASS satellite is about -190 $dBWm^{-2}Hz^{-1}$, or in radio astronomical units 10^7 Jy. For comparison the known OH-IR sources have peak flux densities ranging from a few hundred Jy down to a few mJy. A 70-m class radio telescope with a gain of 60 dBi at 1612 MHz will still collect signals from GLONASS through its far sidelobes. A GLONASS satellite in a 0 dBi sidelobe will appear as strong as a 10 Jy source in the main beam. The situation will be even worse for a smaller radio telescope with less gain in the main beam. Consequently GLONASS satellites with centre frequencies in the radio astronomy band are able to cause interference whenever they are above the horizon, not just when a radio telescope is pointing near them.

The GLONASS navigation signal is phase-modulated with two codes, a low precision code which is switched at 0.511 MHz, and a high precision code which is switched at 5.11 MHz. The switching is abrupt, and generates sinc-squared sidebands at both frequency intervals. These unwanted emissions, which are not needed by the navigation receiver, spread over many hundreds of MHz. Additionally narrow emission spikes, rather like OH masers, are generated at each 5.11 MHz, at the nulls in the sinc-squared pattern. The power levels are such that the unwanted emissions from GLONASS are capable of causing interference in the adjacent radio astronomy band 1660–1670 MHz (Galt 1990) and indeed over hundreds of MHz.

The effects of GLONASS vary for different telescopes and for different types of radio astronomical measurement. For spectral line measurments at 1612 MHz the effects can be broadly classified into spectral artefacts and calibration errors. Spectral artefacts from GLONASS reflect the spectrum of the transmitted signal, and may be narrow band, from the null spikes, or wide band from the sinc-squared sidebands. If position-switching or frequency-switching are employed in the measurements the artefacts are due to the difference in received GLONASS energy in the ON and OFF spectra, rather than the absolute energy received. Calibration errors occur because of the rapidly varying power levels received from GLONASS satellites as they move through the sidelobe pattern of the radio telescope. Unless the calibration signal, usually from a noise diode, is sampled rapidly, systematic errors will be introduced because of the unknown contribution of GLONASS to the noise power at the detector.

4. The GLONASS-Radio Astronomy Experiment

The impact of GLONASS on radio astronomy at 1612 MHz was devestating. Astronomers were dismayed at how quickly and simply a whole area of research could be wiped out by a small number of satellites. The worldwide nature of the problem meant that a global solution had to be found. A series of meetings was set up between the GLONASS Administration and IUCAF, the Inter-Union Commission on Frequency Allocations for Radio Astronomy and Space Research. From these talks came a proposal for a joint experiment to test several ways of reducing the interference to radio astronomy.

The joint experiment took place on 19th-22nd November 1992, with 10 radio astronomy observatories in 8 countries participating. During the three-day period GLONASS satellites were moved in frequency and in some case switched off altogether, so that the effects on the radio astronomy measurements could be investigated (Cohen 1994). The measurements included single telescope spectroscopy, interferometry, and total power (continuum) measurements. In addition the power spectrum of each satellite was monitored at the German Monitoring Station in Leeheim. Knowing the orbits of the satellites and the centre frequencies of their transmissions it was possible to learn exactly how signals from different satellites were entering the radio astronomy receiver and what effect they were having on the measurements.

The outcome of the experiment was an agreement between GLONASS and IUCAF, signed on 4th November 1993. The agreement set out a step-by-step plan to reduce interference to radio astronomy. In the first stage the main transmissions of the low precision code were excluded from the radio astronomy band 1610.6–1613.8 MHz. This was already done in 1993, which immediately lowered the interference levels by an order of magnitude. By 1999 the main transmissions of the high precison code will also be excluded, which will bring a further order of magnitude improvement for radio astronomy. This is being achieved by reusing frequency channels for satellites on opposite sides of the same orbit, so that only 13 channels are occupied, not 25. Meanwhile new-generation GLONASS-M spacecraft are being developed which will carry filters to reduce the unwanted emissions at 1660–1670 MHz below the threshold for interference. The new satellites will operate at lower frequencies with a modified frequency plan, and are expected to be fully in place by the year 2006 (a deadline which is not in the original agreement but which was subsequently adopted).

The step-by-step plan has brought immediate benefits to radio astronomy. It allows useful measurements to be made on strong sources right now, and there is the long-term prospect of a clear 1612-MHz band by the year 2006. Nevertheless prevention would have been better than cure. How did the system fail radio astronomy?

5. Regulatory Matters

The use of radio frequencies is regulated by the Radiocommunications Bureau of the International Telecommunications Union (ITU-R). The rules or Radio Regulations are agreed internationally at World Radio Conferences (WRCs, formerly WARCs). Radio astronomy first entered the Radio Regulations in 1959 when a passive frequency band was allocated to protect the 1420-MHz line of atomic hydrogen. The four OH lines at 1.6 GHz were recognized in 1971 when they were given shared allocations, not passive bands. Shared allocations are common in the table of frequency allocations, reflecting the pressures on the radio spectrum. At the time of the GLONASS launch the OH 1612-MHz band was shared with, among others, the radio navigation service. The launch of GLONASS was officially notified and national administrations had the opportunity to object, but almost nobody realized what was about to happen to radio astronomy at 1612 MHz.

The Radio Regulations contain no penalties for causing interference. Radio astronomy does not have a strong regulatory position within the Radio Regulations in any case, as the protection criteria, which are given in Recommendation RA.769-1 of the ITU-R, have never been made mandatory. It took the growing swell of international unrest about GLONASS, and other political factors within the USSR and elsewhere, to bring the negotiations about.

In order to ensure that there is no repeat of the GLONASS situation the interference levels for radio astronomy will need to be written into the Radio Regulations as mandatory levels, not just recommended levels. In addition the levels of unwanted emissions from transmitters on satellites will need to be tightly specified. At present there are no limits at all! The telecommunications community has shown no wish to constrain itself in these ways, so the pressure will need to come from governments. Reduced levels of radio pollution will benefit all users of the radio spectrum, not just radio astronomers.

6. Interference Mitigation

In response to GLONASS interference radio astronomers have developed mitigation techniques which may stand them in good stead in the future and at other frequencies.

ITU-R RA.769-1 specifies a threshold of -238 $\mathrm{dBWm^{-2}Hz^{-1}}$ for interference detrimental to radio astronomy spectral line measurements at 1612 MHz. The calculation used to derive this threshold assumes values for the receiver noise temperature (20 K), integration time (2000 s) and resolution bandwidth (20 kHz). It further assumes that the interfering signal enters through sidelobes of gain 0 dBi. Under these assumptions a steady interfering signal at the detrimental threshold adds noise fluctuations σ_h to the measurements which are less than ten percent of those due to receiver noise σ_n. GLONASS levels in the band 1610.6–1613.8 MHz are currently almost 40 dB above the threshold for detrimental interference. How is science possible under these conditions?

Firstly radio astronomers take precautions to minimize interference from GLONASS, for example by observing when certain satellites are below the horizon, and by careful editing and processing of corrupted data (Combrink et al. 1996). Analysis of data recorded at Jodrell Bank during the GLONASS experiment indicates that most of the GLONASS signal in a 1200-s integration entered the receiver during a relatively short period of time. It is thus possible to improve the data quality considerably by taking many short integrations and discarding those which are worst affected by interference. Spectral artefacts from GLONASS have known characteristics, which aids in their identification. Observations of narrow-band OH sources are worst affected by the null spikes, which mimic narrow maser features, but they are at known frequencies. The broad-band sinc-squared components can be removed to some extent by fitting polynomial baselines to the spectra.

With the above measures most large radio telescopes can make useful observations of strong narrow-band sources, such as the strongest OH-IR sources. On the other hand it is impossible at the present time for such a telescope to make useful measurements of weak sources or of broad-band sources such as OH megamasers and bipolar outflows like OH231.8. These and other research areas requiring the highest sensitivity are on hold until the year 2006 when the GLONASS step-by-step plan is completed.

Interferometers are less susceptible to interference than single telescopes. The MERLIN spectrum of Figure 1 is only weakly contaminated by GLONASS, at a level 25 dB lower than would be the case for a single telescope. In fact the GLONASS terms are at a similar level to the receiver noise σ_n in a spectral channel (0.02 Jy), and useful science can be done. An equivalent integration with a single telescope would have artefacts of $300 \times \sigma_n$ and would be useless. Interferometers are increasingly being used at 1612 MHz for searches and other high sensitivity programmes. However interferometers offer only a partial solution. They are few in number compared with single telescopes, and they are suitable only for compact sources, not for extended sources.

7. Iridium

At WARC-92 the allocation of the band 1610.6–1613.8 MHz to radio astronomy was upgraded to primary status. At the same time the band 1610–1626.5 MHz was allocated to the mobile satellite service to allow the introduction of a new generation of communications satellites in low Earth orbits (LEOs). All of the proposed systems will use the band 1610–1626.5 MHz for uplink transmissions. In addition one system, Iridium, will operate its downlink within this band. Iridium is the first to fly and will begin commercial operations later this year (1998).

Iridium employs a constellation of 66 satellites in low Earth orbit to provide mobile communications between any two points on the planet. The Iridium downlink will operate in the band 1621.35–1626.5 MHz initially, although the satellites are capable of transmitting down to 1616 MHz and the allocation extends down to 1613.8 MHz. The downlink is for reception by small handheld units and it has a peak spectral power flux density of -160 $\mathrm{dBWm^{-2}Hz^{-1}}$ or 10^{10} Jy, one thousand times GLONASS. For this and for other reasons concerning the antenna beam-forming system the technical challenge to suppress unwanted emissions into the radio astronomy band is greater than for GLONASS. The Iridium downlink was identified as a potential threat to radio astronomy as early as 1991. To safeguard against interference a footnote was modified at WARC-92, at the same time as the allocation for the satellite downlink was made. Footnote S5.372 states that harmful interference shall not be caused to stations of the radio astronomy service using the band 1610.6–1613.8 MHz by stations of the radiodetermination-satellite and mobile-satellite services.

Negotiations between Iridium and the radio astronomy community have been proceeding since 1991. At a certain point it became clear that the Iridium downlink might fail to meet the thresholds for detrimental interference to radio astronomy. The unwanted emissions from Iridium satellites increase with user traffic, and Iridium's own calculations suggested that the fully loaded system could exceed radio astronomy interference thresholds by up to 27 dB. At this point Iridium began to call into question the radio astronomy protection criteria and the interpretation of the Radio Regulations, and some of the negotiations foundered (Feder 1996).

Iridium has declined to discuss the issues globally with IUCAF, as the GLONASS administration did, but has made some progress in discussions with individual observatories. Radio astronomers in the USA have accepted a time-sharing solution in which radio astronomy to the levels of ITU-R RA.769-1 will be guaranteed only during the quiet hours when the phone traffic is low. Radio astronomers outside the USA have so far resisted the pressures to sign similar time-sharing agreements.

8. Future Prospects

The difficulties in doing radio astronomy at 1612 MHz seems as if they may get worse before they get better. Nor is this an isolated problem. The number of cases of interference to radio astronomy from satellites is steadily increasing. An updated list can be inspected on the home page of the European Science Foundation's Committee on Radio Astronomy Frequencies ESF-CRAF (http://www.nfra.nl/craf). In fact 80% of frequency bands with a primary worldwide allocation to radio astronomy are adjacent to satellite downlink bands, and could present similar problems in future. This constitutes a major challenge to the future of radio astronomy. Fortunately most of the downlink allocations have not been taken up yet, so there is time to improve the technology on satellite transmitters and on radio telescopes and receiver systems.

As the millenium approaches the ITU-R itself is undergoing many changes. The radio spectrum has become a valuable commodity. Global corporations can make billions of dollars per Megahertz, and they are able to exert enormous pressure on national administrations and through them on the ITU-R. Millions of dollars are spent at WRCs on food, drink, parties and free gifts for delegates. Many multinational operators are on national delegations both to WRCs and to smaller ITU-R working groups. At the same time adminstrations are seeking to minimize their own role in managing the use of the radio spectrum.

The negotiations with Iridium have brought radio astronomers face to face with the world of corporate lawyers, non-disclosure agreements, commercial confidentiality and industrial espionage. It is an extreme clash of cultures. In this arena radio astronomers need to find new ways to achieve their goals.

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References

Booth, R.S., Kus, A.J., Norris, R.P., Porter, N.D.: 1981, *Nature* **290**, 382.

Cohen, R.J.: 1994, Proceedings of 12th International Wroclaw Symposium on Electromagnetic Compatibility, pp. 530-534, eds. J. Janiszewski, W. Moron and W. Sega.

Combrinck, W.L., West, M.E., Gaylard, M.J.: 1994, *Publ. Astr. Soc. Pacific* **106**, 807.

Feder, T.: 1996, *Physics Today* **49**, No.11 (November 1996), pp.71-73.

Galt, J.: 1990, *Nature* **345**, 483.

Habing, H.J.: 1996, *Astron. Astrophys. Rev.* **7**, 97.

Kellerman, K.I.: 1997, *Sky & Telescope* **94**, No.2 (February 1997), pp.26-33.

Kemball, A.J.: 1992, PhD thesis, Rhodes University, Grahamstown.

Lindqvist, M., Habing, H.J., Winnberg, A.: 1992a, *Astron. Astrophys.* **259**, 118.

Lindqvist, M., Winnberg, A., Habing, H.J., Matthews, H.E.: 1992b, *Astron. Astrophys. Suppl. Ser.* **92**, 43.

Ponsonby, J.E.B.: 1991, *Journal of Navigation* **44**, 392.

Sylvester, R.J., Barlow, M.J., Rieu, N.-Q., Liu, X.-W., Skinner, C.J., Cohen, R.J., Lim, T., Cox, P., Troung-Bach, Smith, H., Habing, H.J.: 1997, *Mon. Not. R. Astr. Soc.* **291**, L42.

Szymczak, M., Cohen, R.J.: 1997, *Mon. Not. R. Astr. Soc.* **288**, 945.

Thompson, A.R., van den Bout, P.A., Gergeley, T.A.: 1991, *Physics Today* **44**, No.11 (November 1991), pp.41-49.

CITY LIGHTS AND URBAN GREEN

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ABSTRACT. The city lights may cause more or less serious damages to the most of the tree close to the sources of the artificial light. In this paper[1] the emission spectra - 350 nm to 800 nm - of the lamps most used or recommended for city lighting have been analysed, and their emission spectra, together with the solar spectrum, have been compared with the absorption spectrum of the main plant pigments and the phytochrome.

1. Introduction

The city lights may cause more or less serious damages to the most of the tree close to the sources of the artificial light (as in avenues and parks) for what concerns the photosyntesis and photoperiod. In fact, the thermal radiation emitted by the lamps causes, in its surroundings, a favourable microclimate, that extends vegetative period of the branches and leaves more directly exposed to it. In addition, the light emitted by the incandescent lamps extends the length of the daytime to the whole day, and consequently increases the photosynthesis activity. Finally, the incandescent lamps stimulates the phytochrome activity in an anomalous way if compared with the length of the daytime, which alters the sprouting and the blooming. The above results are well evident, above all in the city avenues. Here, the branches situated in the lighted side of the tree are much bigger and are clearly leaning toward the source of the light.

2. Results

The emission spectra - 350 nm to 800 nm - of the lamps most used or recommended for city lighting have been analysed, and their emission spectra, together with the solar spectrum (fig. 1), have been compared with the absorption spectrum of the main plant pigments (chlorophyll a, fig. 7, chlorophyll b, fig. 8) and the phytochrome (R, fig. 9, FR, fig. 10). The outcomes show that the traditional incandescent lamps - the most similar to the composition of the solar spectrum - heavily influence, just for this reason, the biological activity of the plants. For this study, the following lamps have been taken into consideration:

a) Incandescent lamps, fig. 2

[1] This work was presented in Italian in Padua during the 2nd Congress of "L'Albero, l'Uomo, La Città" in september 1983 and printed in Giulini (1983)

FIG 1

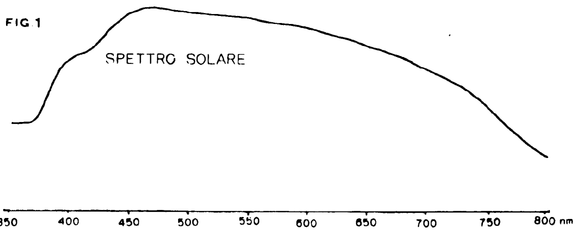


FIG. 2

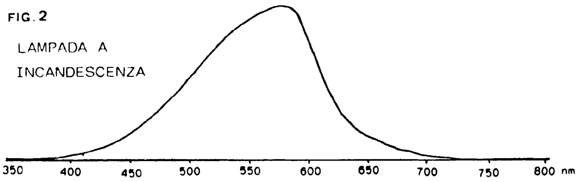


FIG. 3

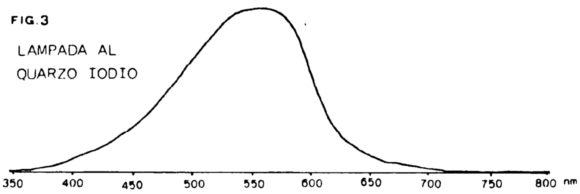


FIG 4

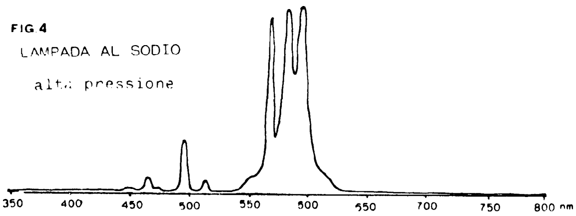
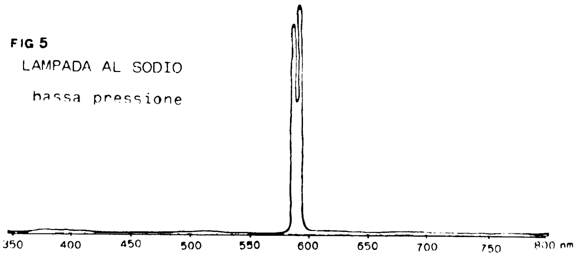


FIG 5



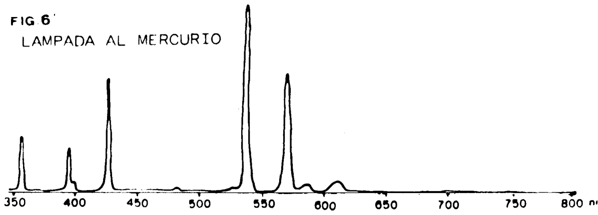


FIG 6 LAMPADA AL MERCURIO

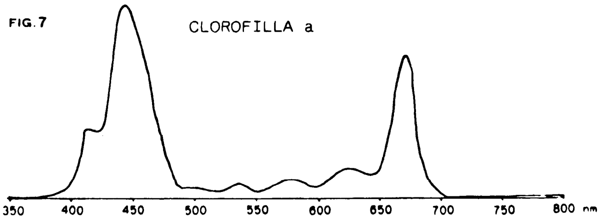


FIG. 7 CLOROFILLA a

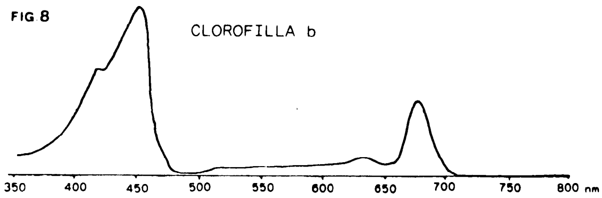


FIG 8 CLOROFILLA b

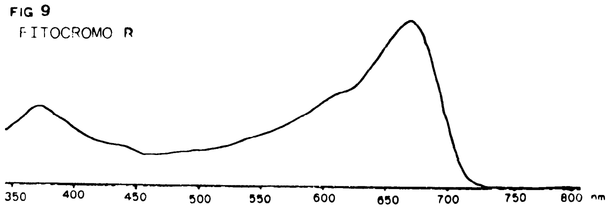


FIG 9 FITOCROMO R

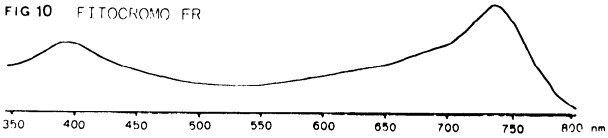


FIG 10 FITOCROMO FR

b) Iodine quartz lamps, fig. 3

c) High-pressure sodium lamps, fig. 4

d) Low-pressure sodium lamps, fig. 5

e) Mercury-vapor lamps, fig. 6

The results of the preliminary tests indicate that: a) and b) lamps cause evident reactions in the plants; the plants lighted up by c) and e) lamps react in an uncertain way; the plants exposed to the low-pressure sodium lamps seem to have no reactions to an extended exposure to these light sources. In short, the low-pressure sodium lamps appear to be the least harmful. These lamps, even if produce a "non-solar light", are likely the most suitable lamps to light up the brick monuments and to enhance their details. The mercury-vapor lamps, already widely used for their energy saving characteristics and the power of the emitted radiation, have a very low effect in avenue and park lighting in comparison with Incandescence and Iodine quartz lamps. Moreover, this kind of lamps has a relatively "white" emission that, even if "cold", is well suited to light up marble monuments and green-blue-brown coloured monuments, such as bronze statues, etc.

References

Giulini, P. (ed.) 1983, *L'Albero, l'Uomo, La Città*, Signum, Padua, 42-44.

LIGHT POLLUTION AND POSSIBLE EFFECTS ON HIGHER PLANTS

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ABSTRACT. Light pollution is a well known problem for astronomic observation of the sky. In this study we aim to verify whether, besides this, it can also be regarded as a more general ecological concern. Preliminary data, reported in this study, seem to indicate that the presence of artificial light in the proximity of some trees can be responsible for impairment of both their photosynthetic efficiency and photoperiod. In the investigation of the physiological state of the photosynthetic apparatus of some selected trees we have used the method of the fluorescence induction which allows a rapid and quantitative measure of an eventual stress condition at the level of the photosynthetic apparatus of a single leave.

1. Introduction

Light pollution is a well known problem for astronomic observation of the sky. In this study we aim to verify whether, besides this, it can also be regarded as a more general ecological concern. Preliminary data, reported in this study, seem to indicate that the presence of artificial light in the proximity of some trees can be responsible for impairment of both their photosynthetic efficiency and photoperiod. In the investigation of the physiological state of the photosynthetic apparatus of some selected trees we have used the method of the fluorescence induction which allows a rapid and quantitative measure of an eventual stress condition at the level of the photosynthetic apparatus of a single leave. To illustrate the method we shall briefly go through the molecular structures and the mechanisms which are involved in this study.

2. Oxygenic photosynthesis

In higher plants algae and cyanobacteria, the molecular device which carry out the conversion of light energy into chemical free energy, is a very complex set of pigment-protein structures located in the thylakoid membrane inside a specialised cell organelle called chloroplasts which has dimension of about 5 x 10 μm. The thylakoid membranes are stacked in substructures known as grana which are interconnected by portions of unstacked membranes called stroma membranes. The whole system defines a continuum internal space called lumen separated from the external space called stroma. The light-gathering apparatus is a complex of lipids and proteins imbedded in the thylakoid membrane of chloroplasts. A group of light absorbing molecules, or chromophores, is intimately associated with the membrane-bound proteins responsible for photosynthesis. The photosynthetic pigments are responsible for efficient capture of the solar radiation. They absorb electromagnetic energy over a range of frequency that spans the visible region and extends into the far infrared in the case of photosynthetic bacteria. Chlorophyll a and b are the major chromophores in green plants, carotenoids acts as accessory pigments and protectors against chlorophyll photo-oxidation. Within photosystems, photosynthetic pigments are located at distance and orientation such as to allow efficient energy transfer among each other in a process called exciton transfer. In each photosystem, the electronic excited state generated by the absorption of a photon by a pigment associated to one of the *antenna* protein is transferred to a nearby pigment until it reaches the *reaction centre*, where the excitation energy is converted into charge separation. An electron transport chain starts which terminates with the oxidation of a specific electron donor and the reduction of a specific acceptor.

3. Photosystem II

Photosynthesis in higher plants requires the cooperation of two distinct molecular assemblies known as *photosystem I* and *photosystem II.* The combined action of these two systems supplies the energy to accomplish three tasks: (1) oxidation of two oxygen atoms of two water molecules to molecular oxygen, (2) reduction of NADP+ to NADPH and (3) phosphorylation of ADP to ATP. Beside the two photosystems, where the so called *light reactions* take place, two other protein assemblies are necessary which are also embedded in the thylakoid membrane; these are the Cytochrome b6/f complex and the ATP syntase complex. Since the phenomenon of fluorescence induction depends almost exclusively on photosystem II, we shall describe the latter in some more details. Photosystem II (PSII) is the protein-pigment sovramolecular complex that carries out the light-catalysed oxidation of water and reduction of the plastoquinone pool, a set of plastoquinone molecules freely dissolved in the lipid bilayer. The primary chlorophyll donor of PSII is called P_{680} and is composed of a chlorophyll a dimer with an absorption maximum at 680 nm. After light absorption, an electron is transferred from the excited state of P_{680} to a pheophytin, which in turn reduces a bound plastoquinone molecule, called Q_A. $Q_A$reduces a second quinone molecule, Q_B

The centre of reaction is constituted of two intrinsic proteins called $D_1$and D_2 (respectively of 32 and 34 kDa); both present molecular portions which are exposed to the stromatic surface and can be phosphorylated. These two proteins, associated as eterodimers, provide the binding sites for: the photochemically active pigment of the reaction centre (P680), constituted of a chlorophyll a dimer, the primary acceptor, pheophytin a (a chlorophyll a without Mg), a first plastoquinon (Q_A), permanently linked to the D_2protein, and a second plastoquinon (Q_B) reversibly bound to the D_1protein. Schematically, the electrons transfer from the reaction centre to the primary acceptors ($Q_A$and Q_B), is shown in figure 2 (the times of passage from a form to the other have

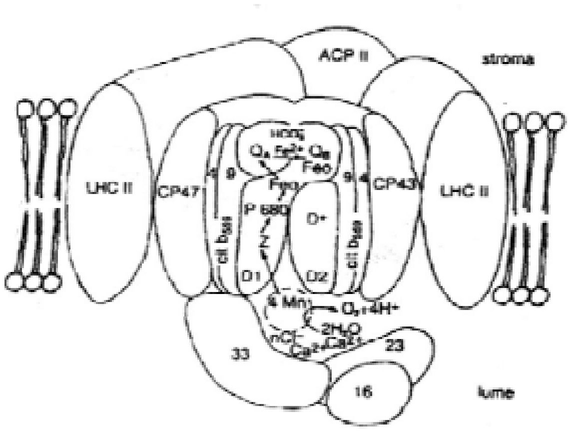

Fig. 1. Schematic model of PS II; as you can see, it is constituted of a reaction centre (P_{680}) and of an inner antenna (chlorophyll a, and of carotenoids) which are common to all organisms; an external antenna, LHC II, different depending on systematic groups (chlorophyll a or b). The polypeptides $D_1$and D_2coordinate both the electrons transport chain acceptors and donors from water to membrane plastoquinons. The OEE (Oxigen Evolving Enhancer) polypeptides belong to an enzimatic site which contains manganese whose function is to oxidise water to molecular oxygen (see also text).

been reported), (Krause and Weis, 1991). Through the same pathway, another electron doubly reduces Q_B, which is there protonated to Q_BH_2 (plastoquinol). In this form the complex brings its electrons to the cytochrome b6/f, and is replaced by another oxidised plastoquinon Q_B. The sites for the plastoquinons are located on the heterodimer D_1/D_2(respectively that of $Q_A$on protein $D_2$and that of $Q_B$on D_1). Other components of the reaction centre located on the $D_1$and D_2proteins, and which are probably involved in electronic transportation, are monomeric forms of chlorophyll a, a second molecule of pheophyitine a, a free radical D+, stable in the dark and identified as a residue of tyrosine on molecule D_2, a primary donor Z+ also consituted of a tyrosine residue present on D_1, and two molecules of bcarotene. The complex OEE (Oxygen Evolving Enhancer), constituted of three extrinsic proteins, respectively of 33000 dalton (OEE1), 23000 dalton (OEE2) and 16000 dalton (OEE3) is located in the stromatic part of the tylacoids, is strongly linked to the proximal antenna of PSII and to the proteins $D_1$and D_2through OEE1. In its catalytic site are also present four atoms of Mn. The complex has the function to reduce, through the catalytic cycle, the tyrosinic residue Z using H_2O as electron donor: it is capable of providing four electrons taken from it, gathering in turn four positive charges (4H+). The process develops through four consecutive stages, in each of which a redox process takes place with the formation of five consecutive S states (S0-S4), the last of which is sufficiently oxidised to be able to oxidate H_2O releasing oxygen in the tylacoidal lumen. The system returns to the initial state S0 (where the cycle restarts). The consequent release of protons in tylakoidal

$Z\ P_{680}\ Pheo\ Q_A\ Q_B$	(open centres)
$\Downarrow h\nu$	
$Z\ P_{680}^{*}\ Pheo\ Q_A\ Q_B$	
$\Downarrow$	2 psec
$Z\ P_{680}^{+}\ Pheo^{-}\ Q_A\ Q_B$	
$\Downarrow$	250 – 300 psec
$Z\ P_{680}^{+}\ Pheo\ Q_A^{-}\ Q_B$	(closed centres)
$\Downarrow$	20 nsec — 35 μsec
$Z^{+}\ P_{680}\ Pheo\ Q_A^{-}\ Q_B$	
$\Downarrow$ (e^{-})	50 μsec — 1,3 msec
$Z\ P_{680}^{+}\ Pheo\ Q_A^{-}\ Q_B$	
$\Downarrow$	100 — 200 μsec
$Z\ P_{680}^{+}\ Pheo\ Q_A\ Q_B^{-}$	(open centres)

Fig. 2. Electrons transfer from the reaction centre to the primary acceptors ($Q_A$and Q_B).

lumen contributes in generating a protoni gradient in the membrane which is exploited by ATPases complex to produce ATP. The inner antenna of PSII transfers excitation energy from the external antenna complexes to reaction centre. Structurally it is constituted of two pigment-protein complexes with about 30 molecules of chlorophyll a; called CP 47 and CP 43 (chlorophyll-protein complex 47 and 43); the second also presents a site of phosphorylation, whose functional role is still uncertain. The inner antenna, is also involved in the stabilization of the reaction centre structure. The external antenna presents characteristics which depend on the systematic groups. In organisms such as clorofites, euglenofites and higher plants the complex of the external antennae is constituted of proteins associated with chlorophyll a, b and xantophylles; the number of chlorophyll molecules can be about 200 units per photosystem, nevertheless the dimensions of the complex can vary depending on the intensity and spectrum of light and temperature. The most important antenna complex in these organisms is LHC II (light harvesting complex II), made of different oligomeric components constituted of proteins of various nature. Actually, LHC II is divided in two subunities the inner of which is tightly linked to the photosystem's nucleus and contains almost exclusively polypeptides of higher molecular weight, while the second possesses proteins with slightly lower molecular mass; and high level of phosphorylation which allows a reversible dissociation that generally occurs following sudden environmental variations, in light intensity and temperature.

4. Fluorescence

Chlorophylls absorb blue (about 420 nm) and red (about 660 nm) light, transmitting and reflecting green. Most of the absorbed energy is conveyed to the reaction centres and transduced into charge separation. However, a small part of it is reemitted, as fluorescence, by chlorophyll a of the antenna system. The emitted fluorescence is in

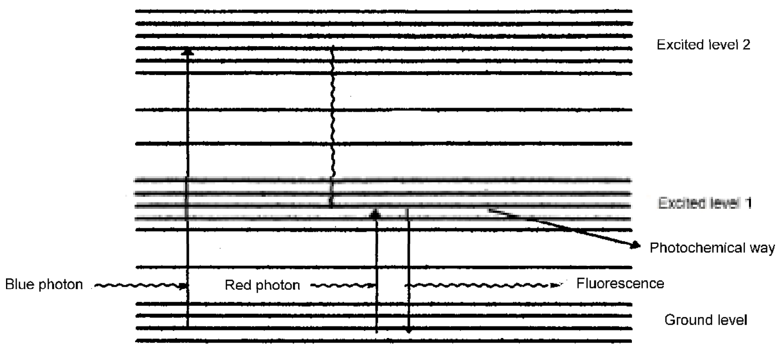

Fig. 3. Chlorophyll excitation by light. The importance of fluorescence emission by photosyntetic complexes (in our case PS II), resides in the possibility of analyzing its intensity variation depending on the time and therefore of evaluating in an indirect way the photochemical events of the photosynthetic system.

the red and far red region of the spectrum and is easily visible when a concentrated solution of chlorophyll is illuminated. In the case of chlorophyll in solution, the fraction of excitation energy dissipated as fluorescence can get to 30 % of the absorbed light, while in vivo this fraction is limited to about 3-5 %.

The Figure 3 schematically illustrates the process of energy dissipation as fluorescence.

5. The Kautsky effect

Figure 4 allows to analyse the kinetics of fluorescence induction (Kautsky effect, 1931), going from darkness conditions to light conditions (Krause and Weis, 1984; Briantais et al., 1986). If a leaf is kept in darkness (or under low intensity light) for a few minutes and then is illuminated with intense attinic light, fluorescence grows within fractions of second, to diminish again after a few seconds or minutes.

It is possible to identify two components in the registered signal: $F_\circ$, registered in conditions of darkness and F_V , the variable component which is observed when the system is illuminated. $F_\circ$ (O), which is the starting signal, is the initial fluorescence which comes from chlorophyll molecules excited in the antenna of PS II when the excitation light is on but its intensity is not sufficient to make a significant number of $Q_A$reduced; its level is determined as the time zero emission when the system has been kept in the darkness as to to guarantee the almost complete oxidation of Q_A. From this point on the fluorescence curve presents a growth to a I level (inflection), then a brief phase of fluorescence decline D (dip) followed by a peak P. The remaining time course is characterized by a comparatively slow fall to a T (terminal) level, going through an

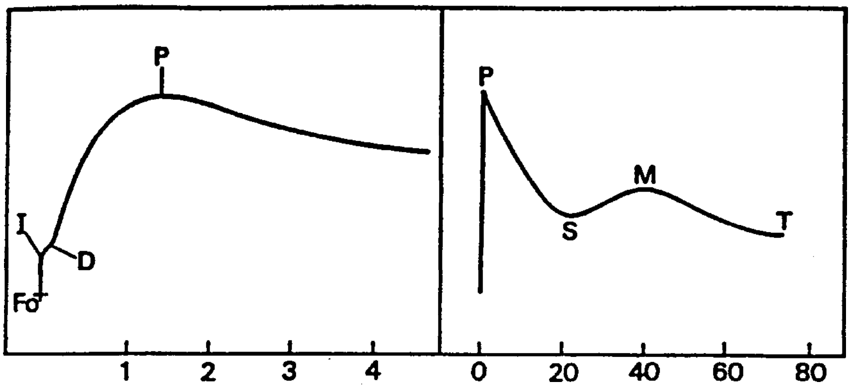

Fig. 4. Kinetics of fluorescence induction; in this representation the OIDPSMT terminology is used (from Lavorell and Etienne, 1977). In this picture O is designated as $F_{\circ}$.

almost stable S state. It is hypothized that the fluorescence growth from state $F_{\circ}$ to I and the following standstill in D mirrors the imbalances between the reduction and re-oxidation of Q_A. The maximum value P is reached after about one and a half second of illumination with intense light. This highest possible value for P is Fm which is obtained when the light intensity is sufficient to saturate the system. The relationship F_V $/F_{\circ}$ (where F_V is equal to F_m -$F_{\circ}$) can vary from 4 to 6 for intact leaves. The following passage from P to T requires much more time if compared to the previous passages. The fluorescence emission speed is influenced by a series of factors that can modify it and that involve different mechanisms which compete with each other when the chlorophyll molecules de-excite back to the fundamental state. These mechanisms are the energy transfer to neighbouring molecules, the internal conversion and the energy conversion in a photochemical reaction. The fluorescence emission intensity can be expressed by the following relation between rate constants:

$$F = Ia\frac{k_F}{k_F + k_D + k_P} \tag{1}$$

where k_F= fluorescence emission k_D= internal conversion k_P= photochemical conversion hence the fluorescence output is:

$$\Phi = \frac{F}{Ia} = \frac{k_F}{k_F + k_D + k_P} \tag{2}$$

It varies from a minimum figure Φ_0, when all the reaction centres are open ($Q_A$oxidised), to a maximum figure Φ_m, when they are closed ($Q_A$reduced):

$$\Phi_0 = \frac{F_0}{Ia} = \frac{k_F}{k_F + k_D + k_P} \tag{3}$$

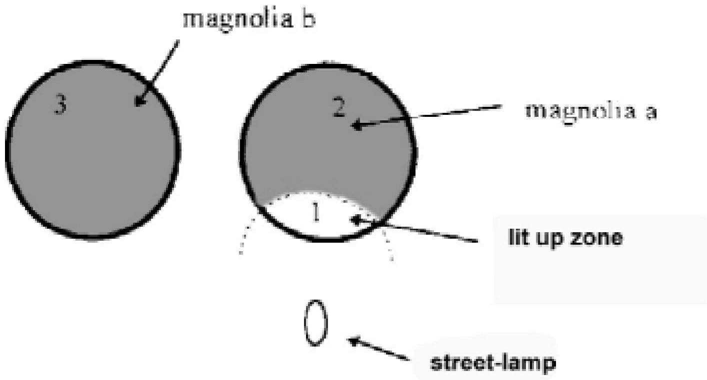

Fig. 5. Entrance of the Botanical Gardens in Padua and location of magnolias: numbers 1,2,3 indicate the sampling areas.

$$\Phi_m = \frac{F_m}{Ia} = \frac{k_F}{k_F + k_D + k_P} \tag{4}$$

In the first case $k_P >> k_F + k_D$, while in the second case $k_P = 0$. From these equations it is possible to get derive the quantum yield for the photochemical process at the reaction centre:

$$\Phi_P = \frac{k_F}{k_F + k_D + k_P} = \frac{(\Phi_m - \Phi_0)}{\Phi_m} = \frac{F_m - F_0}{F_m} = \frac{F_\nu}{m} \tag{5}$$

This is given by the easily measurable parameter $\frac{F_\nu}{m}$, which can thus be used to evaluate the physiological state of the photosynthetic system and in particular PS II.

6. Materials and methods

The samples used for analysis and fluorescence measures are constituted of small discs of magnolia leaf (diameter about 13 mm), taken from the Botanical Gardens of Padua at weekly intervals and always at the same hour of the day (about 9.00 am). The two chosen plants (Magnolia grandiflora L.) are at the entrance of the Gardens (see figure 5) planted in 1800.

The reasons for this choice were the following: i) the Gardens could give logistic support to the sampling of leaf specimens, placed to the height of 3-3,5 meters; ii) in the Botanical Gardens there is a station of meteorological data linked with the regional network surveying, capable of supplying continuous registration of temperature, humidity, radiation etc.; iii) since the plants are evergreen it is possible to collect data all over the year; iv) a portion of one of the two magnolias is illuminated by a street lamp (milk white light), a 125 watts mercury vapour bulb, placed at the height of 6,30 metres and at a minimum distance from the plant of about 2,20 metres: the light flux in this area is about 157 $watt/m^2$. The street lamp is also set by an automatic lighting system, called "crepuscular", which turns the light on 20 minutes after sunset and off 20 minutes before sunrise. The samplings were made in three different areas of the trees, so as to have the data referring to the first plant, in illuminated and dark regions (used at control) and to the second which is not illuminated. Sample leaf discs were placed into separate boxes in order to guarantee their permanence in the dark until the measurement, taken at the Biology Department and measured with a fluorimeter (the interval of time between samplings and measurements was of about 15/20 minutes). The experiment lasted one year (from October 1994 to October 1995) with an interruption during the summer (from half of July to the end of August). (1) In the beginning the specimens where 10 for all the three areas chosen for the samplings, later, in order to avoid deterioration of the esthetical appearance of the plants we decided to reduce samplings respectively to 5 for the two non illuminated parts, keeping the number of ten for the illuminated area.

7. Measured parameters

Performed measurements considered the analysis of fluorescence emission of the sampled leaf samples, therefore the main parameter that we got from the registered curves was:

$$\Phi_P = \frac{F_\nu}{m} \tag{6}$$

Φ_P indicating photosyntetic efficience.

8. The fluorimeter

In order to measure the fluorescence emitted by the leaf samples a special fluorimeter was used, called PAM (photoamplitude modulate chlorophyll fluorimeter, figure 6), made by Schreiber et al. in 1986. The PAM, compared to a normal fluorimeter, uses a technique based on an in-phase coupled amplifier (lock-in amplifier), which allows to measure the excited fluorescence from a low intensity modulated light source (observation light), in presence of a second continuous or flash light (attinic light), much stronger (can be up to 100 times stronger than the observation light) which has the task of inducing photochemical reactions. As only fluorescence induced by the observation light is modulated, it is the only one that gets amplified. With this technique, in fact, fluorescence induced by attinic lights, doesn't get amplified and does not disturb the measure.

9. Results

The results obtained suggest that the presence of a light source near plants can be the cause of a partial decrease of their photosyntetic efficiency. However it is a quantitative evaluation of the level at which artificial light is responsible of such decrease and if this can be considered pathological for the leaves. In fact, there could be other polluting factors which interfere with such efficiency, also considering that the samples analyzed were taken in the open field, which prevents, differently from laboratory conditions, a successful monitoring of environmental conditions that may influence measurements.

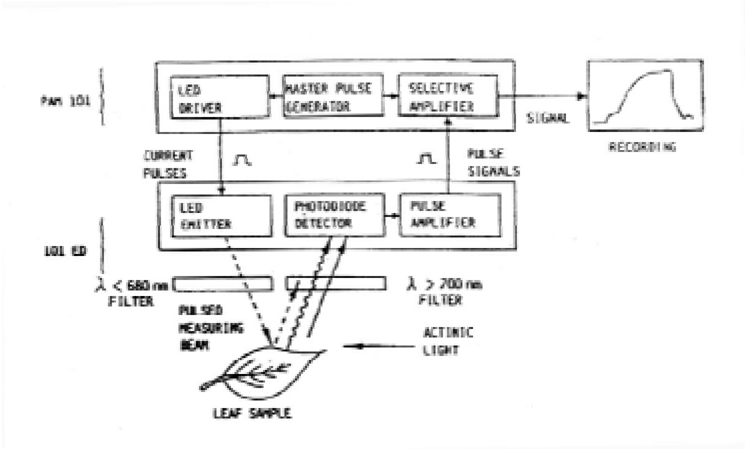

Fig. 6. PAM fluorimeter scheme (photoamplitude modulate chlorophyll fluorimeter) used in fluorescence measurements.

10. Daily averages

The fluorescence curves obtained from each specimen allowed to calculate the constant Φ_P daily average for each sampling area (obtained by arithmetic averages of each single value) and represent its time dependence. Chart 1 and table 2 show how: there is substantial coincidence between non illuminated magnolia a and magnolia b (specimen magnolia) while a significant difference exists between the illuminated part and the non illuminated one of the same magnolia a. It can be hypothesized that one or more factors contribute to the variation of this parameter: it is possible to exclude meteorological changes, such as temperature, humidity, wind strength and direction, etc., as the examined plants are all in the same place. Probably the presence of the street lamp near the plant, constantly on every night of the year, can have determined physiological imbalances (e.g., low chlorophyll production). This phenomenon should also be more evident if the area is illuminated at closer distance. In the same chart another interesting phenomenon is evident: from the first days of February to the first days of April the daily average of the measured parameters tends to diminish progressively; from April (minimum value) the tendence is inverted with a fast reclimbing, until it reaches, in mid-June, values which can be comparable with those of October. This trend is the same for the three areas of the considered plants, but is evident for the one which is illuminated. An explanation for this observation could be that in April magnolias prepare themselves to let the older leaves fall (which are about two years old), where the senescence process is accentuated; therefore it is very probable, compared to other times of the year, to find leaves whose photosyntetic efficiency is lower.

Table 1 -

plant	annual average	standard deviation
magnolia a	0.7251	0.0062
magnolia b (control)	0.7182	0.0053
illuminated magnolia a	0.6006	0.0133

Table 2

date of sampling	magnolia a in the dark	magnolia b (control)	illuminated magnolia a
10 04 94	0.7371	0.7335	
10 11 94	0.7850	0.7638	
10 18 94	0.7844	0.7290	
10 24 94	0.8022	0.7604	
10 31 94	0.7576	0.6496	
11 08 94	0.7776	0.7428	
11 16 94	0.7624	0.7395	
11 22 94		0.7792	0.6545
11 29 94		0.8058	0.5612
12 06 94		0.7648	0.6963
12 13 94	0.7782	0.7757	0.6464
12 20 94	0.7477	0.7808	0.7051
12 29 94	0.7601	0.7542	0.6147
01 04 95	0.8075	0.7651	0.5470
01 10 95	0.7292	0.7000	0.5445
01 17 95	0.7232	0.6508	0.5101
01 24 95	0.7396	0.6669	0.6526
01 31 95	0.7684	0.6926	0.6318
02 09 95	0.7500	0.7180	0.6240
02 16 95	0.7280	0.7210	0.6248
02 21 95	0.7310	0.7175	0.5230
02 28 95	0.7487	0.7220	0.6310
03 07 95	0.7416	0.7188	0.4792
03 14 95	0.7095	0.6303	0.3712
03 21 95	0.7280	0.6598	0.6990
03 29 95	0.6537	0.6176	0.5022
04 05 95	0.6682	0.7504	0.4426
04 11 95	0.7030	0.7801	0.5160
04 20 95	0.6889	0.7205	0.4710
04 27 95	0.7460	0.7686	0.5290
05 04 95	0.6996	0.7371	0.6420
05 09 95	0.6993	0.6532	0.6485
05 16 95	0.7980	0.7538	0.6158
05 23 95	0.6879	0.7146	0.5902
05 30 95	0.7380	0.7547	0.5922
06 14 95	0.7674	0.7880	0.7127
06 27 95	0.7440	0.7812	0.7249
07 12 95	0.7930	0.7490	0.7410
09 21 95	0.6463	0.6986	0.7267
09 27 95	0.7182	0.7390	0.5547
10 05 95	0.7467	0.7195	0.6158
10 12 95	0.7255	0.6222	0.6974
10 19 95	0.7632	0.6248	0.7205

11. Annual averages

From all the daily averages of photosyntetic efficiency (Φ_P) an annual average for each magnolia has been drawn (see table 1). In order to calculate it, one has used statistical relations which kept in mind that every single figure could be the result of a different number of samplings; therefore a weighed average has been obtained. The figures relating to the dark area of magnolia a and of magnolia b can be compared, that is to say they are similar, while those relating to the illuminated area of magnolia a were clearly lower. The standard deviation of the first is lower compared to the second, pointing out the higher variability of the single specimens taken from the latter area.

12. Conclusions

As pointed out above, it is possible to hypothesize that artificial light influences the process of transferring of light energy from the antenna system to the PS II reaction centre. It was not possible to determine how this influence manifests itself biochemically, and it is also difficult to quantify the eventual damage at this level. It is important to point out that if F_m and $F_\circ$ diminish proportionally, so as $F_V\ /F_m$ remains constant, a variation of energy absorption can be hypothesized; if instead it is only F_m to diminish, this could indicate the instauration of a quenching phenomenon the nature of which is however unknown. In our research, for the illuminated magnolia together with a substantial diminishing of F_m , a growth of $F_\circ$ has been found; indicating a higher energy dispersion by the PS II antenna as fluorescence, and a lower energy transfer to the reaction center.

In general, the illuminated area of the plant seems to have a lower photosynthesis activity, as it probably absorbs and uses less natural light, compared to the non illuminated area.

Another possible explanation for the lower efficiency of the illuminated area is a lower content of chlorophyll with respect to non-illuminated areas; this would consequently determine a lower absorption by the antenna systems and therefore also a reduced maximum fluorescence emission.

LIGHT POLLUTION AT MOUNT WILSON: THE EFFECTS OF POPULATION GROWTH AND AIR POLLUTION

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ABSTRACT. This is the first part of a study of the historical growth of light pollution at Mount Wilson Observatory. The night sky brightness at Mount Wilson due to light pollution from the Los Angeles basin was calculated for the years from 1910 to 1990, neglecting changes in lighting technology, and without any air pollution ('smog'). The very large effect of population growth is shown. We made a simple extension of our night sky brightness program to include a layer of smog. Two possibilities are discussed, a layer with density decreasing exponentially with height above the ground, and a layer of constant density and finite thickness. The ground level density is determined by the visibility. We assume a smog layer whose density increases from zero in 1920 to appropriate values for the years from 1950. We added this layer to our model and repeated the Mount Wilson calculations. An average smog layer reduces the visual brightness at the present time by about 6 percent.

1. Introduction

One of the sad happenings in astronomy was the deterioration of the Mount Wilson Observatory as a prime observing site, caused by the growing brightness of the night sky. The latter was caused primarily by the growth of the population in the Los Angeles basin. We are investigating some of the details of this deterioration. We are interested in the sky brightness at Mount Wilson on clear, moonless nights, when there is no fog in the Los Angeles basin but when air pollution (referred to below as 'smog') may be present. We think that the problem may be divided into three parts: (1) The growth of the population, which brought with it increased artificial lighting, (2) the growth of smog in the region and (3) changes in lighting technology, leading from incandescent to mercury to sodium lamps. In this paper we investigate the first and second of these factors.

2. The effect of population growth

We began by calculating the brightness of the sky at Mount Wilson caused by light pollution from cities in the Los Angeles basin. We essentially used our standard model (Garstang 1986, 1989a, 1991), not taking into account any changes in lighting technology, and using the photon emission per person given in Garstang (1989a). We included a total of 124 cities in the Los Angeles basin: these included the City of Los Angeles itself, cities in Los Angeles county outside the City of Los Angeles, and many cities in those parts of Orange, Riverside, San Bernardino and Ventura counties nearest to Mount Wilson. For years from 1940 onwards, for which we had detailed census data, the City of Los Angeles was divided into six and treated as six separate cities. The population of each city (or portion of Los Angeles) was obtained from U.S. Census Bureau publications. Some distant cities were grouped by adding the populations of the separate cities. Only incorporated cities were included in our calculations. Distances from Mount Wilson to each city (or group) were measured on the H. M. Gousha road map of California, estimating the position of the city (or group) center as best we could. We decided not to use a different height above sea level for each city. Taking into consideration the cities that contribute the most to the light pollution at Mount Wilson, we estimated a rough average height above sea level $H = 125$ m: the value is not critical. For the Mount Wilson Observatory, the height above sea level is 1740 m.

We write the law of extinction of light as it passes a distance x through the atmosphere as $I = I_0 \exp(-b_{scatt}x)$, where b_{scatt} is measured per unit distance, and includes contributions for scattering and absorption by molecules (including ozone when necessary) and background aerosols (which are always present even in clear air). If b_{scatt} is function of position, $b_{scatt}x$ must be replaced by the integral of b_{scatt} over x. We formulate b_{scatt} by adding the contributions of the air molecules and aerosols. If $N_m = 2.68 \times 10^{19}$ cm^{-3} is the sea level molecular air density and H is the height of the ground above sea level then the density of the air $N(h)$ at a height h above the ground is

$$N(h) = N_m \exp\,(-cH)\exp\,(-ch)f \tag{1}$$

where $f = 1$ for $h + H < 10$ km and $f = 1.568 \exp(-dh - dH)$ for $h + H \geq 10$ km. The parameters c and d describe the assumed atmospheric density–height model (Garstang, 1991). We adopted $c = 0.113$ km^{-1} and $d = 0.045$ km^{-1}. Then the contribution to the scattering is

$$b_{scatt} = N_m\sigma_R \exp\,(-cH)\exp\,(-ch)f. \tag{2}$$

Here σ_R is the Rayleigh scattering cross section for air molecules at the wavelength being considered. We adopted $N_m\sigma_R = 0.0123$ km^{-1} for the V photometric band and 0.0305 km^{-1} for the B photometric band. The background aerosols are treated as having an exponential distribution decreasing with height h above the ground with reciprocal scale height a, so that the contribution to b_{scatt} is taken as $N_a\sigma_a \exp(-ah)$. The number density of aerosol particles at ground level is N_a and σ_a is the cross section for extinction by a particle. Of course we are actually using the value of $N_a\sigma_a$ averaged over particles of many different kinds and a range of sizes, but the kinds and sizes do not need to be specified in our model. It is convenient to introduce a parameter K as a measure of the scattering by background aerosols. It is defined by the equation [Garstang 1986, equation (4)]

$$b_{scatt} = N_a\sigma_a \exp(-ah) = 11.778KN_m\sigma_R \exp(-cH)\exp(-ah) \tag{3}$$

The coefficient has been increased by 6% to allow for pure absorption by the aerosol particles. The numerical coefficient was originally chosen so that $K = 1$ represented the background aerosols in clear (actually slightly hazy) air on the U.S. east coast. $K = 0.5$

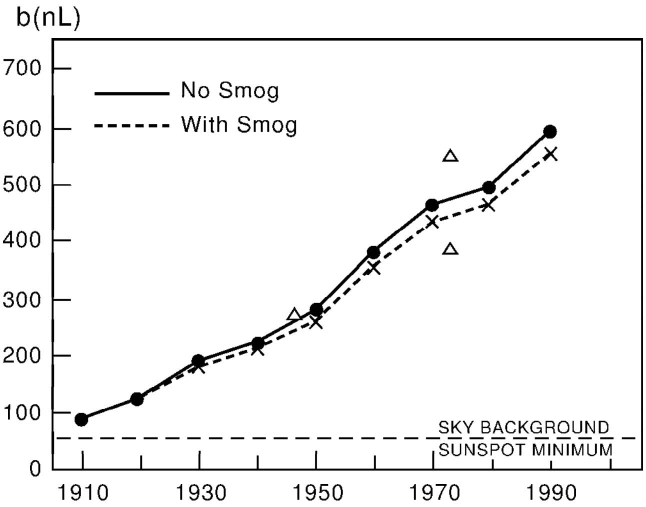

Fig. 1. The brightness b (in nanolamberts) of the zenith sky at Mount Wilson calculated without and with an average smog layer. The results of our reductions of the observations of Bowen in 1947 and of Turnrose in 1973 are shown. All calculations and observations assume a sunspot minimum sky brightness of 55 nL.

is a better approximation for clear air in the western half of the U.S. Using the curved Earth model (Garstang 1989a) it can be shown that for pristine air from the Pacific ocean a value $K = 0.2$ must be assumed to account for visibilities exceeding 110 km that are encountered (Trijonis 1982) in eastern California, Nevada and elsewhere. We used $K = 0.2$ (instead of $K = 0.5$) in all our calculations in this paper. We adopted $a = 0.687$ km^{-1} for the aerosol reciprocal scale height. Other parameters that occur in our model, such as the ground reflectivity and the fraction of light radiated directly upwards, had the usual values we use in our models.

3. Results on population growth effects

Our results are listed in Table I, which gives the B and V brightnesses expressed in magnitudes per square arc second, the photon brightnesses b_B and b_V in photons per square centimeter per second per steradian, the eye brightnesses b in nanolamberts (nL), and the limiting magnitude for a naked eye observer calculated using the program described by Schaefer (1990) with modifications by Garstang (1999). All our results refer to observations at the zenith, and all include night sky background brightnesses corresponding to sunspot minimum, our assumed values for which are listed in the third column of Table I. Our results for the eye brightness are also shown in Fig. 1. The great increase in night sky brightness due to the growth of population is evident.

Our results are subject to some uncertainties. In addition to approximations in the model itself, the population data are subject to uncertainties caused by the large number of incorporations and annexations over the years. We think it not worth the effort it would take to follow all these changes in detail. In addition, we used only incorporated cities: this has proved a satisfactory approximation in our earlier work. The rapid growth after World War I is evident, as is rapid growth after World War II. The reduced growth rate during the depression of the 1930s is also evident.

The rapid growth in the 1980s is due to steady population increases in many cities, especially in the San Fernando Valley and in Orange County. The rate of increase of the Mount Wilson brightness has slowed down somewhat as more of the population increase occurs in cities at larger distances from Mount Wilson. Unfortunately the rate of increase of sky brightness between 1980 and 1990 is about 4% larger than our earlier prediction (Garstang 1989b).

4. Checks on our calculations

There are few observations of the brightness of the night sky at Mount Wilson. However, Turnrose (1974) published two night sky spectra obtained on January 5, 1973. We have integrated the two spectra to find the total sky brightness. His spectra are seriously deficient in one major respect: the bandpasses he used did not include the very strong mercury lines at 5461, 5770 and 5791 Å, although he did give intensities for 4358 Å. We used the strengths of these four lines in the Lick Observatory spectra obtained by Osterbrock, Walker and Koski (1976: we used their Figs. 1 and 2; as they explain, their Fig. 3 is not suitable for this purpose) to make an estimate of the energy missing from Turnrose's results and added our estimates to our calculated sky brightnesses. Turnrose's spectra also omitted the [O I] lines, but in view of the very intense light pollution due to the Los Angeles basin we think that the natural [O I] contribution to the total sky brightness would have been relatively much less important than it was in the Lick spectra, and we did not attempt to estimate it. We obtained for Turnrose's spectrum A (taken at an average zenith distance of 43^o and azimuth 193^o) a sky brightness of 1020 nL, and for spectrum B (average zenith distance 36^o and azimuth 254^o) a brightness of 550 nL. To compare these values with our calculations we must make approximate reductions to the zenith. For this purpose we ran our light pollution program for 1970 and 1980 for the zenith distances and azimuths of Turnrose's spectra and interpolated the results to 1973. We calculated the ratios of the brightnesses from these calculations to the brightnesses interpolated for 1973 from our zenith calculations, and then applied these ratios to Turnrose's observations. We included in our reductions an estimate of the natural sky background brightness in 1973 obtained by using the Ottawa 10.7 cm. flux and the calibration of Walker (1988). The final results we obtained were 550 nL and 380 nL for the two spectra, reduced to the zenith and to sunspot minimum sky background. We show both points in Fig. 1. Both points differ significantly from our calculations, and it is perhaps not valid to average them. However the average does agree very well with our calculations.

Observations of the limiting magnitude of stars viewed with three telescopes at Mount Wilson in 1947 were made by Bowen (1947). A detailed analysis of his observations has been made (Garstang 1999). The best value of the night sky brightness was 330 nL, and the best estimate of the night sky background was 75 nL. In order to reduce this observation to the zenith we ran our program for 1940 and 1950 using zenith distance 30^o and azimuth 90^o, which avoids the worst of the city lights (Bowen said he avoided city lights as much as possible and also avoided the Milky Way). From our calculations we estimated that the pollution part of Bowen's intensity should be reduced by 0.85 to get a zenith estimate. The background estimate of 75 nL refers to the zenith and this should be increased to 79 nL for subtraction from Bowen's total brightness. Thus we estimate the pollution portion of his brightness to be $330 - 79 = 251$ nL, and when reduced to the zenith $0.85 \times 251 = 213$ nL. Adding the sunspot minimum background brightness 55 nL gives a total brightness approximately 270 nL. This value is shown in Fig. 1. The agreement with our calculations is surprisingly good.

5. The smog model

We now turn to the study of the second aspect of night sky brightness at Mount Wilson, the effect of smog. To represent smog we add additional scattering and absorption to that already present in our model. There are two options that are attractive because of their simplicity. In both options the smog is treated as being uniform over the whole city area. One option treats the smog density as decreasing from the ground level upwards according to an exponential law $\exp(-a'h)$, so that we write

$$b_{scatt} = 11.778K'N_m\sigma_R\exp(-cH)\exp(-a'h). \qquad (4)$$

The second option treats the smog as a constant density layer up to a finite height (t) above ground level, and zero density above t, so that

$$b_{scatt} = \begin{bmatrix} 1.778\ K''N_m\sigma_R\exp(-cH) & 0 \le h \le t \\ 0 & h > t\ . \end{bmatrix} \qquad (5)$$

We are mainly interested in the extinction along the light paths taken by city light being scattered in the high atmosphere above the observatory leading to brightening of the sky. We are also interested in light reaching the observatory on a direct line of sight from the city. It is easy to show that the total extinction along a light path is the same in the two models if we take $K' = K''$ and $a' = 1/t$, provided that the observatory is well above the smog layer so that at the height of the observatory the tail of the smog exponential is negligible. (At altitudes within the smog layer the two models will give different results.) This applies for rays travelling at any given angle z to the zenith, when the extinction in passing through the layer is the extinction for a vertically travelling ray multiplied by sec z. It is slightly easier to add a second exponential to our model.

We must also consider the intensity of the smog. If we have certain kinds of observations at various altitudes within the smog we may try to fit our models to the observations. If we do we get values of K' and a$'$ for one model and K'' and t for the second model. We generally find that K' and K'' are unequal. To get a better determination of K' and impose $K'' = K'$ we consider the visibility observed by ground based observers. It is conventional in meteorology (see e.g., Middleton 1952, pp. 4, 63, 94) to adopt as the visibility in daylight (also called the visual range) the distance Δx at which a black object would show a brightness (due to scattered light between the observer and the object) of 0.98 of the brightness of the background horizon beyond the object, this being referred to as a contrast of 0.02. This assumes that the atmosphere is uniform along the line of sight. Using the extinction law for light it can be shown that $\Delta x = 3.91/\ b_{scatt}$. This is known as Koschmieder's formula. (We use this definition, but it is a rather extreme definition, and if a contrast 0.05 were adopted instead the constant 3.91 would be replaced by 3.00.) If distances are measured in kilometers then b_{scatt} must be measured in km^{-1}. In the air pollution literature b_{scatt} is often measured in $(10\ \text{km})^{-1}$, and in these units, with Δx in km, the constant becomes 39.1.

We add to the extinction a term of one of the above forms to represent the smog. We determine K' $(= K'')$ by considering the ground level visibility. In our model [Garstang, 1991, equation (7)] with the additional smog term we have

$$b_{scatt} = N_m \sigma_R [\exp(-ch) + 11.778\ K \exp(-ah) + 11.778\ K' \exp(-a'h)] \exp(-cH) \quad (6)$$

for the exponential model, and the same for the uniform layer model except that K' $\exp(-a'h)$ is replaced by K' for $h \leq t$ and by zero for $h > t$. The horizontal visibility is $3.91/\ b_{scatt}$ where for the ground level with $h = 0$ we have

$$b_{scatt} = N_m \sigma_R [1 + 11.778\ K + 11.778\ K'] \exp(-cH). \quad (7)$$

For the B band we take the value of K to be 0.492 times K for the V band (Garstang 1989a, p. 323). Extinction by smog aerosols has a wavelength dependence of about $\lambda^{-1.8}$ (Ahlquist and Charlson 1969). Combining this with the λ^{-4} dependence for Rayleigh scattering we see from equation (4) above that K' for the B band must be taken as $(4400/5500)^{2.2} = 0.612$ times the K' for the V band.

Before proceeding to study Los Angeles we tried to check the validity of our smog model. McCormick and Baulch (1962) were the first to study atmospheric smog near the ground by measuring the attenuation of solar radiation as a function of altitude. They used a helicopter to carry a Sun photometer and measured the transmissivity of the atmosphere as a function of the height above the ground in Cincinnati. They worked at heights from the ground up to about 180 m. They made measurements on a number of days both of polluted air near the city center and of 'clean' air outside and upwind from the city. The clean air was not really clean, just significantly less polluted than the city center air. We selected the results for one day, December 6, 1961, for which the transmissivity-height curves had a simple form, suggesting that a single smog layer was present. We integrated b_{scatt} from height h to infinite h, and fitted the result to the observations. For the 'clean' air we got a reasonable fit with our model with $K = 3.5$ and $a = 0.9\ \text{km}^{-1}$. This means an aerosol content at ground level of 17 times that of pristine U.S. western air, in a layer which, if it were of uniform density, would have a vertical thickness of 1.1 km. We then fitted our model to the city center observations, and using the same K and a values for the background aerosols, we got an acceptable fit with $K' = 50$, $a' = 10\ \text{km}^{-1}$. This indicates a very dense smog layer with an equivalent uniform thickness of only 100 m.

Improved measurements in Cincinnati were made by Bach (1971). An extensive series of helicopter observations were made on October 4, 1969, an exceptionally smoggy day when it was almost impossible to see the tops of tall buildings from the street. We selected the 8 a.m. data, the earliest in the day, because we thought it would be closest to representing the pollution during the previous night. We made appropriate corrections to our program because the wavelength used was 5000 Å. No clean air data was available for this particular day; after some trials we got a reasonable fit with $K = 1.8$, $a = 1$ km^{-1}. The observations gave the percentage of the solar attenuation in the atmosphere below a stated height. We calculated this from our exponential model, and determined the best fit. We obtained $K' = 120$, $a' = 14$ km^{-1} (mathematically equivalent to a uniform layer of thickness $t = 70$ m). We also modified our program to calculate the vertical extinction through a uniform layer, and our best fit was $K' = 39$, $t = 110$ m. We judged that both models gave acceptable fits with the observations. However, the total absorption from the ground up to the outside of the smog is twice as much in the exponential model as in the uniform layer model. We should make an independent estimate of K', which might come from visibility observations, but no visibility data at Cincinnati were available to me for this date.

These calculations showed that our models could be used to represent smog layers even under rather extreme conditions. Many additional observations were made by McCormick and Baulch and by Bach in Cincinnati, and by various authors in other cities, including Seattle, San Jose, Oakland, Fort Worth, and Phoenix. Our models could be used to analyze much of this data, but we do not think it profitable to continue such studies here.

6. Application to the Los Angeles basin

Los Angeles smog is very variable, both during a single day and from day to day. It tends to be greatest in the middle of the day, and to lessen in the evenings. In consequence the visibility at any site (in the absence of fog) is usually a minimum in the middle of the day, and is much better in the early morning and in the late afternoon. A Stanford Research Institute (1954) study of visibility at Pasadena showed one day when the early morning visibility fluctuated between 20 and 50 km, and it was reduced to 5 km by mid-day. On another day the visibility was 5 km at 1 p.m. and had improved to 16 km by 3 p.m. Variations of a factor of 2 can occur in a period of an hour.

It is clear that there is no need to investigate any individual day in detail. We must adopt representative values of the parameters. A general study of visibility in the Los Angeles basin (and California in general) by Trijonis (1982) gave 1 p.m. data averaged for the years 1974-1976 at 67 locations in California. Along the California-Nevada border the visibility exceeded 110 km, and this requires a value of $K = 0.2$ for pristine Pacific air, as we mentioned earlier. We adopted this for our calculations on the Los Angeles basin. In the center of the Los Angeles basin the median visibility was 13 km. This leads to $K' = 1.83$ for the average mid-day smog. No data were given on night-time visibility. We have made an estimate by assuming that the night-time visibility is twice that of the day-time, and this leads to $K' = 0.77$.

Cass (1979) analyzed some extensive routine measurements of visibility made at ground level in Los Angeles city. These were made from a rooftop at a height of 25 m in downtown Los Angeles over the period 1965–1974. Omitting a few days when the smog was exceptionally bad and a few days when the relative humidity was unusually high, 390 observations gave an average $b_{scatt} = 0.556$ km^{-1} corresponding to a visibility of about 7 km. On individual days the visibility varied from less than 2 km to more than 30 km; the median visibility, exceeded on half the days, was about 8 km. If we double the latter figure for night-time visibility and follow Cass's suggestion of using the Koschmieder formula as $\Delta x = 3.0/\ b_{scatt}$ we get $K' = 1.03$.

The above work on visibility contains no information about the vertical distribution of the aerosols. For the background aerosols we adopted $a = 0.687$ km^{-1}, the value we used above. A good example of the vertical distribution of scattering particles was given by Gloria et al. (1974), who show results quoted from an unpublished study by staff of Meteorologic, Inc. The latter workers used a well-equipped aircraft over Hawthorne Airport in the western Los Angeles basin. They gave the total scattering cross section for light as a function of altitude from the ground up to about 975 m. We analyzed their data assuming $K = 0.2$ and $a = 0.687$ km^{-1} for clear Pacific air. We forced a fit at the ground, which is equivalent to assuming correct ground visibility. For the smog this gave $K' = 3.72$. We then imposed the condition that the total extinction up to height 0.975 km agreed with that calculated from the observations. This gave $a' = 2.55$ km^{-1}, equivalent to a uniform layer of thickness 390 m. We fitted a uniform layer model by the same method, and this gave $K' = 3.72$ and $h_{smog} = 360$ m. The two models are quite different at intermediate altitudes, but this need not concern us as far as our planned application is concerned. The difference between $1/a'$ and h_{smog} is due to the neglect of the tail of the smog exponential above 975 m. If we assume a night time visibility of double that in the day time we get $K' = 1.69$, a rather high value, possibly due to slight fog because the relative humidity at the ground was 75%.

We are also interested in the trends of visibility. Holzworth and Maga (1960) summarized earlier unpublished work by M. Neiberger, who studied visibility in downtown Los Angeles for the period 1932 to 1954, and extended it to 1959. The primary conclusion was that visibility got worse from 1932 to 1947, and stayed about the same from 1948 to 1959. The results clearly showed that visibility improved from noon to 5 p.m. From data in their Table VI we estimate a factor of 1.6 improvement. The improvement probably continued to a somewhat later time, and we think that this is some confirmation of our decision to take the night time visibility as twice that at noon. We took the noon data, estimated the weighted average visibility for 1932, 1947, 1948, and 1959, doubled it, and then calculated the values of K' that resulted. We obtained $K' = 0.27$ (1932), 0.73 (1947), 0.55 (1948 and 1959). The reduction after 1947 is thought to be due to the introduction of the first pollution control regulations.

Trijonis (1982) stated that between 1949 and 1966 nearly all locations showed declining visibility, and between 1966 and 1976 nearly all locations showed improving visibility. For coastal and central Los Angeles visibility improved between 1949 and 1976, while in the inland of the Los Angeles basin the visibility decreased.

Particulates are the principal source of poor visibility. An Environmental Protection Agency Report (1994, Figs. 3-5) summarized particulate matter emissions in the whole of the U.S. for the period from 1940 to 1993. The maximum particulate emission appears to have occurred about 1950, slowly declined until 1970, and declined more rapidly after 1970. Ozone contributes to air pollution through photochemical reactions, which produce other particles (especially sulphates). Turco (1997) gives a summary of ozone concentration in the Los Angeles basin from 1970 to 1988, showing a declining trend of about 1% per annum.

Carlin and Kocher (1971) gave an interesting summary of the sources of pollution in the Los Angeles basin from 1900 to 1980. It is clear that pollution was relatively small in 1920 but increased significantly after that. We assume that it was zero in 1920.

The top of the main smog layer is usually at an altitude of about 300 m. Friends tell me that if you have a house on a hill about 1100 ft, say 330 m, above the general ground level you are above most of the smog on most days. The smog does sometimes extend higher, for example in the work by Gloria et al. (1974) there was a second smog layer at a height of about 500 m. There was a report of fluorocarbons in the Los Angeles basin when the top of the smog was at about 1000 meters altitude (Hester et al. 1974), and the smog sometimes goes over the top of Mount Wilson at 1740 m altitude, but these are worst case scenarios.

Taking all the above into consideration we adopted a value $a' = 3.0$ for our assumed exponential distribution, which corresponds to $t = 330$ meters for the height of a uniform layer. We use the exponential distribution in our calculations on Mount Wilson. We are not particularly interested in intermediate altitudes, but it is our guess that the exponential model distribution would be closer to reality that the uniform layer model.

Looking at the values of K' and ignoring the high value of Gloria et al. (1974), we adopt for night time calculations with smog the values of K' listed in the first row of Table I. Although uncertain, we think that these give fair representative values. Using the calibration of Cass (1979) we find that $K' = 0.75$ corresponds to a particulate loading of about 40 μg/m^3 at night, and in the daytime with half the visibility the particulate loading would be about 90 μg/m^3. These values may be compared with the Federal air pollution standard, which is 50 μg/m^3, with the first level alert at 100 μg/m^3.

We now apply our assumptions to the calculation of the effect of smog on night sky brightness at Mount Wilson. For the aerosols we used $K = 0.2$, $a = 0.687$ km^{-1}, $a' = 3.0$ km^{-1}and the values of K' listed in Table I. We added an approximate correction to our model to allow for the slope of the ground from the sea coast to the foothills, keeping the smog thickness the same everywhere. We added a calculation of the extinction along the direct line of sight from each city to the Mount Wilson Observatory. We calculated the limiting visual magnitude seen by an average naked-eye observer, using the procedure of Schaefer (1990) with minor modifications described in Garstang (1999).

Our results are given in Table I. The night sky brightness at the zenith in 1990 was reduced by about 0.11 mag/sec^2 in B and 0.08 mag/sec^2 in V. In photon units the reductions were about 9% in B and 6% in V. These figures relate to our assumed average smog layer. Smog is very variable, and the brightness reduction on any night may be between zero and at least double our calculated amounts. The effect of the smog on the limiting visual magnitude was negligible. One factor which is of significance is that much of the light from the cities which gets scattered in the atmosphere above Mount Wilson passes through the smog layer at only moderate zenith distances. It suffers much less extinction than one might guess from the visibility at the ground. We also calculated the extinction seen by an observer standing on Mount Wilson looking at the cities of the Los Angeles basin at night. Our results are given in Table II. For a nearby city such as Pasadena the transmission along the line of sight in the V band is 0.73 when there is no smog, and 0.59 when there is an average smog layer. For a distant city, such as the Los Angeles port, the transmission is 0.22 without smog and 0.069 with smog. Thus, for this distant city the brightness observed would be reduced by a factor of about 3 by an average smog layer. We see that the apparent brightness of distant cities may be significantly reduced by smog, even if the reduction in sky brightness at the Mount Wilson zenith is relatively small.

We have also given in Table I a few results for the contributions to b_V of Pasadena, Los Angeles, and the nearer part of Orange County. These results illustrate the increasing contributions from distant cities.

The conclusion is clear. The presence or absence of smog in the Los Angeles basin has made very little difference to the sky brightness at Mount Wilson. The huge brightness increase is largely due to the large growth of population in the Los Angeles basin. We hope to deal with the effects of changing lighting technology in a future paper.

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TABLE I

Night sky brightness at Mount Wilson*

	Smog	Sky	1910	1920	1930	1940	1950	1960	1970	1980	1990
K'	Yes		0	0	0.25	0.50	0.75	0.75	0.75	0.70	0.65
B	No	22.99	22.37	22.00	21.54	21.34	21.10	20.76	20.55	20.49	20.30
	Yes				21.57	21.41	21.20	20.87	20.66	20.60	20.41
b_B	No	0.39	0.69	0.97	1.49	1.77	2.22	3.03	3.69	3.90	4.65
	Yes				1.45	1.68	2.03	2.74	3.32	3.52	4.21
V	No	21.99	21.44	21.10	20.64	20.46	20.22	19.88	19.66	19.60	19.40
	Yes				20.66	20.50	20.28	19.95	19.74	19.67	19.48
b_V	No	0.60	1.00	1.37	2.08	2.46	3.07	4.20	5.13	5.46	6.51
	Yes				2.05	2.38	2.90	3.93	4.78	5.10	6.10
Eye	No	55	91	124	188	223	278	380	465	494	590
	Yes				185	215	262	356	433	462	552
Mag	No	6.19	5.95	5.79	5.57	5.49	5.37	5.21	5.11	5.08	5.00
	Yes				5.58	5.50	5.40	5.25	5.15	5.12	5.03
LA_V	Yes		0.23	0.43	0.64	0.80	0.89	1.06	1.17	1.27	1.49
P_V	Yes		0.11	0.16	0.29	0.31	0.39	0.43	0.42	0.44	0.49
O_V	Yes		—	—	0.01	0.01	0.01	0.06	0.11	0.14	0.17

*K' is the parameter measuring the intensity of the smog. B and V are in magnitudes per square arc second. b_B and b_V are in units of 10^8 photons/cm^2/sec/steradian. 'Eye' is in nanolamberts. 'Mag' is an estimate of the limiting visual magnitude. 'Smog' - no indicates no smog in calculations, yes indicates the values of K' used were those given in the Table. LA_V, P_V and O_V denote the contributions to b_V from Los Angeles city, Pasadena and the nearer part of Orange County, all in units of 10^8 photons/cm^2/sec/steradian.

TABLE II

Extinction of light from a city that reaches an observer directly

Date	City	Smog		No Smog	
		B	V	B	V
1990	Pasadena	0.42	0.59	0.58	0.73
	Central Los Angeles city	0.082	0.22	0.22	0.42
	Los Angeles port area	0.013	0.069	0.075	0.22

References

Ahlquist, N. C. and Charlson, R. J. 1969, Atmos. Environ. **3**, 551.

Bach, W. 1971, J. Air Pollution Control Assoc. **21**, 621.

Bowen, I. S. 1947, Publ. Astron. Soc. Pac. **59**, 253.

Carlin, A. P. and Kocher, G. E. 1971, *Environmental Problems: Their Causes, Cures and Evolution, using Southern California Smog as an Example*, Rand Corporation - Carnegie Corporation Report R-640-CC/RC.

Cass, G. R. 1979, Atmos. Environ. **13**, 1069.

Environmental Protection Agency, 1994, National Air Pollutant Emission Trends, 1900—1993, Report EPA-450/R-94-027.

Garstang, R. H. 1986, Publ. Astron. Soc. Pac. **98**, 364.

–, 1989a, Publ. Astron. Soc. Pac. **101**, 306.

–, 1989b, Ann. Rev. Astron. Astrophys. **27**, 19.

–, 1991, Publ. Astron. Soc. Pac. **103**, 1109.

–, 1999, in this volume.

Gloria, H. R., Bradburn, G., Reinisch, R. F., Pitts, J. N., Behar, J. V. and Zafonte, L. 1974, J. Air Pollution Control Assoc. **24**, 645.

Hester, N. E., Stephens, E. R. and Taylor, O. C. 1974, J. Air Pollution Control Association **24**, 591.

Holzworth, G. C. and Maga, J. A. 1960, J. Air Pollution Control Assoc. **10**, 430.

McCormick, R. A. and Baulch, D. M. 1962, J. Air Pollution Control Assoc. **12**, 492.

Middleton, W. E. K. 1952, *Vision Through the Atmosphere*, Toronto University Press.

Osterbrock, D. E., Walker, M. F. and Koski, A. T. 1976, Publ. Astron. Soc. Pac. **88**, 349.

Schaefer, B. J. 1990, Publ. Astron. Soc. Pac. **102**, 212.

Stanford Research Institute 1954, *The Smog Problem in Los Angeles County*, Western Oil and Gas Assoc., pp. 107-108.

Trijonis, John 1982, J. Air Pollution Control Assoc. **32**, 165.

Turco, R. P. 1997, *Earth under Siege, From Air Pollution to Global Change*, Oxford University Press, New York, p. 162.

Turnrose, B. E. 1974, Publ. Astron. Soc. Pac. **86**, 545.

Walker, M. F. 1988, Publ. Astron. Soc. Pac., **100**, 496.

LIMITING VISUAL MAGNITUDE AND NIGHT SKY BRIGHTNESS

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ABSTRACT. We review the theory of visual thresholds and applications to the limiting magnitude of a telescope and of the eyes, based on Schaefer's model with minor improvements. We apply our formulation to the Yerkes Observatory refractor and to naked eye observations at Mount Wilson Observatory. We reanalyze Bowen's telescopic observations at Mount Wilson by his approximate method and by our more elaborate theory. An extension of his method leads to a determination of the night sky brightness if the visual acuity of the observer is assumed to be average. Our more elaborate method allows a determination of the sky brightness, the visual acuity of the observer, and the average seeing during the observations.

1. Introduction

It has been of much interest in the past to ask what is the faintest stellar magnitude which can be seen by the naked eye with or without a telescope. Various formulae have been quoted for this purpose, but usually they have not taken into account the brightness of the night sky. For example, the traditional formula for the limiting visual magnitude m of a telescope can be put into the form

$$m = N + 5 \log D, \tag{1}$$

where D is the aperture of the telescope in centimeters and N is supposedly a constant. For many years, apparently starting with Young (1888, p. 470), the value $N = 7$ was used, and this was copied in many later books. Steavenson (1915a) drew attention to the disagreement between the traditional limiting magnitude formula (1) and observed values. Subsequent work showed that many observers can see stars fainter than equation (1) predicts. Various values of N have been proposed, ranging from 6.8 (Dimitroff and Baker, 1945, p. 44) to 8.7 based on an observation by Steavenson (1915b) of an 11.9 mag star using a 4.3 cm diameter objective. A still higher value of N would be needed to cover exceptional cases such as O'Meara's eyesight (discussed by Schaefer 1990). In the present author's opinion the best value for general use is perhaps that of Sinnott (1973) who proposed that $N = 7.7$. Improved methods of predicting m are desirable. One improvement was made by Bowen (1947), as will be discussed below, but not much use seems to have been made of his work. Major improvements were made by Schaefer and our own calculations described below follow his work with some relatively minor improvements. We have attempted to standardize our units by expressing telescope apertures, exit pupil diameters and eye pupil diameters in centimeters, illuminances in lux, and laboratory and sky background brightnesses in nanolamberts (abbreviated nL). This has the effect of making certain constants (such as N) have unfamiliar numerical values.

2. General formulae

We denote by i the illumination received directly from a star which is at the threshold of visibility to an observer, and by b the brightness of the night sky background. These are related by a formula $i = f(b)$. One important limitation in Bowen's work was his use of

$$i = f(b) = kb^{1/2}. \tag{2}$$

This may not be too bad an average if one must cover a range of 10^9 in background brightness with a single simple formula, but it is a poor approximation for small b, which is of interest in light pollution studies, because as b tends to zero i should tend to a constant threshold value. The formula does lead to simple results which we shall discuss in Section 6. Knoll, Tousey and Hulburt (1946) made a series of experimental determinations of the threshold for a point source seen against an illuminated background. They showed that their results could be represented by a relation of the form $f(b) = P(1 + kb)^{1/2}$, where $P = 1.076 \times 10^{-9}$ and $k = 1$ (by chance) if b is in nL and i is in lux. This equation does have the correct threshold behavior, but it only represents their data to within a factor 3 over their range of 10^9 in b. We shall not use this relation because better formulae can be obtained.

The problem of getting an appropriate relation between i and b was studied by Hecht (1934). On the basis of his chemical theory of vision he proposed a relation of the form

$$i = f(b) = C(1 + Kb^{1/2})^2, \tag{3}$$

where C and K are constants. The chemical theory of vision used by Hecht to justify using this form of equation is no longer accepted physiological theory, but the form of equation seems to describe the observed relationships remarkably well. On the basis of the observations by Knoll, Tousey and Hulburt (1946) of threshold intensities Hecht (1947) proposed using two relations of the same form, one for faint illuminances when the rods of the retina are dominant, and one for bright illuminances when the cones of the retina dominate. The numerical equations given by Hecht were used by Weaver (1947), Garstang (1986) and Schaefer in studies of the naked eye visibility of stars under various conditions of sky brightness.

Blackwell (1946) described a very large set of laboratory naked eye binocular observations of threshold contrast as a function of b (about 2 million observations were made and 450,000 analyzed). We use the final results in his Table VIII, which were based on about 90,000 observations by seven observers whose average age was about 23 years. Seven circular disks of various diameters were used as stimuli against a large background whose brightness could be varied from 10^9 nL down to 10 nL. The experiments determined the threshold contrast for seeing a disk against the background. Tousey and

Hulburt (1948) modified Blackwell's data by changing from threshold contrasts to absolute thresholds, changing the units, and doubling the values of i to change the threshold criterion from a 50% probability of detection to a 98% probability of detection. We further changed the units of i to lux and the units of b to nanolamberts. All the photometry was expressed in terms of the photopic response curve. We applied a correction to the observations of Blackwell in the scotopic region to allow for the difference of color temperatures between his sources and those of Knoll, Tousey and Hulburt. (The latter authors had 2360° K; Tousey and Hulburt stated that Blackwell had 2850° K.) Some additional experiments were performed with zero background brightness (Blackwell 1946, Table IV). We converted these measurements to values of i in lux. Finally we applied small systematic corrections to Blackwell's data for each background brightness separately so that for effectively point sources Blackwell's data would agree with Knoll, Tousey and Hulburt. The effect of this is to ensure that the Knoll, Tousey and Hulburt data were used for point sources and the contrast ratios measured by Blackwell were used for larger sources.

We wanted to use equations of the basic form (3), but we sought to generalize the equations to include the effect of stimulus size θ as described by Blackwell's data. In astronomical applications θ is the seeing disk diameter. Blackwell gave θ in arc minutes. We also wanted to smooth out the transition between scotopic and photopic formulae to eliminate the discontinuity in the use of two separate Hecht type formulae without losing much of the character of the two formulae. After some trials we adopted the following formulae:

$$i_1 = c_1(1 + k_1 b^{1/2})^2(1 + \alpha_1\theta^2 + y_1 b^{z_1}\theta^2) \tag{4a}$$

$$i_2 = c_2(1 + k_2 b^{1/2})^2(1 + \alpha_2\theta^2 + y_2 b^{z_2}\theta^2) \tag{4b}$$

$$i = i_1 i_2/(i_1 + i_2) \tag{4c}$$

These three equations represent the function $f(b)$. Unlike earlier authors we must evaluate both i_1 and i_2 for all values of b. Equation (4c) is a purely mathematical artifact which we have introduced to provide a smooth transition from the response function of the rods to that of the cones. This smooth transition seems apparent in the final results of Knoll, Tousey and Hulburt. For small b we find that i_1 is appreciably smaller than i_2 so that $i = f(b)$ does not differ greatly from the scotopic threshold i_1, while for large b we find that $i_1 \gg i_2$ so that $i = f(b)$ is nearly equal to the photopic threshold i_2. We tried some other formulae, but we did not find one better than (4c). Then we took our combination of Knoll, Tousey and Hulburt's data and Blackwell's data, and determined the best fit of our formulae. We found that the best fit was given by omitting the data for $b = 10^9$ nL and $\theta = 360$ arc minutes. We obtained $c_1 = 3.451 \times 10^{-9}$, $c_2 = 4.276 \times 10^{-8}$, $k_1 = 0.109$, $k_2 = 1.51 \times 10^{-3}$, $y_1 = 2.0 \times 10^{-5}$, $\mathrm{y}_2 = 1.29 \times 10^{-3}$, $z_1 = 0.174$, $z_2 = 0.0587$, $\alpha_1 = 2.35 \times 10^{-4}$, $\alpha_2 = 5.81 \times 10^{-3}$. The values $b = 10^9$ nL and $\theta = 360'$ are rather extreme, and not of interest for our planned calculations, but in spite of our omitting them from the fitting our formulae do give reasonably good predictions of i if either $b = 10^9$ nL or $\theta = 360'$ or both. To convert i into magnitudes we use the relation (Allen 1973 p. 197)

$$m = -13.98 - 2.5 \log i \tag{5}$$

where i is expressed in lux.

Strictly speaking, our formulae apply to observers aged about 23 years. To apply our formulae to observers of other ages we need a formula for the diameter of the eye pupil p as a function of the age of the observer A and the brightness of the sky background b. We considered the papers by Kadlecova et. al. (1958) and Kumnick (1954). From these we estimated the variation of pupil diameter with age for dark backgrounds assuming a linear relation. From Kumnick's data we estimated (including the filter factor) that her data for bright backgrounds was obtained with a background of $b = 2.5 \times 10^6$ nL, and we obtained the variation with age as a linear relation. Finally we used the form of relationship used by Moon and Spencer (1944) to combine the dark and bright relationships into a single formula. We obtained

$$p = 0.534 - 0.00211A - (0.236 - 0.00127A) \tanh (0.40 \log b - 2.20) \qquad (6)$$

Our result agrees quite closely with diameters obtained by Schaefer (1990, equation (5)) for ages between 20 and 90. Although not needed for most light pollution work, our formula will work for skies as bright as daylight. Individual observers may show significant deviations from the average represented by equation (6). After the present paper had been completed we found the results of I. E. Loewenfeld (quoted by MacRobert 1992). If we had included her results in our averages we would have obtained an average dark sky pupil diameter 0.2 or 0.3 mm smaller at all ages from 20 to 90. Our results would be only slightly affected.

Schaefer (1990) gave an extensive discussion of additional factors which must be included to obtain accurate results. All the correction factors are defined in the sense that i_1 and i_2 must be multiplied by the appropriate factors to give the correct threshold. The correction factors must be determined separately for i_1 and i_2. The appropriate corrections must also be applied to b. The factors are: (a) a factor F_b to take into account that one eye is used in telescopic observations, while binocular vision was used in obtaining the relations between i and b, (b) a factor F_e to allow for extinction in the terrestrial atmosphere, (c) a factor F_t to allow for the loss of light in the telescope, F_t being the reciprocal of the transmission t through the telescope and eyepieces, (d) a factor F_p to allow for the loss of light if the telescope exit pupil is larger than the eye pupil, (e) a factor F_a to take into account the ratio of the area of the telescope to that of the naked eye, (f) a factor F_m to allow for the reduction of the sky brightness by the telescope magnification, (f) a factor F_{SC} to take the Stiles-Crawford effect into account, (g) a factor F_c to allow for the difference in color between the laboratory sources used in determining the relationships between i and b and the stars being observed, and (h) a factor F_s to allow for the acuity of any particular observer, defined so that $F_s < 1$ leads to a lower threshold i and therefore implies an eye sensitivity higher than average.

For telescopic observations we must replace the image size θ by $M\theta$ in our equations (4), where M is the magnification of the telescope. Then Schaefer's F_r is not needed because we have already included the image size in our equations (4). Schaefer also gave an experience correction. This can be used if desired; we did not use it, the effect of experience is included in our F_s. In calculating the correction factors we have followed Schaefer closely, except that for F_{SC} we used the formulation of Moon and Spencer (1944), which gives results almost the same as Schaefer's formulation (after correction for an important misprint in Schaefer's work: his formulae for F_{SC} are the inverses of the correct formulae, so that his formulae give $1/F_{SC}$). It is perhaps a misnomer to call F_a and F_m correction factors because they are primary factors allowing a telescope to see objects fainter that the eye can see. In fact $F_a = p^2/D^2$, where D is the aperture of the telescope, and $F_m = M^2$. We refer the reader to Schaefer's paper for detailed discussion and formulae for all the other factors.

The factors can be combined as

$$F = F_b F_e F_t F_p F_a F_{SC} F_c F_s \tag{7}$$

$$G = 1/(F_b F_t F_p F_a F_m F_{SC} F_c) \tag{8}$$

The individual correction factors must be calculated separately for the scotopic and photopic cases. We use additional subscripts 1 for scotopic and subscripts 2 for photopic correction factors. Then c_1 must be replaced by $F_1 c_1$ in equation (4a) and c_2 must be replaced by $F_2 c_2$ in equation (4b). We must replace b by $G_1 b$ in equation (4a), b by $G_2 b$ in equation (4b), b by $G_1 b$ or $G_2 b$, as appropriate, in equation (6), and θ by $M\theta$ in equations (4a) and (4b). Note that F_m does not occur in F and that F_e and F_s do not occur in G.

3. Naked eye observations

Our method can be applied to observations made with the naked eye. Some of the corrections discussed above do not apply to the eyes, and a different formula is needed for F_a. If p_0 is the pupil diameter used by the average of the Knoll, Tousey, Hulburt and Blackwell observers, who are assumed to have been age 23, and p is the pupil diameter used by some other observer, calculated from equation (6) above, then $F_a = p_0^2/p^2$. The correction factors are given by

$$F = F_a F_{SC} F_c F_e F_s \tag{9}$$

$$G = 1/(F_a F_{SC} F_c) \tag{10}$$

They must be calculated for scotopic and photopic conditions separately, and applied in the manner described above, with $M = 1$.

4. Application to Yerkes Observatory

We felt the need for a check on our method. Barnard (1913) observed the long-period variable star AG Cygni, and his observations showed that the limiting magnitude of the Yerkes 102 cm refractor was about 17.0. These observations make a valuable benchmark even today, for not only were they made by an experienced observer with the largest refractor in the world, but they were made in the days when light pollution at Yerkes Observatory was negligible. He observed AG Cygni on 80 nights between November 1910 and April 1913. He missed a maximum which occurred in January 1912, and so the period is one half of what he thought. We used a period 292 days (slightly shorter than the modern value) which fits Barnard's observations and replotted his observations with this period. A very presentable light curve appeared, though with a large scatter of the observations, the light curve being very similar in form to that of R Aur (Isles and Saw 1987). The curve shows a nice minimum at about magnitude 17.0, in agreement with Steavenson (1915a). We estimate the uncertainty as two or three tenths of a magnitude. There are other difficulties in Barnard's work, including uncertainities of the comparison star magnitudes and the general effects of the rather poor atmospheric conditions at Yerkes Observatory.

We used our program described above to calculate the limiting magnitude of the Yerkes refractor. We assumed age 55 for Barnard, magnifications 460 and 700 which were used by Barnard, an extinction of 0.32 magnitude, a telescope transmission of 0.61 based on estimates of the reflection losses and absorption in the objective and eyepieces, and other parameters with their usual values. We verified by using our programs that light pollution would have been negligible. Barnard's observations were made at a time when the sunspot counts were very low, so we assumed a solar minimum night sky background brightness of 55 nL. We assumed limiting magnitudes of 17.0 with $M = 460$ and 17.1 with $M = 700$, based on Barnard's statements on several occasions that he could not see AG Cygni with $M = 460$ but he could glimpse it with $M = 700$. The best fits we obtained were with $F_s = 0.65$, $\theta = 1.5''$ and $F_s = 0.68$, $\theta = 1''$, there being little to choose between these. The seeing is not well determined, its value depends on the difference we assume between the limiting magnitudes for $M = 460$ and $M = 700$. The limiting magnitude for $M = 700$ is quite close to the optimum value of M, beyond which for larger M the limiting magnitude becomes brighter; for $\theta = 1.5''$ the optimum from our calculations is $M = 800$. The value of F_s significantly smaller than unity is a confirmation of the well known above average eyesight of Barnard. The fit we have obtained seems to confirm the broad correctness of our model.

5. Application to Mount Wilson

The simple formulae mentioned at the beginning of this paper made no reference to the increased brightness of the night sky background due to light pollution. This was of no importance in the calculations above on Yerkes Observatory. However, at Mount Wilson Observatory light pollution is substantial, and this affects the limiting magnitude which can be observed. We calculated the limiting magnitude for a naked eye observer aged 40 at Mount Wilson, using the night sky brightnesses which we have calculated (Garstang 1999). The results are given in Table I of that paper. The results illustrate very well the steady worsening of the night sky at Mount Wilson.

6. Bowen's approximate formula

Another simple application of the above method is to the derivation of a simple formula given by Bowen and obtained by him in a direct way. We put $F_{SC} = 1$, $F_c = 1$ and $F_b = 1.41$ for a single eye. We use the appropriate formulae for F_p so that we take account of whether the exit pupil is larger or smaller than the eye pupil. Finally, we use equation (2) instead of our equations (4). The value of k is that given by Langmuir and Westendorp (1931), which when changed into our units and doubled to give a detection probability of 98% is $k = 1.25 \times 10^{-9}$.

We write $E = D/M$ for the diameter of the exit pupil of the telescope. Putting in the formulae for the correction factors we find after some algebra that

$$E > p \quad m = C + 5 \log D - 5 \log E + 2.5 \log p + 1.25 \log t, \tag{11}$$

$$E \leq p \quad m = C + 5 \log D - 2.5 \log E + 1.25 \log t. \tag{12}$$

where C is now defined by

$$C = 8.09 - 2.5 \log p - 1.25 \log b - x - 2.5 \log F_s \tag{13}$$

and x is the extinction in magnitudes suffered by the starlight. Bowen did not include t in his formulae, but he did mention its importance for the 152 cm telescope at Mount Wilson. If we put $t = 1$ and $E = D/M$ in equation (12) we get

$$E \leq p \quad m = C + 2.5 \log D + 2.5 \log M \tag{14}$$

the formula given by Bowen. Bowen did not give the formula (13) for C, and hence he did not obtain any value of b.

It is important to note that C is not necessarily a constant. Even if we neglect variations of p, C depends on b and on x. C may be treated as a constant for a given observatory if an average sky brightness is assumed and an average extinction is valid, the averages being taken over the part of the sky of interest (usually not excessively far from the zenith). That is essentially what Bowen did. We have reanalyzed the data given by Bowen (1947, Fig. 1). He gave limiting magnitudes observed at the Mount Wilson Observatory using three telescopes and various magnifications. Two were refractors with coated objectives having $D = 0.84$ cm and $D = 15$ cm. The third was a reflector having $D = 152$ cm (the famous 60-inch reflector, which is a 3 mirror cassegrain). We estimated the transmissions of the telescopes, assuming non-reflection coatings on all air-glass lens interfaces including the eyepieces, and allowing for the losses at the three reflections and the loss by secondary support obstruction in the reflector. We obtained $t = 0.92$ for the refractors and $t = 0.58$ for the reflector. The adopted values of t are not critical. We then calculated the quantity $m - 5 \log D - 1.25 \log t$, and plotted it against $-\log E$. The resulting diagram (Fig. 1) is very similar to Bowen's diagram, but the points for the 152 cm telescope are closer to those for the other telescopes. It shows a nearly linear relationship. We omitted the two points with $-\log E = 0.99$ and 1.28 because we believe that the former is severely affected by seeing and the latter is severely affected by the failure of the Langmuir-Westendorp relation at small b. We used least squares to fit two straight lines of slopes 2.5 and 5 according to equations (11) and (12) to the remaining points and obtained the constant in equation (13) as $C = 5.64$. We used equation (6) to estimate p, taking $A = 48$ for Bowen in 1947 and examining the variation of p over various background brightnesses b. We adopted $p = 0.60$ cm. We took $x = 0.20$ as an average value of the extinction at scotopic wavelength 510 nm within about 40° of the zenith. We assumed that $F_s = 1$. Equation (13) then allowed us to calculate b,

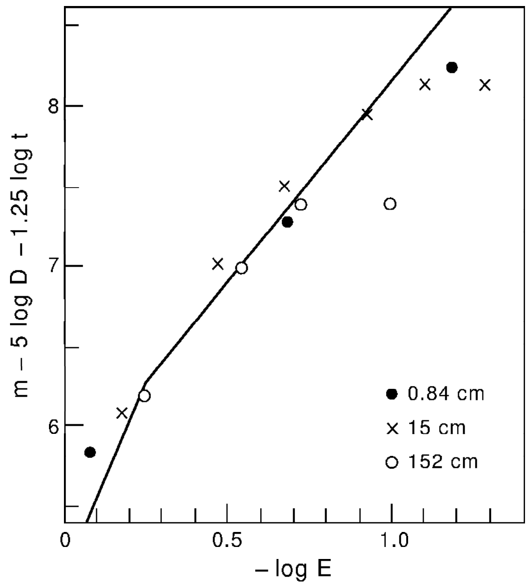

Fig. 1. Bowen's diagram of limiting visual magnitude as a function of the diameter of the exit pupil E, replotted with changed units and with the inclusion of the correction (t) for telescope losses. The lines are the best fit of equations (11) and (12), omitting the points with $-\log E = 0.99$ and 1.28. The slope changes at the value $E = p = 0.60$ cm.

with the result b = 170 nL. This value is of course subject to uncertainty from many causes, including the fitting process, the failure of Langmuir and Westendorp's relation for small b, whether their value of k (as modified by us) is appropriate for the threshold criterion used by Bowen, whether $F_s = 1$ is a correct description of Bowen's visual acuity, and whether our chosen value of p is a fair average for Bowen's eye under various magnifications and hence background brightnesses. We estimate the uncertainty to be at least a factor of 2. It should be noted that, according to equation (12), b and F_s cannot be determined independently by Bowen's method. We actually have determined $bF_s^2 = 170$ nL and assumed that $F_s = 1$.

7. More accurate analysis of Bowen's observations

It is interesting that we have been able to make an estimate of the night sky brightness at Mount Wilson in 1947: this is of interest for our work on light pollution because there are few published measures of the brightness in the literature. It is therefore worth while making a more accurate analysis of Bowen's observations. We took the theory described in Section 2 above, and calculated all the correction factors. We assumed an extinction of 0.17 in V magnitudes for an average zenith distance of perhaps 30^o. We assumed a star color of B − V = 0.7. Consideration shows that there are 3 significant unknowns

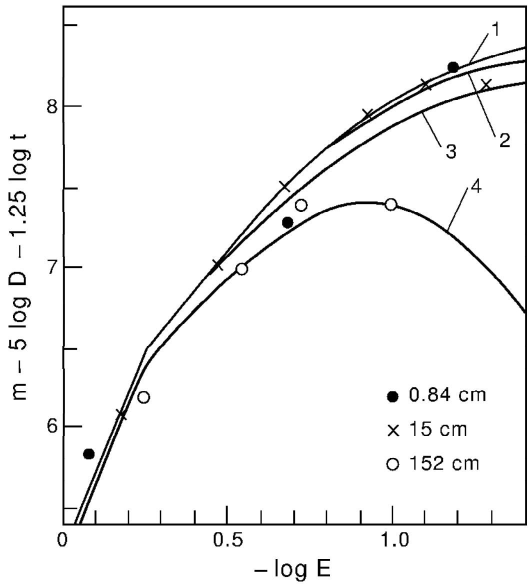

Fig. 2. Bowen's observed points are plotted for telescopes with $D = 0.84$ cm, $D = 15$ cm and $D = 152$ cm. Curve 1 is for $D = 0.84$ cm with any value of the seeing. The curve for $D = 15$ cm and $\theta = 0$ is indistinguishable from curve 1. Curve 2 is for $D = 15$ cm and $\theta = 1''.5$. Curve 3 is for $D = 152$ cm and $\theta = 0$. Curve 4 is for $D = 152$ cm and $\theta = 1''.5$. Curves 1, 2 and 4 were derived from parameters derived from a least-squares fitting to all the points in a single set of calculations. The parameters were $F_s = 0.69$, $\theta = 1''.5$ and $b = 330$ nL. Curve 4 shows that the seeing is primarily determined by the observation with the 152 cm telescope and the highest magnification used ($M = 1500$).

in our problem (i.e., quantities which we cannot guess), the brightness b, the seeing θ and the factor F_s. We performed calculations for ranges of values of b, θ and F_s and determined the values of b, θ and F_s which minimized the least squares deviations between our calculated values and Bowen's observations for all three telescopes in a single calculation. Our final results are $b = 330$ nL, $s = 1''.50$ and $F_s = 0.69$. Our theory not only produces a value of the night sky brightness, but it also gives a value of the seeing at Mount Wilson during Bowen's observations and an estimate of F_s. Because $F_s < 1$ it shows that Bowen had a fainter than average threshold. This may be due to above average retinal sensitivity, to his scientific experience, and possibly to an above average eye pupil size. Other factors such as errors in the comparison star magnitudes may also contribute. If we accept the value $b = 330$ nL as the best attainable, we may ask if the value is reasonable. We note that when Bowen was observing solar activity was rising towards maximum. We do not know the dates of his observations, but in late 1946 and early 1947 the sunspot number averaged roughly 120 (Waldmeier 1961). The correlation of Walker (1988) leads to an estimate of 75 nL for the natural night sky background brightness. There is a residual of 255 nL which we attribute to light pollution at Mount Wilson from the Los Angeles basin. This estimate is of importance as a check on our light pollution calculations for Mount Wilson, and it is discussed in Garstang (1999). We conclude that the study of limiting visual magnitudes can give useful information on night sky brightnesses in cases where there is severe light pollution.

References

Allen, C. W. 1973, Astrophysical Quantities, 3rd Ed. (London: Athlone).

Barnard, E. E. 1913, MN 73, 500.

Blackwell, H. R. 1946, J. Opt. Soc. Am. 36, 624.

Bowen, I. S. 1947, Publ. Astron. Soc. Pac. 59, 253.

Dimitroff, G. Z., and Baker, J. G. 1945, Telescopes and Accessories (Philadelphia: Blakiston).

Garstang, R. H. 1986, Publ. Astron. Soc. Pac. 98, 364.

Garstang, R. H. 1999, in this volume.

Hecht, S. 1934, Proc. Nat. Acad. Sci. 20, 644.

Hecht, S. 1947, J. Opt. Soc. Am. 37, 59.

Isles, J. E. and Saw, D. R. B. 1987, J. Brit. Astron. Assoc. 97, 106.

Kadlecova, V., Peleska, M. and Vasko, A. 1958, Nature 182, 1520.

Knoll, H. A., Tousey, R., and Hulburt, E. O. 1946, J. Opt. Soc. Am. 36, 480.

Kumnick, L. S. 1954, J. Opt. Soc. Am. 44, 735.

Langmuir, I. and Westendorp, W. F. 1931, J. Appl. Phys. 1, 273.

MacRobert, A. 1992, S&T 83, 503.

Moon, P. and Spencer, D. E. 1944, J. Opt. Soc. Am. 34, 319.

Schaefer, B. E. 1990, Publ. Astron. Soc. Pac. 102, 212.

Sinnott, R. W. 1973, S&T 45, 401.

Steavenson, W. H. 1915a, J. Brit. Astron. Assoc. 25, 186.

–, 1915b, J. Brit Astron. Assoc. 25, 229.

Tousey, R. and Hulburt, E. O. 1948 J. Opt. Soc. Am. 38, 886.

Waldmeier, M. 1961, The Sunspot-Activity in the Years 1610–1960 (Zürich: Schulthess)

Walker, M. F. 1988, Publ. Astron. Soc. Pac. 100, 496.

Weaver, H. F. 1947, Publ. Astron. Soc. Pac. 59, 232.

Young, C. A. 1888, A Text Book of General Astronomy (Boston: Ginn and Co.).

THE PROPAGATION OF LIGHT POLLUTION IN DIFFUSELY URBANISED AREAS

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ABSTRACT. The knowledge of the contribution $b_d(d)$ to the artificial sky luminance in a given point of the sky of a site produced by the sources beyond a given distance d from it is important to understand the behaviour of light pollution in diffusely urbanized areas and to estimate which fraction of the artificial luminance would be regulated by norms or laws limiting the light wasted upward within protection areas of given radii.

I studied the behaviour of $b_d(d)$ constructing a model for the propagation of the light pollution based on the modelling technique introduced by Garstang which allows to calculate the contribution to the artificial luminance in a given point of the sky of a site of given altitude above sea level, produced by a source of given emission and geographic position. I obtained $b_d(d)$ integrating the contribution to the artificial luminance from every source situated at a distance greater than d. I also presented an analitical expression for $b_d(d)$ depending mainly from one parameter, a core radius, well reproducing model's results. The artificial sky luminance $b_d(d)$ produced in a given point of the sky of a site from the sources situated at a distance greater than d from the site decrease in diffusely urbanized areas as $d^{-0.5}$ i.e. much slowler than the artificial luminance of a single source which decrease as $d^{-2.5}$. In this paper I present the results for $b_d(d)$ at some Italian Astronomical Observatories. In a diffusely urbanised territory the artificial sky luminance produced by sources located at large distances from the site is not negligible due at the additive character of light pollution and its propagation at large distances. Only when the core radius is small, e.g. for sites in the inner outskirts of a city, the sky luminance from sources beyond few kilometers is negligible. The radii of protection zones around Observatories needs to be large in order that prescriptions limiting upward light be really effective.

1. Introduction

Light pollution is a quantity characterized by additivity and propagation at large distances. Walker (1970, 1973) showed that the light coming from a big city can pollute the sky at a great distance from it. Garstang (1989b) calculated with numerical models the artificial sky luminance in some quite isolated Astronomical Observatories of worldwide interest showing the frequent presence of non negligible pollution coming from light propagating there from very far sources. Already Bertiau et al (1973) showed the dramatic impact of additive behaviour of artificial light scattered by atmospheric particles and molecules in determining the sky luminance and the related limiting magnitude loss.

The artificial sky luminance produced in a site from a single source, like a city, decreases rather rapidly with the distance from the source. In fact roughly $b \propto d^{-2.5}$

(Walker 1973; see also Garstang 1991a). This slope might wrongly suggest that in territories where there aren't big cities able to produce light pollution to great distances only the sources of light pollution situated in the neighbourhood of a site are responsible of the artificial luminance of its sky. This is not true in diffusely populated areas where there aren't big cities but a spread-out myriad of small cities because the artificial sky luminance produced from each source sums together. In this case the effects depend strictly on the sources distribution. When a territory is so diffusely populated that the distribution of sources can be considered a continuum, circular sections with constant thickness and increasing radius centered on the site contain an increasing number of sources so that the diminution of their effects on the sky at the site due to the increased average distance is somehow counterbalanced by the growth of the number of sources. So the global effects of all sources beyond a given distance decrease with this distance much slower than the effect of a single source. This is a fundamental phenomenon in areas, like as an example the Padana plain in Veneto (Italy), where the population is distributed in a myriad of cities and towns in such way to cover almost all the entire territory. This means that zones of territory even very far from the site can contribute remarkably to the luminance of its sky. This implies that laws for the protection of the sky of a site must be able to act on polluting sources at remarkable distances from the site, otherwise their efficacy would be scarce.

In this paper I demonstrate, both with simple analytical and detailed numerical modeling for light pollution propagation, that contributions to the zenith sky luminance from areas beyond a given distance decrease slowly in diffusely urbanized areas with increasing distance. I also present an analytic formula working for diffusely populated territories and results for some Italian Observatory sites. In section 2 the analytic formula for the sky luminance produced by sources beyond a circular area of given radius is presented and discussed. In section 3 the detailed modelling technique is illustrated. In section 4 the results are compared with those obtained with other laws. In section 5 results for some Italian Observatories are presented. The section 6 contains my conclusions.

2. Elementary theoretics

In order to understand the behaviour of light pollution in diffusely urbanized areas, let's calculate the zenith sky luminance at a site produced from the sources beyond a given distance d from it. Let's assume that in a territory the population is distributed homogeneously with a density of p inhabitants for unit of surface. This happens, as an example, in the Veneto's plain (Italy) where the population is distributed in a myriad of cities and towns so it covers almost all the territory. Let's also assume that a law of the type $b = p\ f(r)$ is valid there which gives the artificial luminance b at the zenith produced by a source city of given population p in function of the distance r from it and that this law can be applied to each area of territory of population p.

The area of an infinitesimal circular section of thickness dr at the distance r from the site and centered on it, is $2\pi r dr$ and its total population is $2\pi p_0 r dr$, where p_0 is the population for surface units in the considered territory. The sky luminance produced at the zenith of the site from this infinitesimal circular section is $2\pi p_0 r f(r) dr$. In order to compute the sky luminance b_d produced by all the sources outside the distance d we need to integrate the last expression between d and infinity :

$$b_d = 2\pi p_0 \int_d^{\infty} f(r) r dr \qquad (1)$$

Even without performing the computation of the integral, readers can see that on increasing the distance from the site b_d decreases slower than the function $f(d)$.

In order to compute the integral (1) we need a Law giving the sky luminance at the zenith. In order to became simple, we will assume $f(r) \propto r^{-\nu}$ which is an extension of Walker Law. The exponent ν depends on the aerosol content of the atmosphere through its optical thickness and on the zenith and azimuth angles of the direction of observation (Joseph et al. 1991; Garstang 1986). We assumed at zenith $\nu \approx 2.5$ which is valid in the range between 1 and 30 km for an optical thickness of ~ 0.25 (Joseph et al. 1991, fig. 5 - 6) giving a vertical extinction of $k_V \sim 0.3$ mag V. Garstang (1986, 1989) showed that a power law relation between the artificial sky luminance and the distance r of its source is not exact, the exponent ν of Walker Law becoming larger for increasing distance r. The effects of Earth curvature contribute to this tendency. Nevertheless, $\nu = const.$ *everywhere* is an adequate approximation for the purposes of this computation. Other propagation laws, like e.g. the Treanor Law (Treanor 1973), can be used in (1), as well more sophisticated computations like that I used in section 4.1, which will be described in section 3.

With $f(r) \propto r^{-2.5}$ the integral solved gives (Cinzano 1997):

$$b_d \propto p_0 \times d^{-0.5} \qquad (2)$$

This law expresses the contribution b_d to the total artificial luminance at the zenith in a site produced from all the territory situated outside a given distance d.

It can be improved taking in account two phenomena: (i) when the distance from a site is under a given value that we can call " Core radius " the uniformity of the distribution of the sources stops because the scale comes down to the level of the irregularities in the distribution itself. Therefore b_d deviates from the expression (2) and tends to become constant in the neighbourhood of the site where there aren't light sources. (ii) the curvature of the Earth diminishes in a non negligible way the contribution of the areas beyond about 80 km. In order to mimic approximately the behaviour produced by (i), I corrected the expression (2) inserting a "core". In order to mimic approximately the behaviour given by (ii), I inserted in the expression (2) a little correction factor $k(d)$ taking in account the diminution of contribution from distant sources. If the law is not applied beyond about 100 km from the site, in first approximation k can be considered a constant which subtracts the overestimated contribution from sources outside this distance. Taking into account both phenomena we can write:

$$b_d \propto p_0 \left((d_c^{\alpha} + d^{\alpha})^{-0.5/\alpha} - k \right) \qquad (3)$$

where d_c is the core radius, α is a parameter giving the shape of the curve in the core, where $d \leq d_c$. For $d >> d_c$ the slope of b_d is like expression (2) and for $d << d_c$ it becomes constant. The core radius d_c isn't the distance from the site of the nearest source but it is the scale distance under which the uniformity of population distribution vanishes.

Normalizing the formula (3) so that $b = 1$ for $d = 0$, we obtain:

$$b_d = \frac{\left((d_c^\alpha + d^\alpha)^{-0.5/\alpha} - k\right)}{d_c^{-0.5} - k} \approx \left(1 + \left(\frac{d}{d_c}\right)^\alpha\right)^{-0.5/\alpha} - kd_c^{0.5} \tag{4}$$

because $k << d_c^{-0.5}$. Some applications of this formula will be presented in section 4. The core radius is strictly depending on the distribution of sources around the site. The slope parameters and the k coefficient are less sensitive and typical values are respectively $\alpha = 3$ and $k = (120)^{-0.5}$.

3. Detailed modelling

In order to study with more detail the artificial sky luminance $b_d(d)$ produced in a given point of the sky of a site from the sources situated at a distance greater than d from the site, I applied a model for the propagation of the light pollution based on the modelling technique introduced by Garstang (1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999). The model allows to calculate the contribution to the artificial luminance in a given position on the sky of a site of given altitude above sea level, produced by a source of given emission and geographic position. I obtained $b_d(d)$ integrating the contribution to the artificial luminance of every source situated at a distance greater than d. Readers are referred to the papers cited above for a detailed description and discussion of the models. Here I will describe their outline.

For every infinitesimal volume of atmosphere along the line of sight, I calculated the illuminance produced directly by the source and that produced by the light scattered there from molecules and aerosols, estimated according to the method of Treanor (1973) extended by Garstang (1986, 1989). Then I computed the quantity of light scattered in direction of the observer by the molecules and the aerosols in the infinitesimal volume. Integrating along the line-of-sight, I obtained the artificial luminance of the sky. In photometrical bands different from the visual band, as the astronomical B band, the photon radiance can be obtained. If required, they can be transformed in brightnesses in $mag/arcsec^2$ with Garstang (1989) formulae.

As Garstang(1986, 1989a), I assumed that the distribution of the upward emission of light from a city is axisymmetric, i.e. it depends only on the angle θ with the vertical, and that it is expressed by a function $f(\theta)$ that will be discussed in section 4. I assumed that the lighting habits are similar in all the cities of the considered territory, and than the quantity of light wasted from the night-time external lighting system of a city is proportional to its population (e.g. Walker 1988). Falchi and Cinzano(1999) analyzing some night-time satellite images of Italy pointed out that the upward emission of italian cities might depend on a power of 0.8 of their population. Nevertheless in the range of population considered here the direct proportionality between the upflux and the population is a good approximation for the purposes of this paper. I assumed that differences from the mean were casually distributed in the territory. Considering economically homogenous zones, not larger than 120-150 km, I had not to insert in the calculation a coefficient of city development connected with the geographic position as Bertiau et al. (1973). The population data refers to the year 1995 and geographical positions and radii of cities refers to 1991. They were provided by the Istituto Nazionale di Statistica (ISTAT). I have considered as point sources the cities when the line of sight did not approach them closer than 12 times their radius and I have used in the other cases a seven points approximation (Abramowitz and Stegun 1964). I assumed that the density of molecules and aerosols decreases exponentially with the altitude. The angular scattering function of the atmospheric aerosols was given by Garstang (1991b) interpolating measurements from McClatchey et al. (1978).

The aim of the model is the computation of the artificial luminance in a site not far from very populated areas and not the computation of the small luminance produced by far sources in very good international observatory sites like e.g. Garstang (1989b), so I have neglected to take in account the Earth curvature. The inclusion of earth curvature causes luminance contributions from distant cities to fall off more rapidly with distance than for a flat Earth model (Garstang 1989a). The effects of the land curving on the luminance near the zenith are of the order of 2 percent for sources outside 50 km and can reach 35-40 percent at about 100km (Garstang 1989a). In the applications that have been made, a predominant fraction of luminance was produced within the first 60 km from the site and less than 5 percent outside about 90 km, so the choice to neglect curvature is adequate.

In the calculation I have not taken in account that mountains can shield part of the light of a source to the atmospheric particles situated along the line of sight of the observer at the site. Mountains between source and observatory shield the light emitted from the source with an angle less than $\theta = arctg\frac{H}{p}$ where H is the height of the mountain and p its distance from the source. The ratio between the luminance in the shielded and not shielded cases is given, in first approximation, by the ratio between the number of particles illuminated in the two cases:

$$\frac{b_s}{b_{ns}} \approx \frac{\left[\int_{Hq/p}^{\infty} N_a(h)dh\right] \sigma_a(\psi) + \left[\int_{Hq/p}^{\infty} N_m(h)dh\right] \sigma_m(\psi)}{\left[\int_0^{\infty} N_a(h)dh\right] \sigma_a(\psi) + \left[\int_0^{\infty} N_m(h)dh\right] \sigma_m(\psi)} \quad (5)$$

where q is the distance of the site from the source, $N_a(h)$, $N_m(h)$, $\sigma_a(\psi)$ and $\sigma_m(\psi)$ are respectively the number of particles of aerosol and molecules at the altitude h and their angular scattering sections and roughly $\psi \approx \pi - \theta$. This expression show that, taken in account the vertical size of the atmosphere in respect the height of mountains, shielding has a not negligible effect only when the source is quite near to the mountain and both are very far from the site: $\frac{q}{p} >> \frac{a}{H}$. This condition in the territories considered could apply for few sources only. I neglected the effects of the the Ozone layer and the volcanic powder studied by Garstang (1991). This kind of model has been already widely tested by Garstang (see ref. above). I successfully tested my set of models in Italy comparing the predicted sky luminance distribution in some italian sites with measurements. Results of tests were reported elsewhere (Cinzano 1999). In next section I will also compare the b_d obtained with the model for a test site and that obtained with the Treanor Law.

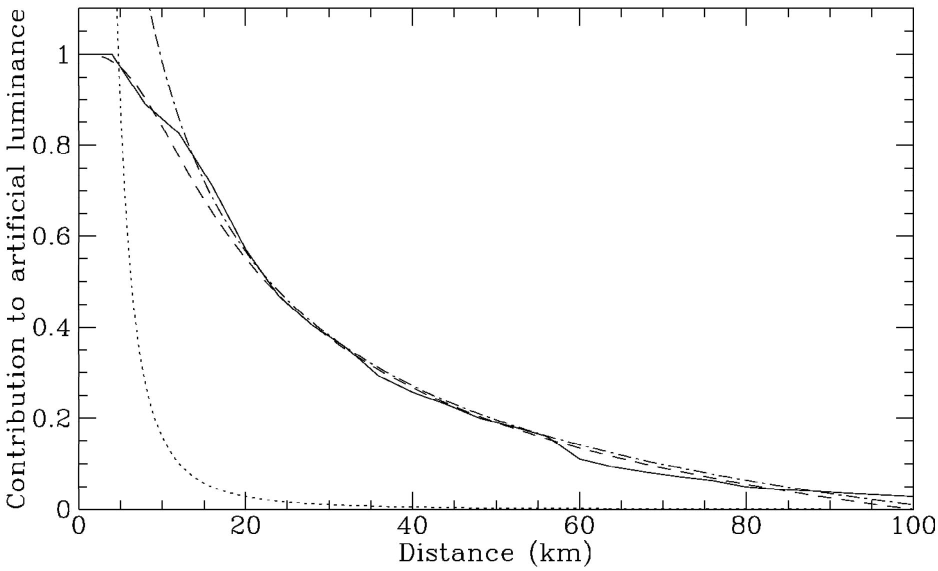

Fig. 1. Comparison between $b_d(d)$ curves. The solid curve is the model prediction and the dashed curve is the best fit of expression (4). The Walker Law ($b \propto d^{-2.5}$) (dotted curve) and the $b \propto d^{-0.5}$ Law (dot-dashed curve) were also plotted.

4. Comparison tests.

I compared the expression (4) with the normalized $b_d(d)$ curve obtained for the Astronomical Observatory of Ekar with the models described above (see sec. 4.1). The surrounding territory of the Veneto plain is in fact studded with many cities and small towns in nearly continuous way. The results are presented in figure 1. The solid curve is the model prediction and the dashed curve is the best fit of expression (4). The Walker Law ($b \propto d^{-2.5}$) (dotted curve) and the $b \propto d^{-0.5}$ Law (dot-dashed curve) were also plotted. I obtained a good agreement for $\alpha = 3$, $d_c = 10$ km and k=0.06. This value of the Core radius corresponds roughly to the distance of the Observatory from the surrounding plain. The choice of the parameter α does not influence strongly the results because its effect is non negligible only for $d \leq d_c$ and the contribution of the zones inside this distance is rather small compared with contributions coming from greater distances.

I also compared the normalized $b_d(d)$ curve predicted for Mount Ekar Astronomical Observatory with the curve obtained calculating the contribution one by one of all the sources of the surrounding territory with the Treanor law (1973):

$$b = b_0 I_0 \left(\frac{A}{X} + \frac{B}{X^2} \right) \ e^{-kX} \qquad (6)$$

where A,B,k, I_0, b_0 are constant and X is the distance of the site from the source.

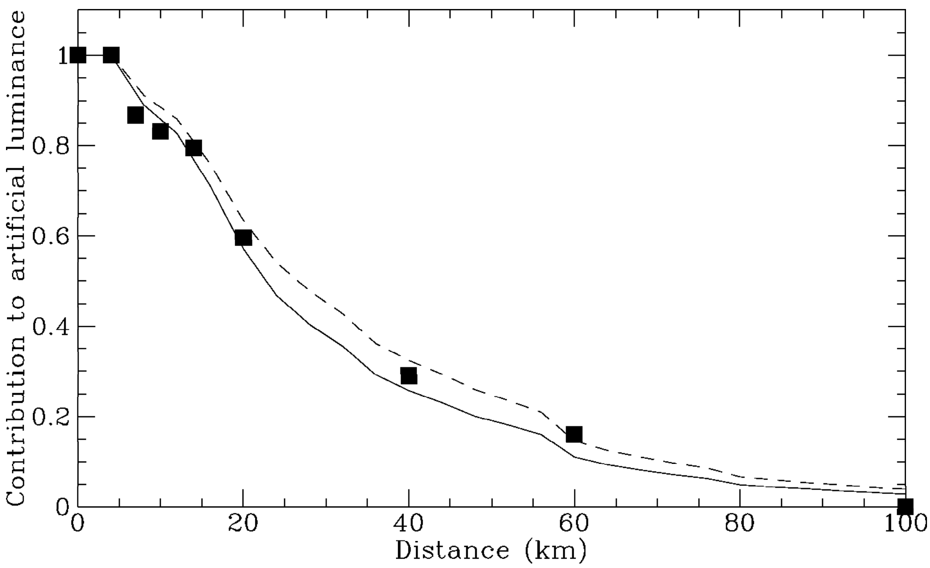

Fig. 2. Prediction of $b_d(d)$ obtained for Mount Ekar Astronomical Observatory in B band (solid curve) and in V band(dashed curve) with the model and in B band with the Treanor Law (squares).

The Treanor law refers to a simple model with homogenous atmosphere, the heights of scattering particles are small respect the distance between the site and the source, and the scattering is assumed to be limited to a cone of small angle around the direction of the incident light. These hypotheses are justified in first approximation from the limited scale height of atmospheric particles and from the characteristics of forward scattering of the aerosols. The model neglects the scattering of higher order than the second. The Treanor law, even if based on a simple model, fitted well the measurements carried out by Bertiau et al (1973) in Italy. The term $1/X^2$ give the contribution to the illuminance of the atmospheric particles along the vertical column at the site produced by light coming directly from the source, the term $1/X$ gives the contribution of the light scattered once, the term e^{-kX} takes into account the extinction of the light along its way. In applying this law I considered still valid the calibration of the ratio B/A and the coefficient k from Bertiau et al (1973) in B band because these depend only on the mean conditions of the atmosphere in clear nights which I supposed unchanged from 1973, neglecting the seasonal variations and the effects of the changes in atmospheric pollution. The effect of the altitude H of the observatory is to cut all the light that in a site on the sea level would come from particles situated along the vertical at a lower height than the altitude H of the site. In a rough approximation, the luminance is overestimated for a fraction given by the ratio between the number of scattering in the vertical column over the site

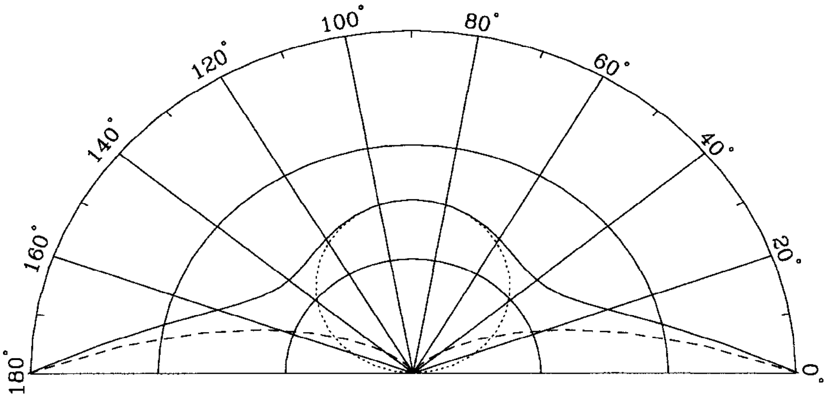

Fig. 3. Mean upward emission function of cities from Garstang (1986) with G=0.15, F=0.15.

in the case of altitude H and in the case of altitude zero.

$$\frac{b_H}{b_0} \approx \frac{n_h}{n_0} = \frac{\left[\int_H^\infty N_a(h)dh\right]\sigma_a(90^\circ) + \left[\int_H^\infty N_m(h)dh\right]\sigma_m(90^\circ)}{\left[\int_0^\infty N_a(h)dh\right]\sigma_a(90^\circ) + \left[\int_0^\infty N_m(h)dh\right]\sigma_m(90^\circ)} \tag{7}$$

where $N_a(h)$, $N_m(h)$, $\sigma_a(\psi)$ and $\sigma_m(\psi)$ are respectively the number of particles of aerosol and molecules at the altitude h and their angular scattering cross sections. With the expressions and the parameters in Garstang (1986) I estimate that the effect of the altitude diminishes the values of approximately 20% for the observatory. However, all the contributions are affected in the same way from the minor number of atmospheric particles, so that, in first approximation, relative contributions do not need any correction.

Figure 2 shows the results of the computations of $b_d(d)$ with Treanor Law (squares) and the model predictions in B band (solid curve) and in V band (dashed curve). Differences between the curves in V and B bands are likely to be of the same order as differences produced by fluctuations in atmospheric conditions. Measurements of Walker (1977, table II, col (2))in V and B bands at Salinas are almost indistinguishable from 10 km to 30km. The Treanor Law (valid for B band) and the Walker Law (obtained for V band) were found in fairly good agreement (Walker 1977). The differences on the propagation of light pollution in B band and in V band are shown in Cinzano & Stagni (1999).

The average upward emission function of cities $I(\theta)$ was never studied so far in Italy or elsewhere. Garstang in all his papers cited here used successfully a semi-empirical function:

$$I(\theta) = q\frac{1000}{2\pi}\left[2G(1-F)\cos\left(\frac{\pi}{2}-\theta\right) + 0.554F\left(\frac{\pi}{2}-\theta\right)^4\right] \tag{8}$$

where q is a calibration constant unimportant in the normalized computation of this paper and $I(\theta)$ is in lm/sr. This function was implicitly tested by Garstang with many

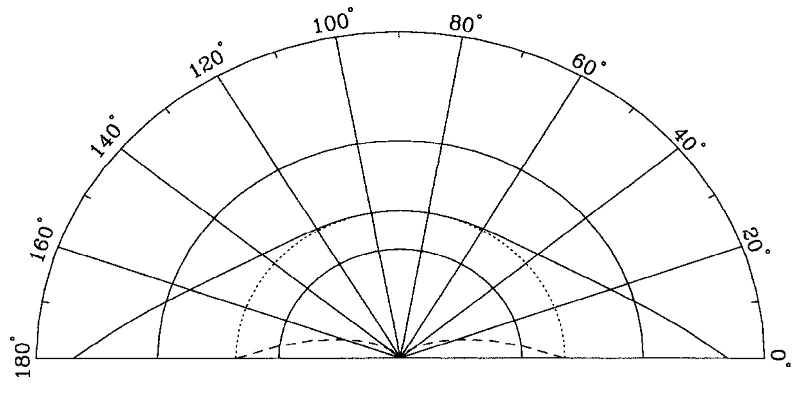

Fig. 4. Mean upward emission function of cities: alternative form in eq. 9.

comparison between model predictions and measurements. I compared the $b_d(d)$ curve obtained with three different average upward emission functions $I(\theta)$. The first, shown in figure 3, was the previous eq. 8, with G=0.15 and F=0.15. Note that G and F must be considered here only shape parameters without the meaning given by Garstang (1986) of, respectively, direct and reflected light ratios because emission at low angles above the horizon can come both from direct emission by luminaires and from reflection by lighted surfaces (horizontal and vertical) and emission near the zenith can come both from reflexion by surfaces and from direct emission by unshielded luminaires. The second function, shown in figure 4, was the sum of a constant intensity and a power law:

$$I(\theta) = q\frac{1000}{2\pi}\left[G(1-F) + 0.554F\left(\frac{\pi}{2}-\theta\right)^4\right] \tag{9}$$

with G=0.3 and F=0.075. This function assumes an higher emission at intermediate angles in respect to the function 8. As third function I used a constant intensity $I(\theta) = const.$ In figure 5 I plotted the $b_d(d)$ curve obtained with the function (8) (solid curve), the function (9) (dotted curve), and the constant intensity (dashed curve). Differences in $b_d(d)$ shape are little even for the case of constant intensity.

The propagation of light pollution depends on atmospheric clarity, i.e. on the aerosol content of the atmosphere, which in the models is expressed by a clarity parameter K (Garstang 1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999). In computing $b_d(d)$ curve I assumed *typical clean air at sea level*, i.e. K=1 as defined by Garstang (1986). A clarity K=0.5 would correspond to very clean air. So results in this paper refers to clean atmosphere not to mean atmospheric conditions at the studied sites, which are difficult to define. In figure 6 I compared the $b_d(d)$ curve obtained for Mount Ekar Observatory for K=1 (solid curve), K=0.5 (dotted curve) and K=2 (dashed curve). An increase in aerosol content produces a steeper decrease of $b_d(d)$ for increasing d. This is due at the increase of scattering which produces a stronger extinction. This

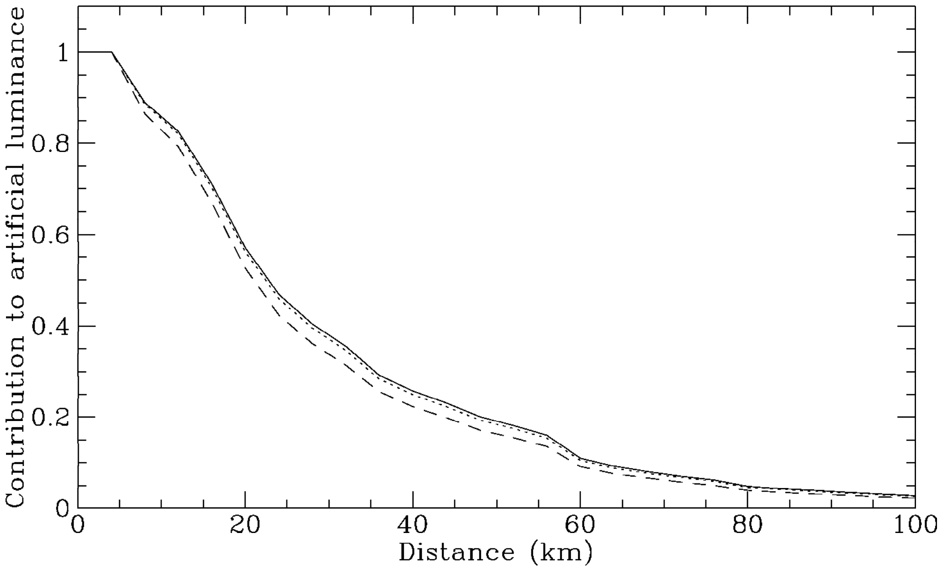

Fig. 5. $b_d(d)$ curve obtained with the function (8) (solid curve), the function (9) (dotted curve), and a constant intensity (dashed curve).

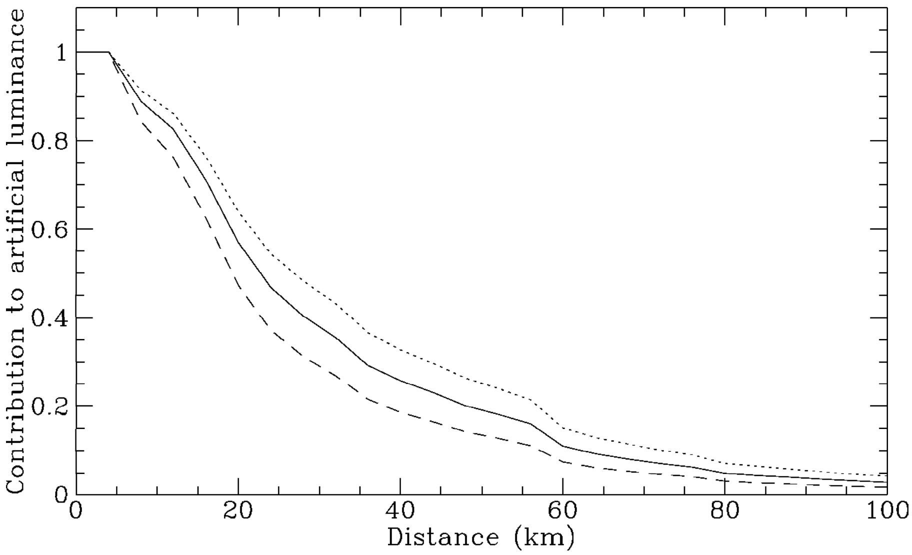

Fig. 6. $b_d(d)$ curve obtained for Mount Ekar Observatory for K=1 (solid curve), K=0.5 (dotted curve) and K=2 (dashed curve).

was already shown by Garstang (1986) for the city of Denver, where on increasing K the artificial luminance contribution decreases outside the city while increases inside the city. A comparison between curves of figure 6 and figure 2 shows that the model for K=2 does not agree with the curve obtained with the Treanor Law as calibrated with measurement in Italy (Bertiau et al. 1973). So atmospheric conditions at which Treanor Law was calibrated seems to correspond to an aerosol content $K \sim 1$. In table 2 I will show for each Observatory the vertical extinction in V and B band predicted by the model (Garstang 1991) for K=1 and K=2. The horizontal daylight visibility, defined as the distance at which black object would show a luminance (due to scattered light between the observer and the object) of 0.98 of the luminance of horizon behind the object, computed as Garstang (1991), is $\Delta x = 48$ km for $K = 0.5$, $\Delta x = 26$ km for $K = 1$ and $\Delta x = 14$ km for $K = 2$ at sea level.

4.1. Results

I computed $b_d(d)$ with the detailed modelling described in section 3 for the Italian Observatories listed in table 1. Table 1 shows for each Observatory the adopted geographical position and altitude above the sea level.

Tab. 1 - Adopted geographic positions of Observatories

Observatory	Longitude ° ′ ″	Latitude ° ′ ″	Height m.s.l.
Mount Ekar Obs. (Asiago)	11 34 18	45 50 36	1350
Bologna Univ. Obs. (Loiano)	11 20 0	44 15 23	714
Brera-Milan Ast. Obs. (Merate)	9 25 42	45 41 58	330
Catania Obs. Stellar Sta. (Serra La Nave)	14 58 24	37 41 30	1735
Collurania Ast. Obs. (Teramo)	13 44 0	42 39 30	388
Chaonis Obs. (Chions)	12 42 42	45 50 36	15
"G. Ruggieri" Obs. (Padova)	11 53 20	45 25 10	20
S. Benedetto Po Ast. Obs. (S.Benedetto Po)	10 55 10	45 3 4	1.

As already discussed, results were obtained for conditions of clean atmosphere (i.e. assuming for the Garstang (1989) clarity parameter $K = 1$). Table 2 shows for each Observatory the vertical extinction in V and B band predicted by the model (Garstang 1991)for K=1 and K=2.

The $b_d(d)$ curves in figures are normalized to the total artificial sky luminance at the zenith of the site. They are computed for light in the photometric band of eye sensitivity and they can be considered also valid for light in the astronomical V band. The curves are computed every 4 km and linearly interpolated in the plots. A better space resolution would be sometime confusing because the city position data do not give the exact position of light baricenter but only the position of a geographic reference point in the center of the city.

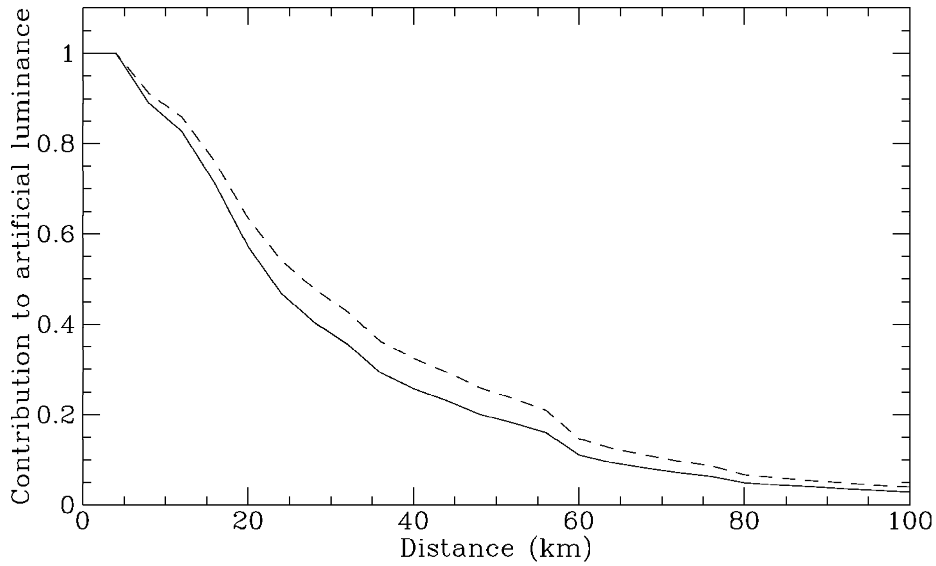

Fig. 7. $b_d(d)$ curve for Mount Ekar Observatory.

Tab. 2 - Vertical extinction predicted by the models

Observatory	K=1		K=2	
	k_V	k_B	k_V	k_B
Mount Ekar Obs. (Asiago)	0.19	0.36	0.24	0.43
Bologna Univ. Obs. (Loiano)	0.24	0.43	0.34	0.56
Brera-Milan Ast. Obs. (Merate)	0.28	0.50	0.42	0.66
Catania Obs. Stellar Sta. (Serra La Nave)	0.16	0.32	0.20	0.38
Collurania Ast. Obs. (Teramo)	0.28	0.48	0.40	0.64
Chaonis Obs. (Chions)	0.33	0.56	0.50	0.78
"G. Ruggieri" Obs. (Padova)	0.33	0.56	0.50	0.78
S. Benedetto Po Ast. Obs. (S.Benedetto Po)	0.33	0.56	0.51	0.78

Figure 7 shows the $b_d(d)$ curve for the Mount Ekar Observatory. The artificial sky luminance at the zenith of this Observatory in clear nights is produced mainly by the light dispersed from sources situated in the Veneto plain. Approximately 50% of the artificial sky luminance at Ekar is produced within 30 km from the observatory and 75% within 50 km. As already shown in figure 1 the shape of $b_d(d)$ is exactly that expected for a uniformly populated territory, except for a core in the inner 10 km produced by the lower population density in the mountain. The figure 8 shows the derivative $\frac{\partial b}{\partial d}$. Main peaks correspond to the main sources like Asiago (at $\sim 5km$), Bassano, Thiene and Schio (from 10 to $20km$), Vicenza (at $\sim 35km$), Treviso (at $\sim 56km$), Padova (at $\sim 60km$). The continuum is produced by the other cities. I counted 1350 cities inside

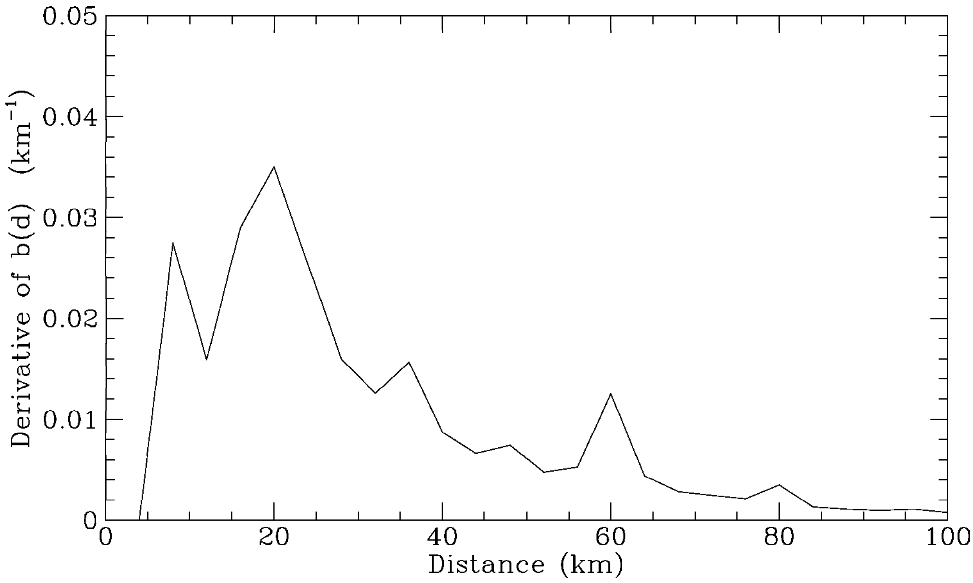

Fig. 8. The derivative $\frac{\partial b}{\partial d}$ of the $b_d(d)$ curve for Mount Ekar Observatory.

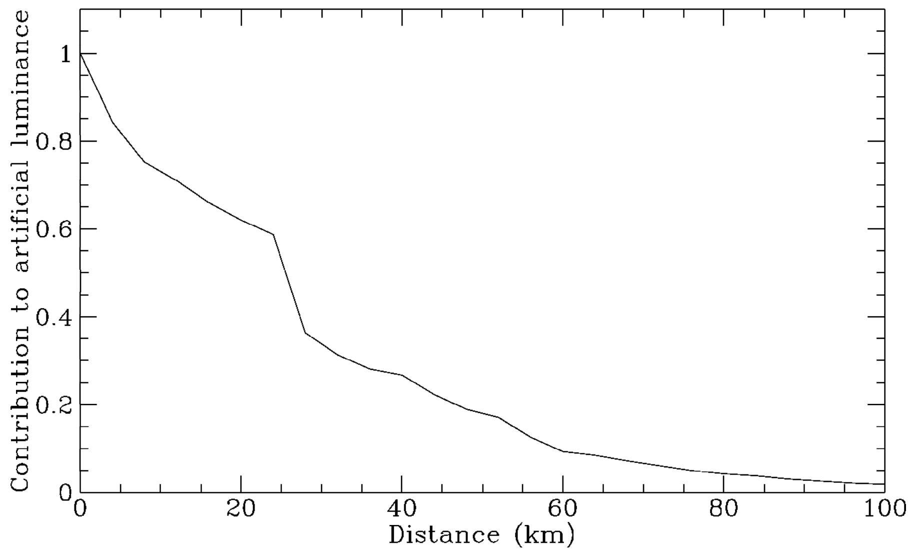

Fig. 9. $b_d(d)$ curve for Bologna University Observatory at Loiano.

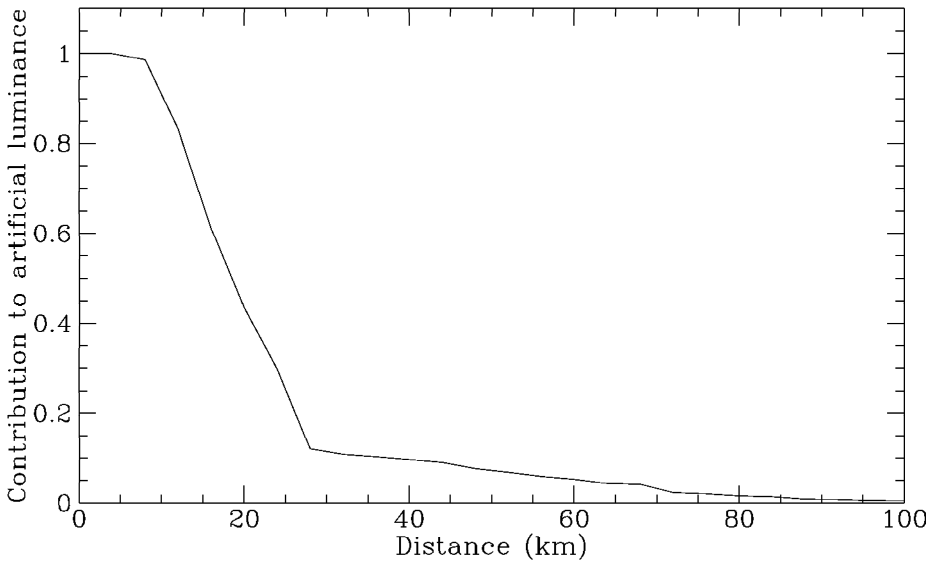

Fig. 10. $b_d(d)$ curve for Catania Observatory Stellar Station at Serra La Nave.

100km from the site.

Figure 9 shows the $b_d(d)$ curve for Bologna University Observatory at Loiano. Readers can note the absence of the core due to the presence of the Loiano town near the Observatory and the strong bump at about 25 km produced by the big city of Bologna. Approximately 50% of the artificial sky luminance at Loiano Observatory in clean nights is produced within 30 km from the observatory and 75% within 50 km.

It is interesting to compare the $b_d(d)$ curve of Catania Observatory Stellar Station at Serra La Nave in figure 10, Brera-Milano Astronomical Observatory at Merate in figure 11 and Collurania Observatory at Teramo in figure 13. Catania Observatory shows a large core due to the inhabitated Etna mountain and a rapid decrease between $\sim 10km$ to $\sim 25km$ produced by the fact that the city of Catania and its neighbour towns are the main contributors to the sky luminance at the site. Approximately 50% of the artificial sky luminance at Serra is produced within 30 km from the observatory and 75% within 50 km. The contribution from higher distances is little due to the presence of the sea and to the absence of many other cities. Inside a radius of 120 km there are only 362 cities. Brera-Milan Astronomical Observatory at Merate, on the contrary, do not show a core but a high peak because the observatory is almost surrounded from the city of Merate. The big number of cities in the land (2171 cities inside a circle of 120 km of radius around the site) produces the well prominent wing outside $\sim 5km$. The diffuse population distribution produces a $b_d(d)$ curve well fitted by the extended $d^{-0.5}$ law (eq. 4) as shown in figure 12 ($\alpha = 1.5$, $d_c = 2.5$ km and k=0.12). The discontinuity at about 30 km in figure 11 is produced from the contribution of the city of Milano. A similar

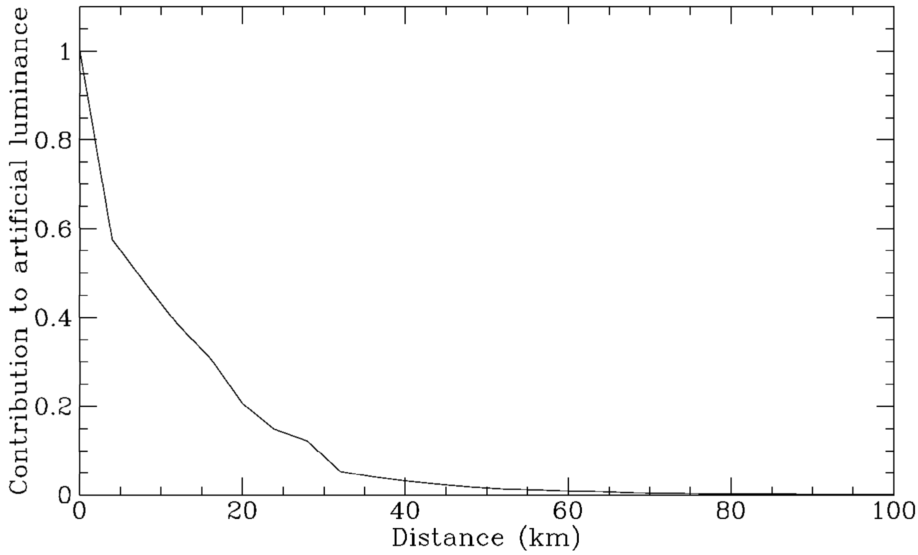

Fig. 11. $b_d(d)$ curve for Brera-Milan Astronomical Observatory in Merate.

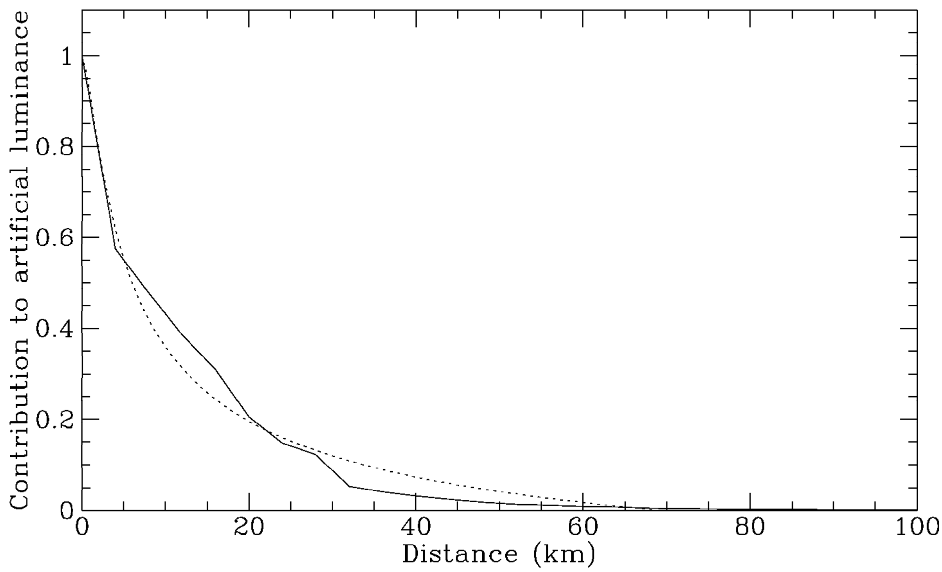

Fig. 12. The $b_d(d)$ curve for Brera-Milan Astronomical Observatory in Merate is well fitted by the $d^{-0.5}$ law.

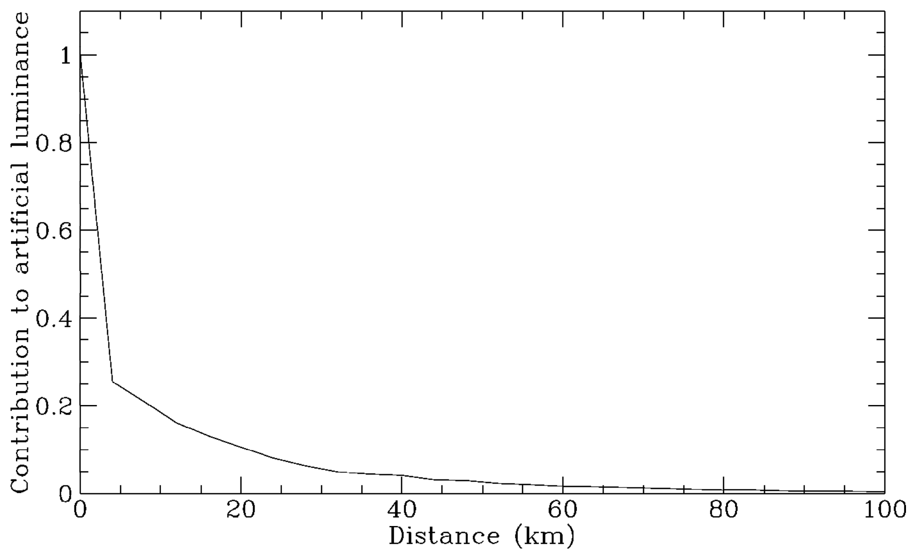

Fig. 13. $b_d(d)$ curve for Collurania Observatory at Teramo.

behaviour of $b_d(d)$ curve appear for the Collurania Observatory at Teramo where the contribution from the near city appears to overhang the contribution of the surrounding territory.

I also computed the $b_d(d)$ curve for three amateur observatories. Chaonis Observatory in figure 14 shows a core of 5 km and a wing produced by the sources in the country, while the San Benedetto Po Observatory in figure 15 shows a wing but the core is replaced by a peak probably produced by the town in the nearby of the observatory. The bump at $\sim 16km$ is produced by the city of Mantova. A little bump at $\sim 40km$ is likely to be produced by the sum of the cities of Modena, Reggio Emilia and Verona.

The *G. Ruggieri* Observatory in figure 16 is inside the city of Padova. The curve $b_d(d)$ shows the overhelming contribution coming inside the first 4 km. It is interesting to note that the wing produced by the other cities of the Veneto plain is quite well fitted by the $d^{-0.5}$ law ($\alpha = 0$, $d_c = 0.4$ km and k=0.045) as shown in figure 17.

5. Conclusions

The knowledge of the artificial sky luminance $b_d(d)$ produced in a given point of the sky of a site from the sources situated at a distance greater than d from the site is important in order to understand the behaviour of light pollution in diffusely urbanized areas and it is useful in order to estimate which fraction of the artificial luminance would be regulated by norms or laws limiting the light wasted upward within protection areas of given radii.

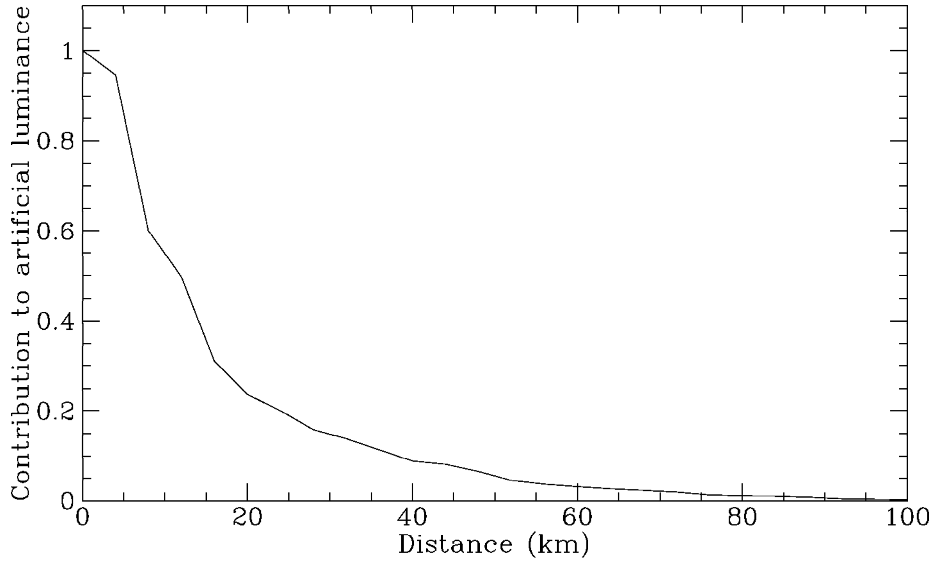

Fig. 14. $b_d(d)$ curve for Chaonis Observatory.

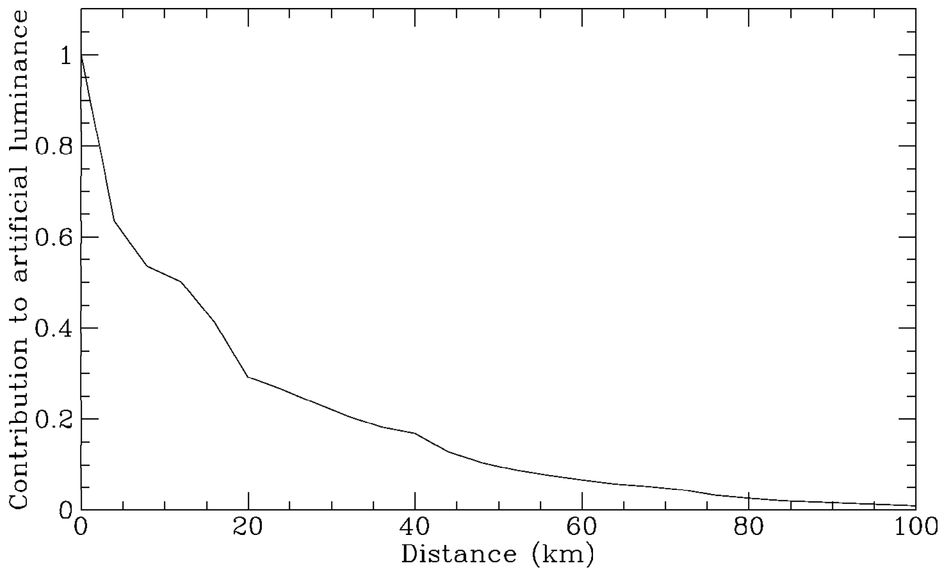

Fig. 15. $b_d(d)$ curve for San Benedetto Po Observatory.

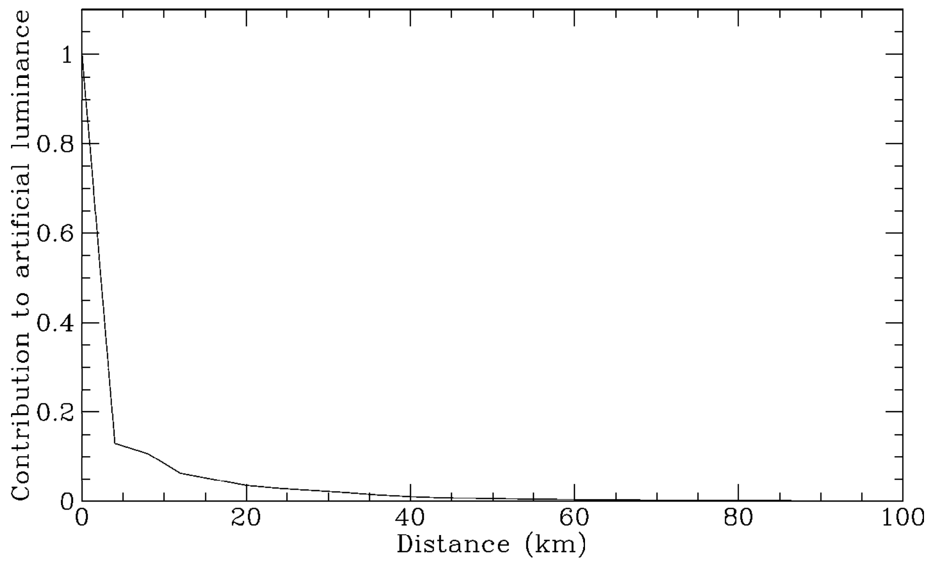

Fig. 16. $b_d(d)$ curve inside the city of Padova.

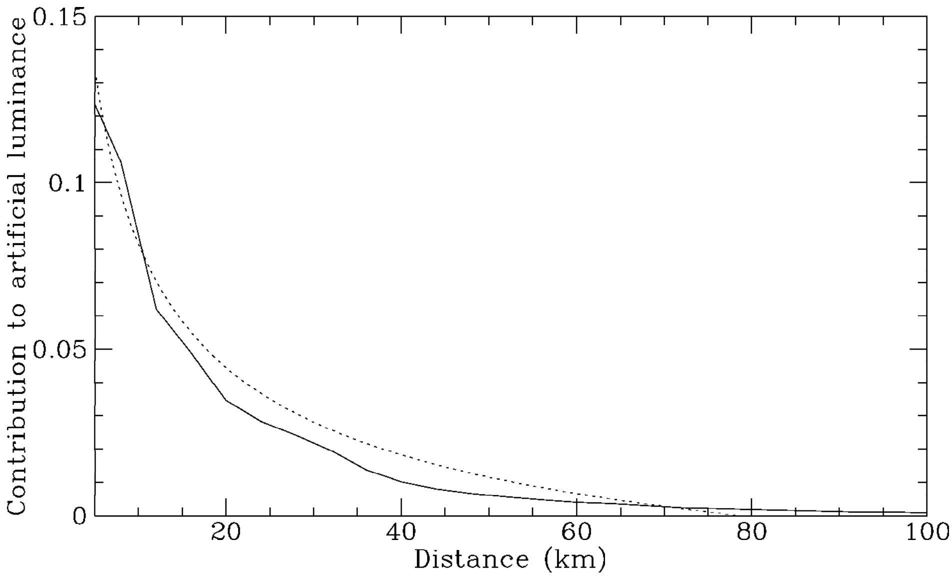

Fig. 17. The outer wing of $b_d(d)$ curve for "G. Ruggieri" Observatory produced by the other cities of the Veneto plain is well fitted by the $d^{-0.5}$ law.

I studied the behaviour of $b_d(d)$ applying a model for the propagation of the light pollution based on the modelling technique introduced by Garstang (1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999) which allows us to calculate the artificial luminance in a given position on the sky of a site of given altitude on the sea level, produced by a source of given emission and geographic position. I obtained $b_d(d)$ integrating the contribution to the artificial luminance of all the sources situated at a distance greater than d.

Main results are:

1. Artificial sky luminance in a site in a diffusely urbanised territory produced by sources located at large distances from the site is not negligible due at the addittive character of light pollution and its propagation at large distances.
2. The contribution $b_d(d)$ to the artificial sky luminance produced in given point of the sky of a site by the sources situated at a distance greater than a given distance d from the site decrease as $d^{-0.5}$ i.e. much slower than the contribution of a single source which goes as $d^{-2.5}$.
3. With inclusion of a core, the expression (4) well express the behaviour of $b_d(d)$ from 0 km to about 100 km.
4. The radii of protection zones around Observatories needs to be large in order that prescriptions limiting upward light be really effective.
5. Only when the core radius is small, e.g. for Observatories located near a city, the sky luminance contribution from sources inside a small protection zone tends to be predominant.

In the Web Site *Light Pollution in Italy*, actually at the address www.pd.astro.it/cinzano/ is presented a simple didactic Java Applet called LPCALC which allows to calculate $b_d(d)$ from the geographic position of a site. It works only for sites in Italy.

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References

Abramowitz M., Stegun I.A. 1964, Handbook of Mathematical Functions, Washington, NBS.

Berry, R. 1976, J. Royal Astron. Soc. Canada, 70, 97-115.

Bertiau, F.C.S.J., de Graeve, E.S.J. & Treanor, P.J.S.J. 1973, Vatican Observatory Publ., 1, 4, 159-179.

Cinzano, P. 1997, Inquinamento luminoso e protezione del cielo notturno (in italian) (Venezia: Istituto Veneto di Scienze, Lettere ed Arti), 224 pp.

Falchi, F. & Cinzano, P. 1999, in this volume.

Cinzano, P. 1999, in this volume.

Cinzano, P. & Stagni, R. 1999, in this volume.

Garstang, R.H. 1984, The Observatory, 104, 196-197.

Garstang, R.H. 1986, Publ. Astron. Soc. Pacific, 98, 364-375.

Garstang, R.H. 1987, in Identification, optimization and protection of optical observatory sites, eds. R.L. Millis, O.G. Franz, H.D. Ables & C.C. Dahn (Flagstaff: Lowell Observatory), p. 199-202.

Garstang, R.H. 1988, The Observatory, 108, 159-161.

Garstang, R.H. 1989a, Publ. Astron. Soc. Pacific, 101, 306-329.

Garstang, R.H. 1989b, Ann. Rev. Astron. Astrophys., 27, 19-40.

Garstang, R.H. 1989c, Bull. of American Astron. Soc., 21, 2, 759-760.

Garstang, R.H. 1991a, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conf. Series 17, p. 56-69.

Garstang, R.H. 1991b, Publ. Astron. Soc. Pacific, 103, 1109-1116.

Garstang, R.H. 1991c, The Observatory, 111, 239-243.

Garstang, R.H. 1992, Bull. of American Astron. Soc., 24, 740.

Garstang, R.H. 1993, Bull. of American Astron. Soc., 25, 1306.

Garstang, R.H. 1999, in this volume.

McClatchey, R.A., Fenn, R.W., Selby, J.E.A., Volz, F.E., Garing, J.S. 1978, Handbook of Optics, ed. W.G. Driscoll and W. Vaughan, McGraw-Hill, New York.

Pike, R. 1976, J. Royal Astron. Soc. Canada, 70, 116-126.

Treanor, P.J.S.J. 1973, The Observatory, 93, 117-120.

Walker, M.F. 1970, The California Site Survey, Publ. Astron. Soc. Pacific, 82, 672-698.

Walker, M.F. 1973, Light pollution in California and Arizona ,Publ. Astron. Soc. Pacific, 85, 508-519.

Walker, M.F. 1977, PASP, 89, 405-409.

Walker, M.F. 1988, Publ. Astron. Soc. Pacific, 100, 496.

Yocke, M.A., Hogo, H. & Henderson, D. 1986, Publ. Astron. Soc. Pacific, 98, 889-893.

DISENTANGLING ARTIFICIAL SKY BRIGHTNESS FROM SINGLE SOURCES IN DIFFUSELY URBANIZED AREAS

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ABSTRACT. The impact of single sources on the sky brightness of a site can be evaluated by computing the artificial sky brightness distribution which they produce with detailed models for light pollution propagation. The upward emission function of sources can be constrained with the condition that the sum of all contributions, including the natural sky brightness, fits the observed sky brightness in one or more sites of the country. Here I present some applications in Italy of Garstang models. Due to the fast growth with time of total upward flux of cities in Italy, the calibration of models resulted in a function of time.

1. Introduction

Light Pollution is characterized by additivity and propagation at large distances. In diffusely populated countries the artificial sky brightness in a site is the sum of the contributions of a large number of sources (e.g. cities) and the contribution of each source is mostly indistiguishable. This missing information is important in order to understand what are the sources producing the stronger impact on the site's sky and to undertake appropriate actions in order to limit their pollution.

Experimental observations cannot give help. An exam of the sky brightness distribution could sometimes be misleading. When in the country there are many well spread-out sources, their contributions add and smooth together so that apparent gradients of the sky brightness are noticeable only for nearby sources and at low altitude in the sky. Nevertheless the absolute value of the artificial sky brightness near the zenith could be mainly produced by many far sources. Spectroscopical measurements, on the other hand, could disentangle single sources only if their lighting park is very different from that of other sources.

A way to evaluate the impact of single sources on the sky brightness of a site is to compute their contribution to the artificial sky brightness distribution with a propagation model for light pollution applied to the sources on the basis of their known geographical positions and altitudes. Free functions and parameters can be constrained with the condition that the sum of all the contributions, including the natural sky brightness, fits the observed sky brightness distribution in the site or in several sites. With this aim, I constructed models for the propagation of light pollution based on the modelling technique introduced and developed by Garstang (1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999). With them, it is possible to evaluate the sky brightness distribution on the sky of a site of given altitude above sea level produced by a set of sources of given geographic positions, altitude and upward emission. In each point of the sky, it is possible to predict both the value of sky brightness and its gradient, and analyze the distribution of the artificial sky brightness contribution produced by each source.

The outline of the modelling technique is presented and discussed in section 2. In section 3 a preliminary calibration is discussed and the average upward flux by italian cities is estimated. The results for sky brightness distribution in some italian sites are presented, discussed and compared with available observations in section 4. Contributions from some single sources are also presented. Section 5 draws the conclusions.

2. Description of the modelling technique

The models are based on the modelling technique introduced and developed by Garstang (1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999). Here I will only illustrate the main steps. The reader is referred to the cited papers for a discussion of the details (see also Cinzano 1999a). Given that the aim of this work is to model the sky brightness in a site not far from areas strongly urbanized and not in an isolated astronomical site as Garstang (1991b), I neglected the curvature of the Earth. In the applications of this paper a big fraction of artificial sky brightness is produced inside the first 50 km from the site (see Cinzano 1999a) where the effects of the curvature of the Earth, increasing with distance, reach 2 percent (Garstang 1989). The computation of the sky brightness is done in a grid of 19×74 points equispaced in zenith distance and in azimuth. For each infinitesimal volume of atmosphere along the line-of-sight, the direct illuminance produced by each source and the illuminance due at light scattered once from molecules and aerosols are computed, this last estimed with the approach of Treanor (1973) as extended by Garstang (1984, 1986). The total flux that molecules and aerosols in the infinitesimal volume scatter toward the observer is computed from the illuminance, and, with an integration, the artificial sky brightness of the sky in that direction is obtained. Extinction along light paths are included. The model assumes Rayleigh scattering by molecules and Mie scattering by aerosols.

The same atmospheric model as Garstang (1996, 1991) was assumed, with the density of molecules and aerosols decreasing exponentially with the height. The angular scattering function of aerosols was studied by many authors measuring daily skylight scattering (e.g. Volz 1987) or searchlight beam brightness (e.g. Hulburt 1941). The average scattering function of aerosols adopted is the representation of Garstang (1991) of the function measured by McClatchey et al. (1978).

The sources of upward light are cities and towns in the country. Their geographical positions and altitudes at 1991 were obtained from Istituto Italiano di Statistica (ISTAT). In order to became simple, I assumed that the lighting habits are similar in all the cities of the considered territory. This is likely because I considered areas of not more than 120 km around each site. I considered as point sources the cities when the line of sight did not approach them more than 12 times their radius and I used in the other cases a seven points approximation (Abramowitz and Stegun 1964). I neglected the presence of mountains which might shield the light emitted from the sources to a fraction of the atmospheric particles along the line-of-sight of the observer. Given the vertical extent of the atmosphere in respect to the highness of the mountains, the shielding is not negligible only when the source is very near the mountain and both are quite far from the site (Garstang 1989, see also Cinzano 1999a). I neglected the effects of the Ozone layer and the presence of volcanic dust studied by Garstang (1991b, 1991c) (see also sec. 3).

The computation of the natural sky brightness in each direction follow the Garstang (1986) approach. It assumes that the light coming from the higher atmosphere has a distribution based on the analysis of Roach and Meinel (1955) and reaches the observer either directly or by scattering from atmospheric aerosols and by Rayleigh scattering from atmospheric molecules. The computation is done for conditions of minimum solar activity in order to neglect the effects of solar activity on the airglow natural emission (Walker 1988).

Sky brightness expressed in magnitudes is obtained from sky luminance expressed in cd/m^2 or from photon radiance in $ph\ cm^{-2}s^{-1}sr^{-1}$ with formulae in Garstang (1986, 1989a).

Free parameters and functions of the models are:

1. The aerosol content of the atmosphere.
2. The normalized average city emission function giving the relative intensity in each direction of the total upward light emission of cities both coming directly from its lighting fixtures and from reflections from lighted surfaces.
3. The total upward flux emitted by each city.

Other parameters as the scale radius of vertical distribution of aerosols and molecules, their scattering sections,the altitude of the van Rhijn layer for airglow emission and the natural sky brightness in the higher atmosphere, are likely not much variable. To account for presence of sporadic denser aerosol layers at various heights or at ground level as Garstang (1991b) is beyond the scope of this paper.

2.1. Aerosol content of the atmosphere

The propagation of light pollution depends on aerosol content. The atmospheric content of aerosols is variable in dependence of atmospheric conditions and it is expressed in models by the atmospheric clarity K, a parameter introduced by Garstang (1986) which is essentially a measure of the aerosol-to-molecule ratio at ground level. Atmospheric clarity in fact is not a free parameter because it is related to the vertical extinction (Garstang 1988, eq.1) at the site and to the horizontal daylight visibility (Garstang 1991, eq.7). These quantities can constrain the atmospheric clarity in a specific night. Nevertheless, in this paper computations were done for standard clear atmosphere (K=1 in Garstang 1996) in order to obtain standard results without the necessity to determine what are the mean atmospheric conditions for each site. An increase of aerosol content usually produces a decrease of sky brightness in sites outside the cities boundaries due to the increase of extinction along light paths. On the contrary, it produces an increase

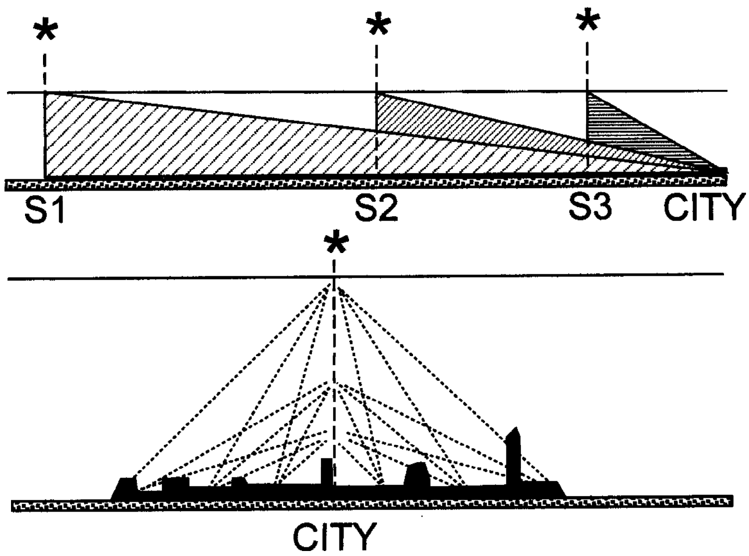

Fig. 1. Range of elevation angles involved in illumination of particles along the line-of-sight of an observer looking at the zenith and (above) far from the source more than scale height of atmosphere, or (below) inside a source.

of sky brightness inside city boundaries due to the increased scattering (e.g. Garstang 1986, fig.3, for Denver).

2.2. Normalized average city emission function

The normalized average emission function of cities is the sum of the direct emission from fixtures and the reflected emission from lighted surfaces, normalized to its integral and is not well known. In future it will be possible to obtain it directly by integrating upward emission from all lighting fixtures and all lighted surfaces on the basis of lighting engineering measurements and models as soon as they will be available. Actually, this function can be constrained comparing predictions of models and measurements. A comparison with measurements at different distances from an isolated city would be useful because for geometrical reasons light emitted at lower angles above the horizon propagates far contributing to the artificial brightness at far sites and light emitted at higher angles above the horizon contributes mainly to sky brightness at lower distances, wherever the emission near the zenith contributes only to the sky brightness near the city center as shown in figure 1.

In Italy, where isolated cities are rare, a first constraint is that the predictions of the zenith artificial brightness as a function of distance cannot be too much different from the Treanor Law which was tested in Italy by Bertiau et al. (1973). The presence of many cities at different distances around a site (e.g. more than 2000 inside 120

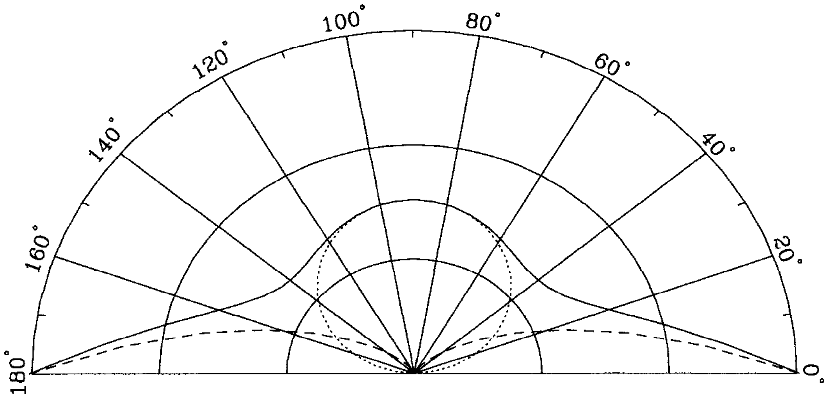

Fig. 2. Normalized average city emission function from Garstang (1986).

km from Brera-Milan Observatory in Merate) (a) smooths very much the shape of the normalized average emission function so that it can be considered in first approximation axisimmetric; (b) smooths very much the effects of changes in the shape of the function, so in order to better constrain it, measurements of sky brightness in many sites are needed and in different configurations (sites inside cities, sites near cities, sites far from main cities, etc.).

Given the limited number of measurement in Italy so far, I started adopting the normalized average city emission function from Garstang (1986) which worked well with his many comparisons of models to observational data. This function is semi-empirical in the sense that the author assumed it be produced by the sum of direct emission from fixtures at high zenith distances and Lambertian emission from lighted horizontal surfaces at higher zenith angles. Nevertheless, upward flux can be emitted at all zenith angles both from fixtures and vertical or horizontal surfaces, so I considered Garstang's parameters G and F only as shape parameters without any meaning of fraction of direct and reflected light. Here I used always G=0.15, F=0.15. I plan to constrain the average city emission function in subsequent works as soon as more observations will be available. Comparison of effects of different normalized average city emission functions are presented by Cinzano (1999a).

2.3. Total upward flux emitted by each city

The total upward flux is the integral of the city emission function of each city. I assumed that the upward light emission of each source be function of its population in agreement with results of satellite measurements of upward fluxes in Italy by Falchi and Cinzano (1999): $u \propto qf(P)$ where q is a scale parameter. The population of cities at 1995 was provided from Istituto Italiano di Statistica (ISTAT). At short distances from a city differences between geographic positions of the city and the position of its light emission baricenter can be source of errors as well as the limits of the adopted seven-points approximation. I plan to use directly satellite data as soon as they will be available. The functional form giving the total upward flux in function of population of the city is discussed in section 3.

3. Calibration of models and upward flux from Italian cities.

The calibration of the artificial sky brightness predicted by the models depends on the parameter q. The upward emissions of cities are rapidly increasing with the time as shown for the Veneto plain in Cinzano (1999b). If, in first approximation, geographical gradients of the growth ratio of upward emission can be assumed negligible (this is under study by Falchi and Cinzano), the scale parameter q depends only on time. I obtained a preliminary calibration for V band comparing the ratio $q(t)$ between measured and predicted artificial sky luminances in some italian observatory sites in different epochs. I selected sky brightness measurements in V band in periods near minimum solar activity, I converted them into luminances with formulae in Garstang (1986) and I subtracted the natural sky luminances obtained by the model, except for a measurement obtained in 1990 which was corrected subtracting an estimated natural sky luminance for mean solar activity of 300 cd/m^2.

Figure 3 shows the ratios versus the year of measurement for the adopted calibration. In left panel are shown ratios for models with $f(P) = P$ and in right panel are shown ratios for models with $f(P) = P^{0.8}$ (see Falchi & Cinzano 1999). The measurements refers, in sequence, to Mount Ekar Observatory (Cinzano 1999b), "G.Ruggieri" Observatory in Padova (Favero et al. 1999), Bologna University Observatory in Loiano(Zitelli 1999), Brera-Milan Astronomical Observatory in Merate (Poretti & Scardia 1999), Mount Ekar Observatory (Cinzano 1999b), Catania Observatory - Stellar Station in Serra La Nave (Catanzaro and Catalano 1999), Collurania Astronomical Observatory in Teramo (Piersimoni et al. 1999) and "G. Ruggieri" Observatory in Padova (Favero et al. 1999).

The little number of measurements does not allow to distinguish between the two functional forms of $f(P)$ suggested by Falchi & Cinzano (1999). Models with $f(P) = P^{0.8}$ (right panel) show a better agreement together than models with $f(P) = P$ (left panel) but sky luminance at "G.Ruggieri" Observatory (triangles) and Collurania Astronomical Observatory (dot) is mainly produced by one city and a lower emission from two cities does not require necessarily a $f(P) = P^{0.8}$ functional form to be explained, given the scatter between a city and another. Sites where sky luminance is determined by a big number of sources as Mount Ekar Observatory or Bologna University Observatory in Loiano (squares) are much less sensitive to scatter in upward emission of cities.

The figures show that the upperflux is rapidly growing. For comparison the dashed curves show an exponential increase from 1982 to 1998 with an yearly increase of 9 percent. This growth rate fits quite well and is in good agreement with growth rates in Cinzano (1999b). The figure shows that the standard output of models refers to 1990. At that epoch the total upward city emission required by the models with $f(P) = P$ to fit observations with the Garstang city emission function was 277 lm per head. The

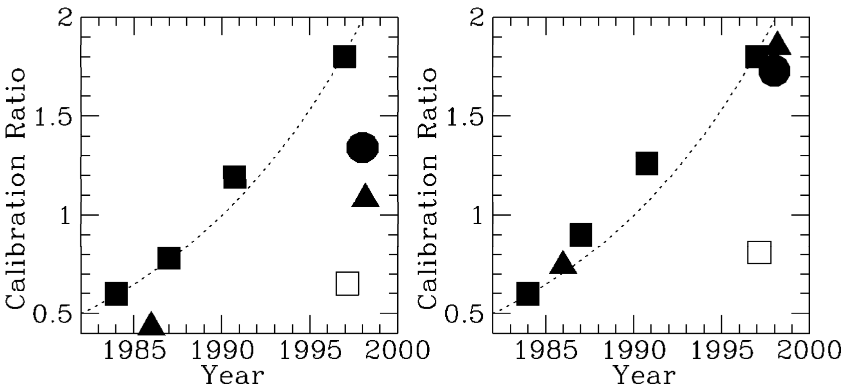

Fig. 3. Time dipendence of the scale parameter q.

scale parameter $q(t)$ that I adopted for models is:

$$q(t) = (1 + x)^{(t-t_0)} \quad (1)$$

with $x = 0.09$, $t_0 = 1990.0$. More measurements are needed in order to confirm these results.

In this calibration I assumed that all observations are done in clean atmospheric conditions. The upward flux required by the models might be lower if the air clarity would be higher than the typical clear air at sea level, an unlikely event in the climate of Pianura Padana. If the clarity is lower as for the model with K=2, the upward flux per inhabitant requested by the models would be higher. In future work when more sky brightness measurements will be available together with the extinction in the same night, I plan to recalibrate more accurately the models taking in account aerosol content of each nights. The calibration assumes the absence of geographical gradients in upward emission as the satellite measurements by Falchi and Cinzano (1999) seems to show. The prediction of artificial sky luminance for Catania Observatory Stellar Station in Serra La Nave (open symbol) is clearly overestimated in respect to the measurement. This is probably due to the presence of volcanic dust or other kind of aerosol layers. The quite high extinction at the 1725 m of height o. s. l. of the observatory, $k_\nu = 0.2422$ (Catanzaro and Catalano 1999), confirms the presence of an high aerosol content. This value of k_ν at 1725 m requires a clarity parameter approximately double than e.g. at the 1350 m of Mount Ekar Observatory. If this behaviour, under study, is produced by a layer of volcanic dust or other aerosols, its extinction of the light from the city of Catania might explain the quite dark sky measured at the observatory (see e.g. Garstang 1991b).

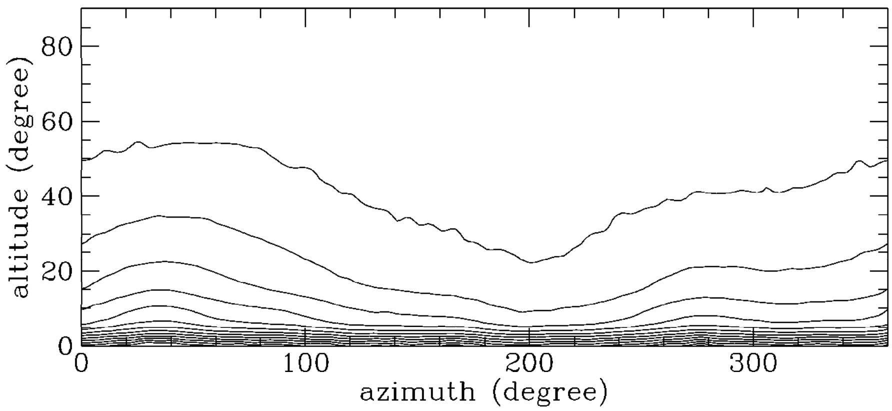

Fig. 4. Sky brightness distribution at Brera Milan Observatory in Merate. Isophotes show respectively a sky brightness increase of 4.0, 4.5, 5.0, 5.5 etc. over the natural level in 1990.

4. Results

With the models described above I computed the sky brightness distribution in V band for some Italian Observatory sites and the contributions of some single sources. In few cases it was possible to compare predicted sky brightness with observations. In other cases only measurements near the zenith were available and they were used to calibrate the models in section 2. All models presented here assume $f(P) = P$ except for "Guido Ruggieri" Observatory which required a lower emission from Padova.

Figure 4 presents the model predictions of the sky brightness distribution at the Brera-Milan Astronomical Observatory in Merate (long. $-9°25'42"$, lat. $45°41'58"$ alt. $330m$ o.s.l.). Isophotes shows the brightness increases over the natural sky value obtained taking in account 2171 towns inside 120 km from the observatory. The origin of the azimuth is South and it increase toward West.

The comparison between the total sky brightness predicted by the model along the meridian toward South for some zenith distances and the available photometric measurements in clean nights (Poretti & Scardia 1999) give:

z (degrees)	0	10	20	30	40	50
ΔV_{obs} (V mag/arcsec^2)	0.00	-0.08	-0.19	-0.4	-0.6	-0.9
ΔV_{calc} (V mag/arcsec^2)	0.00	-0.05	-0.14	-0.3	-0.5	-0.8

Between measured zenith sky brightness and predicted zenith sky brightness for September 1990 there is a difference of -0.11 mag. Measurement could not be corrected for solar activity, crepuscular decay of airglow emission, galactic longitude and latitude, zodiacal light contribution. Nevertheless, the corrections would be in this case very little given the amount of the artificial sky brightness. I tested the effect of an increase of aerosol content in the atmosphere computing the total brightness for K=2: the relative sky brightness distribution resulted poorly sensitive to the value of K whereas the brightness values

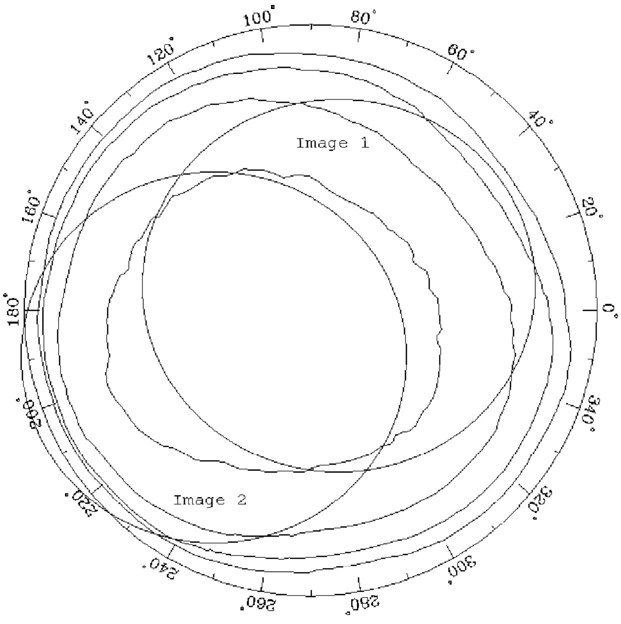

Fig. 5. Predicted isophotes of sky brightness at Brera-Milan Observatory in Merate. In the figure are shown indicatively the field covered by the image of figure fig. 6 (image 1) and by the image in Poretti & Scardia (1999) (image 2).

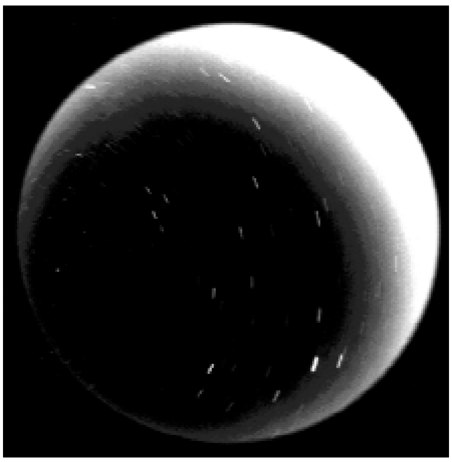

Fig. 6. Fish-eye image of the sky at Brera-Milan Observatory in Merate kindly provided by E. Poretti & M. Scardia. The field of view is shown in figure 5 (image 1).

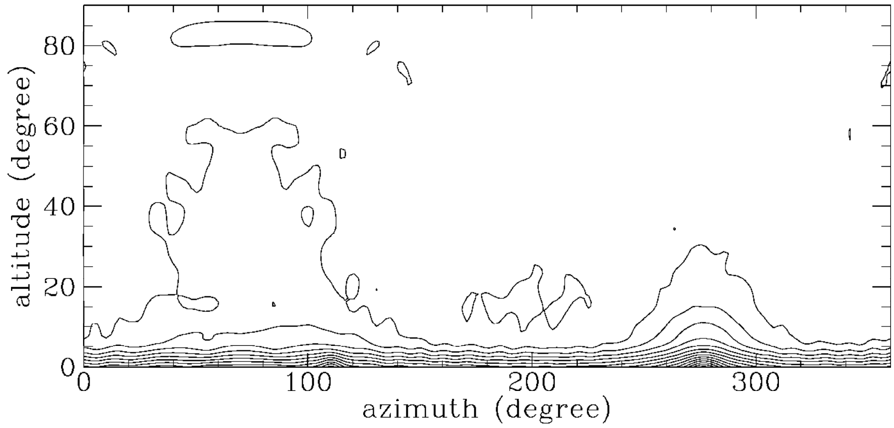

Fig. 7. Contribution to the sky brightness distribution produced by the cities of Merate, Como and Bergamo (from left to right). Isophotes show respectively a sky brightness increase of 2.5, 3.0, 3.5 etc. over the natural level in 1990.

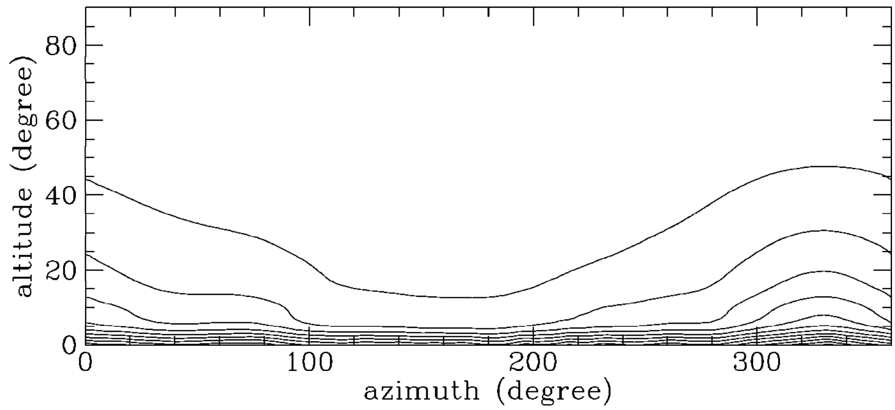

Fig. 8. Sky brightness distribution at Catania Astronomical Observatory in Serra La Nave. Isophotes show respectively a sky brightness increase of 2.0, 2.5, 3.0, 3.5 etc. over the natural level in 1990.

decrease as expected due at the increase of extinction of the light from far sources.

Figure 5 shows predicted isophotes of sky brightness at Brera-Milan Observatory in projection. In the figure are shown indicatively the fields of view covered by the fish eye images of figure 6 (image 1) and in Poretti & Scardia (1999) in this book (image 2), useful for comparison. For details on these images see the cited paper. When comparing the images and the figure 5, the orientation must be checked from field stars positions. I also present in figure 7 the contribution to the sky brightness distribution produced by the cities of Merate, Como and Bergamo alone.

Figure 8 presents the model predictions of the sky brightness distribution at the Catania Astronomical Observatory Stellar Station in Serra La Nave (long. $-14°58'24"$, lat. $37°41'30"$ alt. $1735m$ o.s.l.), taking in account the 362 towns inside 120 km from the site. The predictions reproduce very well the sky brightness distribution measured by Catanzaro and Catalano (1999) as shown by a comparison with the figure 2 of the cited paper in this book. The origin of azimuth in figure 8 is South whereas in the figure of Catanzaro and Catalano (1999) the origin is North. The effect of the high aerosol content (see sec. 3) seems to be more effective on the absolute values of sky brightness than on its distribution on the sky. The contribution of Catania city alone at the zenith of the observatory is the 17% percent of the total artificial brightness in this model (K=1). Even if this is the main source, the main pollution is produced by the sum of the contributions from many other towns like Adrano (7%), Paternó (6%), Biancavilla (6%), Belpasso (4%), Acireale (4%), etc.

I computed the sky brightness distributions for Mount Ekar Observatory (long. $-11°34'18"$, lat. $45°50'36"$ alt. $1350m$ o.s.l.) and Bologna Observatory in Loiano (long. $-11°20'0"$, lat. $44°15'23"$ alt. $714m$ o.s.l.) shown respectively in figure 9 and 11. The contribution to sky brightness distribution from some sources in their surrounding territory are shown in figures 10 and 12. The contribution of Bologna to the artificial zenith sky brightness of Bologna Astronomical Observatory in Loiano is 18%. Its contribution at 45° of zenith distance towards the city was $341 \mu cd/m^2$ in 1990, twice the natural sky brightness. The contribution of Loiano town has to be considered quite uncertain due to the extreme proximity to the observatory which can be sensitive to the limits of the seven point approximation used to describe the city and to the difference between the geographical position and the position of the baricenter of the light emission of the city. Contribution at the zenith sky brightness of Mount Ekar Observatory from some cities in the surrounding land are listed in table I. The table shows that the sky glow at the observatory is produced by the sum of many little contributions. I counted 1819 cities and towns in a radius of 150 km around the observatory. Note that the contributions from Asiago, the area of Thiene, the area of Piovene, the area of Schio, the area of Zugliano, the city of Bassano, the city of Vicenza and the Province of Padova are of the same order of magnitude.

In diffusely and strongly urbanized areas where cities and towns are distributed sparsely on the territory, the sky brightness can be decomposed in two components: a background component slowly changing when moving the observation site in the country and produced by the total contribution of sources which smooth together and a vicinal component strongly floating which has maxima when the observation site is near or inside a source city and with minimum when it is at a distance from nearby cities.

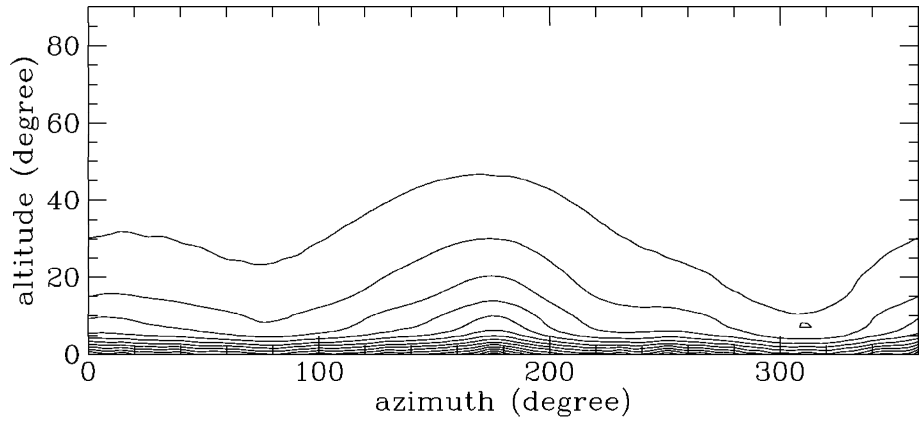

Fig. 9. Sky brightness distribution at Bologna Astronomical Observatory in Loiano. Isophotes show respectively a sky brightness increase of 2.0, 2.5, 3.0, 3.5, 4.0 etc. over the natural level in 1990.

artificial sky brightness

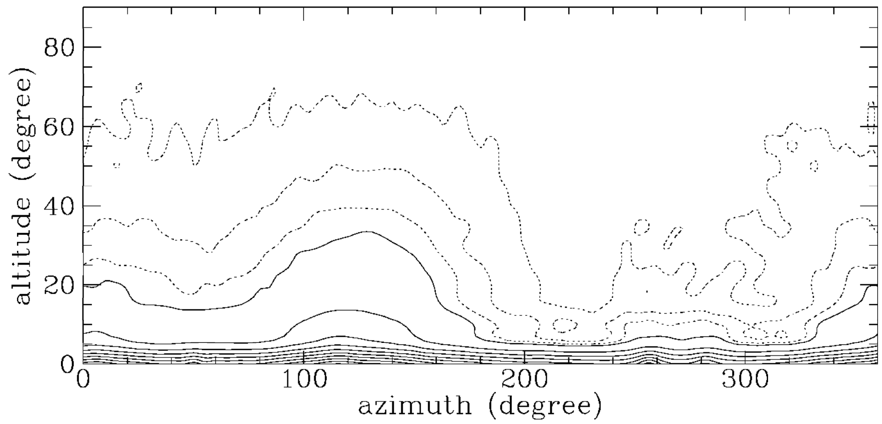

Fig. 10. Contribution to the sky brightness distribution at Bologna Astronomical Observatory in Loiano produced by the cities of Monghidoro ($\sim 0°$), Monzino and Loiano ($\sim 100 - 140°$), Ravenna, Rimini e Riccione ($\sim 250 - 270°$). Isophotes show respectively a sky brightness increase of 0.7, 0.8, 0.9 (dotted lines), 1.0, 1.5, 2.0 etc. (solid lines) over the natural level in 1990.

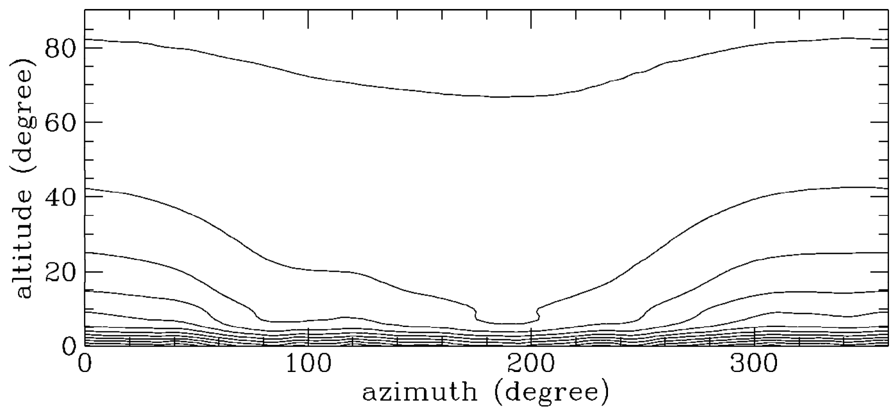

Fig. 11. Sky brightness distribution at Mount Ekar Observatory. Isophotes show respectively a sky brightness increase of 1.5, 2.0, 2.5, 3.0, 3.5, etc. over the natural level in 1990.

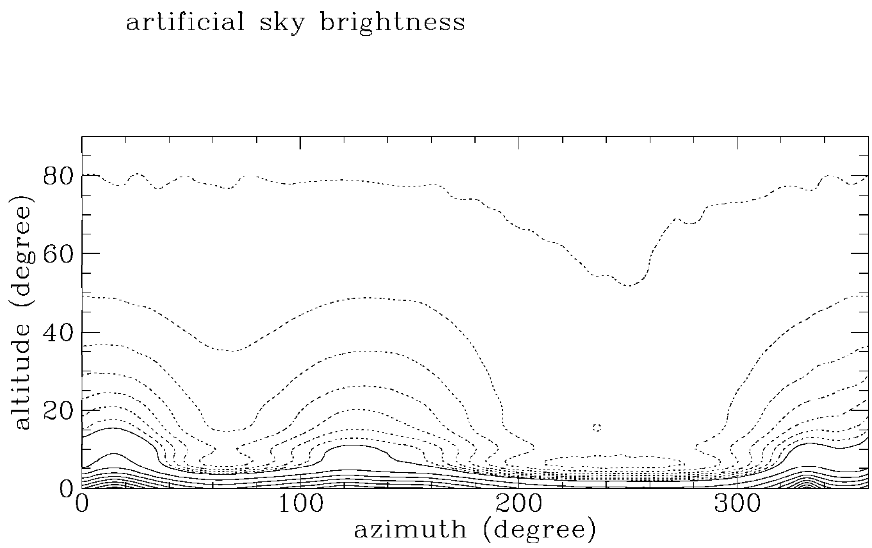

Fig. 12. Contribution to the sky brightness distribution at Mount Ekar Observatory produced by the cities of Thiene ($\sim 8°$), Asiago ($\sim 120°$), Gallio ($\sim 160°$), Padova ($\sim 330°$). Isophotes show respectively a sky brightness increase of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 etc. over the natural level in 1990.

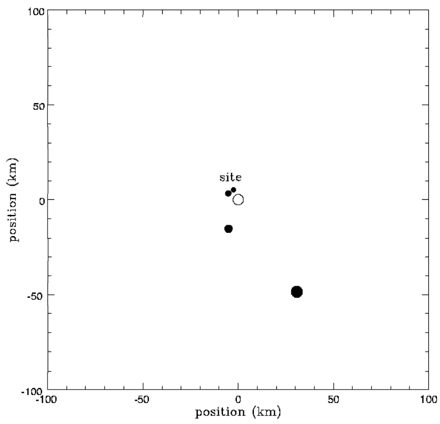

Fig. 13. Map of the sources of previous figure.

TABLE I
Artificial sky brightness contributions at Mount Ekar Observatory from some cities.

Source	p inhab.	d km	b %	Source	p inhab.	d km	b %
Asiago	6652	5.2	4.6	Area of Zugliano	14115	13	3.4
Gallio	2340	4.6	1.6	Zugliano	5677		1.2
Roana	3747	8.8	1.6	Lugo	3696		1.0
Rotzo	604	13	0.1	Fara Vic.	3732		0.9
Conco	2250	6.8	1.5	Salcedo	1010		0.3
Lusiana	2881	7.6	1.7	Marostica	12610	14	2.2
Arsiero	3313	18	0.4	Breganze	7500	16	1.1
Area of Piovene	17165	14	3.7	Bassano	39289	17	5.1
Piovene	7340		1.4	Vicenza	107786	34	3.0
Carré	2950		0.6	Padova	212731	55	1.3
Chiuppano	2422		0.6	Cittadella	18324	28	0.7
Cogollo	3212		0.7	Grisignano	4099	55	0.5
Calvene	1241		0.4	Treviso	81195	56	0.5
Area of Thiene	34250	18	4.3	Castelfranco	30079	34	0.7
Thiene	20476		2.7	Mestre-Venezia	298915	70	0.7
Zané	5548		0.8	Trento	103181	56	1.3
Marano	8226		0.8	Belluno	35375	66	0.2
Area of Schio	41631	23	3.5	Verona	254145	64	1.5
Schio	36601		2.9				
Santorso	5030		0.6				

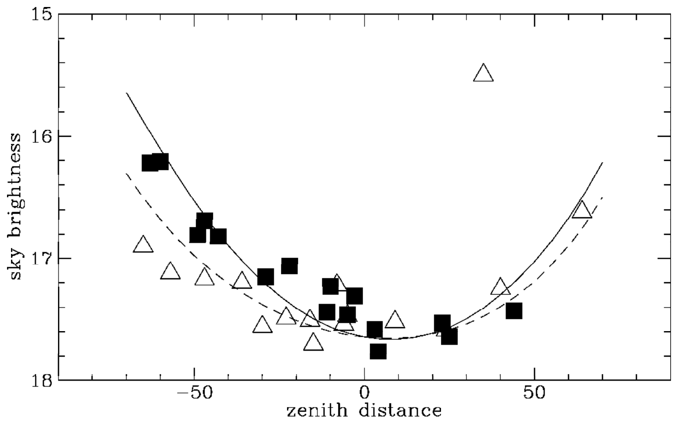

Fig. 14. Model predictions and sky brightness measurements at "G. Ruggieri" Observatory in Padova (Favero et al. 1999). Solid squares are measurements with azimuth ±45° from the meridian, open triangles are measurements with azimuth ±45° from the West-to-East circle. Solid line is the model prediction along the meridian and dashed line is the prediction along the West-to-East circle. Zenith distance is negative toward Padova city center.

When map of light pollution in a large territory are computed as done by Bertiau et al (1973) or Falchi and Cinzano (1999), the mean contribution in each considered grid point is calculated neglecting the effects of the casual presence of a source near the observation site. All sources are assumed to be at a minimum given distance. It is interesting to check how big could be the fluctuations gived by the casual presence of a source near the site. This is also interesting in order to determine what could be the minimum and maximum sky brightness that on a clear night could be found in a given area of the territory. The background component constitutes a lower limit, the higher being given by the sum of the background and the maximum fluctuation. Moreover, it is interesting to check inside cities what fraction of sky brightness is produced by the city itself and what fraction by the background. At last, it would be interesting to determine what is the population level at which the local brightness produced by the city became comparable to the background brightness.

These questions can be answered with the models applied in this paper. As an example I computed the sky brightness at a site inside the city of Padova, the "G. Ruggieri" Observatory (long. −11°53′20", lat. 45°25′10" alt. 20m o.s.l.) both including and excluding the contribution of the city. This model assume $f(P) = P^{0.8}$ in order to fit observations of Favero et al. (1999) as discussed in sec. 3. The good agreement of predicted sky brightness distribution with measurements obtained by Favero et al. (1999) is shown in figure 14. In order to obtain the better fit, the predictions needed to be increased by 0.15 mag. Figure 15 and figure 16 show the sky brightness distribution at the site with and without the city. I found that 74 percent of artificial brightness at the zenith of the site is coming from Padova and 26 percent from the background. Note

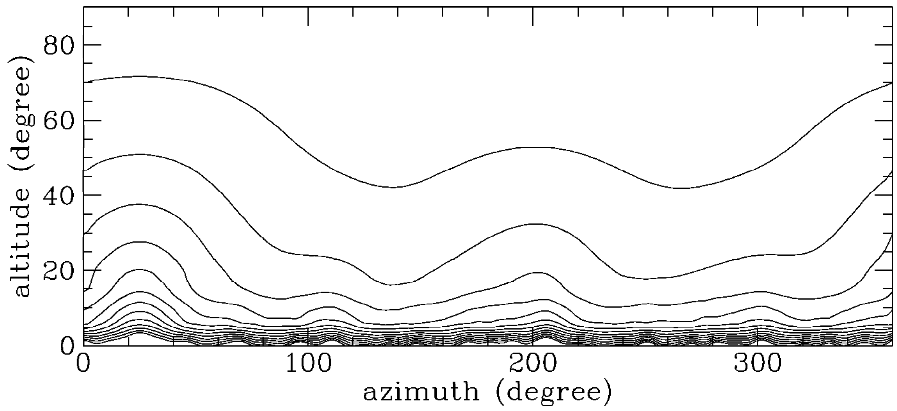

Fig. 15. Sky brightness distribution at "G. Ruggieri" Observatory in Padova. Isophotes shows respectively a sky brightness increase of 4.0, 4.5, 5.0, 5.5 etc. over the natural level in 1990. At low altitudes the 7-point approximation for Padova show its limits.

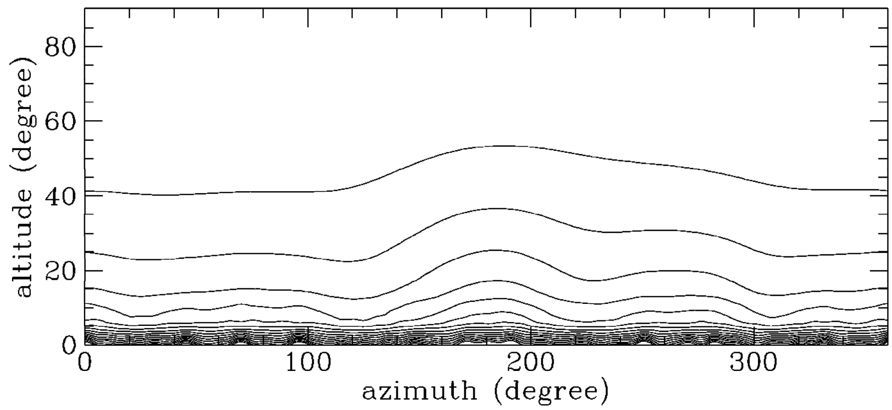

Fig. 16. Contribution to the sky brightness distribution produced at "G. Ruggieri" Observatory in Padova by all the cities excluding Padova. Isophotes show respectively a sky brightness increase of 3.0, 3.5, 4.0, 4.5, 5.0 etc. over the natural level in 1990.

that the contribution of the surrounding country is not negligible even in a site inside a city of 210000 inhabitants like Padova.

5. Conclusions

The impact of single sources on the sky brightness of a site was evaluated by computing the artificial sky brightness distribution which they produce with detailed models for light pollution propagation. The upward emission of cities in function of their population and the time was constrained with the condition that the sum of all contributions, including the natural sky brightness, fits the available measurements in some sites. The conclusions are:

1. Detailed models are usefull for disentangle contribution of single sources in diffusely urbanized areas.
2. Models well predict the sky brightness distribution in the studied sites showing that Garstang modelling technique works well in Italy too.
3. The preliminary calibration requires that the total upward flux from cities increases at about 9 percent per year in Italy, in good agreement with Cinzano (1999b), with an average total upward emission of 277 lm per head in 1990 (for models with $f(P) = P$).
4. Given the little number of available measurements it isn't possible to distinguish between the two functional forms of the total upward city flux versus city population pointed out by Falchi and Cinzano (1999).

More work is still necessary to better constrain average city emission function and the total upward flux calibration.

Acknowledgements

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References

Abramowitz M., Stegun I.A. 1964, Handbook of Mathematical Functions, Washington, NBS.

Bertiau, F.C.S.J., de Graeve, E.S.J. & Treanor, P.J.S.J. 1973, Vatican Observatory Publ., 1, 4, 159-179.

Catanzaro, G., Catalano, F.A. 1999, in this volume.

Cinzano, P. 1997, Inquinamento luminoso e protezione del cielo notturno (in italian) (Venezia: Istituto Veneto di Scienze, Lettere ed Arti), 224 pp.

Cinzano, P. 1999a, in this volume.

Cinzano, P. 1999b, in this volume.

Falchi, F. & Cinzano, P. 1999, in this volume.

Falchi, F. 1999, Thesis, in prep.

Favero, G., Federici, A., Blanco, A.R., Stagni, R. 1999, in this volume.

Garstang, R.H. 1984, The Observatory, 104, 196-197.

Garstang, R.H. 1986, Publ. Astron. Soc. Pacific, 98, 364-375.

Garstang, R.H. 1987, in Identification, optimization and protection of optical observatory sites, eds. R.L. Millis, O.G. Franz, H.D. Ables & C.C. Dahn (Flagstaff: Lowell Observatory), p. 199-202.

Garstang, R.H. 1988, The Observatory, 108, 159-161.

Garstang, R.H. 1989a, Publ. Astron. Soc. Pacific, 101, 306-329.

Garstang, R.H. 1989b, Ann. Rev. Astron. Astrophys., 27, 19-40.

Garstang, R.H. 1989c, Bull. of American Astron. Soc., 21, 2, 759-760.

Garstang, R.H. 1991a, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conf. Series 17, p. 56-69.

Garstang, R.H. 1991b, Publ. Astron. Soc. Pacific, 103, 1109-1116.

Garstang, R.H. 1991c, The Observatory, 111, 239-243.

Garstang, R.H. 1992, Bull. of American Astron. Soc., 24, 740.

Garstang, R.H. 1993, Bull. of American Astron. Soc., 25, 1306.

Garstang, R.H. 1999, in this volume.

Hulburt, E. O. 1941, J. Opt. Soc. Am, 31, 467-476.

McClatchey, R.A., Fenn, R.W., Selby, J.E.A., Volz, F.E., Garing, J.S. 1978, Handbook of Optics, ed. W.G. Driscoll and W. Vaughan, McGraw-Hill, New York.

Piersimoni, A., Di Paolantonio, A., Brocato, E. 1999, in this volume.

Poretti, E. & Scardia, M. 1999, in this volume.

Treanor, P.J.S.J. 1973, The Observatory, 93, 117-120.

Volz, F.E. 1987, Appl. Optics, 26, 4098.

Walker, M.F. 1970, The California Site Survey, Publ. Astron. Soc. Pacific, 82, 672-698.

Walker, M.F. 1973, Light pollution in California and Arizona ,Publ. Astron. Soc. Pacific, 85, 508-519.

Walker, M.F. 1977, PASP, 89, 405-409.

Walker, M.F. 1988, Publ. Astron. Soc. Pacific, 100, 496.

Zitelli, V. 1999, in this volume.

MONITORING LIGHT ENERGY LOSS ESTIMATED BY THE DMSP SATELLITES

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ABSTRACT. Data obtained by US DMSP satellites were analyzed to obtain light energy loss in order to monitor light pollution in Japan. From data of 1993-1996, we found 10 to 20 percent increase of light energy loss at all the 5 cities for which our measurements had been carried out. We will proceed our measurements for the other cities in Japan and also in the other countries. Data at 3 specific days in 1997, which were observed at a low gain mode and have practically no saturation points, gave absolute values of light energy loss and we got values around 900 GW x hour and 20 billion yen of its loss in a year assuming 10 hour light-on and electric energy cost of 25 yen per 1 kW x hour (currently 1 US dollar is equal to 130 yen).

1. Introduction

It is clear that a condition for astronomical observations is becoming worse and worse owing to light pollution. However, it is inevitable that society produce light from lamps in order to make human life convenient, and don't take care much on astronomical observations. Astronomers can directly oppose people producing useless light, but it is usually hard work since many people like bright lighting. A way to minimize light pollution is to make people realize what they are loosing (Isobe 1998). The US Defense Meteorological Satellite Program (DMSP) started to produce night-time terrestrial images in 1972, but till 1992 those images were available in a form of photographic prints. Fortunately, digital data became available from 1993. Those data containing clear views were obtained from the US National Geographic Data Center (NGDC) and were used to estimate the energy loss of city light into space. Isobe and Hamamura (1998) showed some preliminary results using the data in a period of 1993 to 1996. In this paper, we will show the further results including the total light energy loss into space in a year.

2. Data analysis

The DMSP has a sensitive detector with different gain mode. Since it is a defense satellite, it is usually used at a high-gain mode. Its current detection level is within 2×10^{-9} Watt/cm^2/st/μm - 2×10^{-8} Watt/cm^2/st/μm which is too much sensitive, and therefore, most of the cities in Japan have saturated images (Isobe and Hamamura, 1998). Because of a strong request by the NGDC, the US Air force tried to reduce its gain on January 7, 13, and February 9, 1997 and fortunately it was mostly cloudless in these 3 nights. This detection level is within $4x10^{-9}$ Watt/cm^2/st/μm - $3x10^{-7}$

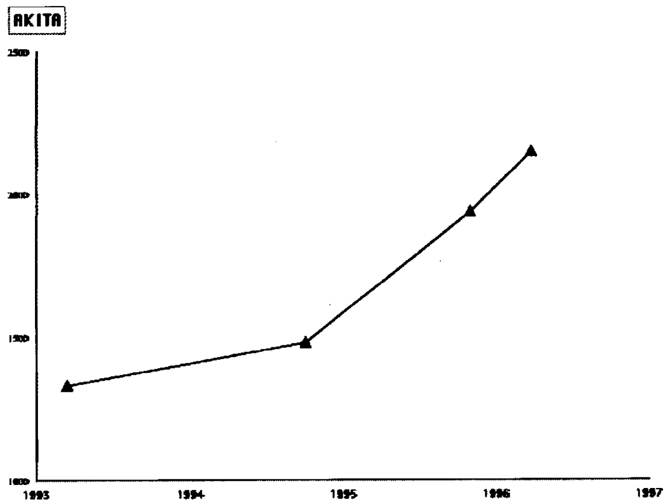


Fig. 1. Time dependent relative index of light loss at Akita city from 1993 to 1996.

Watt/cm^2/st/μm. Then, we can estimate the total energy loss into space in these 3 nights. An energy flux, F, ejected in a wavelength range of 0.4 - 0.7 μm to its telescope (its aperture of 20 cm) from an area (1.2 km x 1.2 km) corresponding to a detector pixel at an altitude of 835 km is given by

$$F = 4.56 \times 10^7 \times E \quad Watt \tag{1}$$

Here, E is energy flux detected. Therefore, its detection limits is 9.12×10^{-2} Watt. Assuming that an amount of light energy loss into space is constant in 10 hours of night through a year, one can estimate the total amount of light energy loss per year. Then, taking a typical price of electrically usage in Japan (25 yen/KW x hour), an amount of money lost by light energy per year can be estimated.

3. Results

In a paper (Isobe and Hamamura 1998), we show a time dependence of relative light energy loss from 1993 to 1996 at the 5 cities (Akita city, Shizuoka city, Hiroshima city, Tokushima city, and Matsuyama city). Here, we will show a reliable example of Akita city (figure 1) where number of saturated pixel is relatively small. One should remind that we can not measure its absolute value because of an inclusion of saturated pixel. Under this limited condition, an increase of light energy loss in an order of 40 % can be easily identified. Since a bullet train line had been expected to reach the city in 1997, it was just a period that its commercial activities became higher and higher. Figure 2

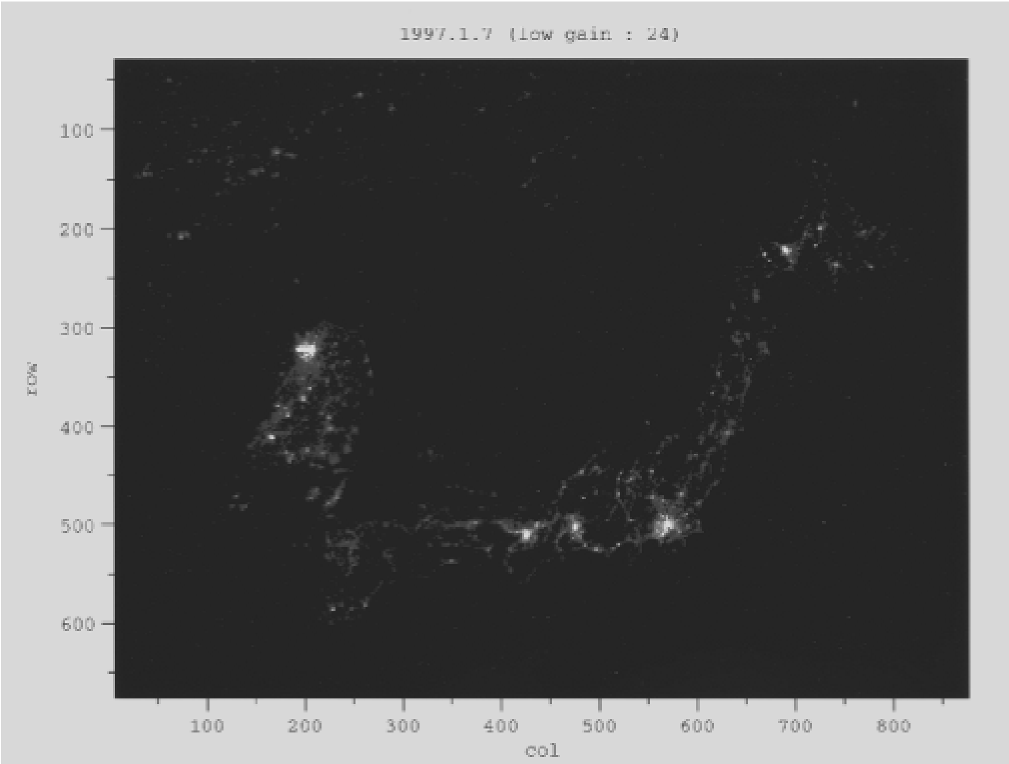


Fig. 2. Night time brightness distribution of Japan on January 7, 1997.

shows a night time brightness distribution of Japan obtained from the low gain data of January 7, 1997, and Figure 3 shows its enlarged map of Kanto plain including the capital of Tokyo which has still some number of saturated pixels. In this map, one can easily identify all the cities within the map as well as skiing resorts. Although the DMSP data are obtained at midnight, one tries to make those skiing areas by machines and need much light for those activities. We tentatively measured light energy loss within 30 km, 60 km, 90 km, 120 km, and 150 km square areas centered at the center of Tokyo and calculated those in each area between two consecutive areas (table 1). It is clear that the nearer the area is the more the light energy is lost. Only Tokyo city lost about 10 % of light energy loss in the whole Japan. The total light energy loss of Japan per year estimated from the data of January 7, 13, and February 9 are shown in table 1. There is 15 % fluctuation. Since Japan is a very long country (∼3,000 km), it is rare to have a clear weather all over the country. When we see its infrared data, some thin cloud can be seen from place to place. This is one of causes of error. There are many working fishing boats surrounding Japan, which eject much light to sea surfaces to collect fishes. This reflected light becomes bright light source detected by the DMSP satellites. This light fluctuation is also a cause of error. Therefore, our estimates in table 1 are reasonably

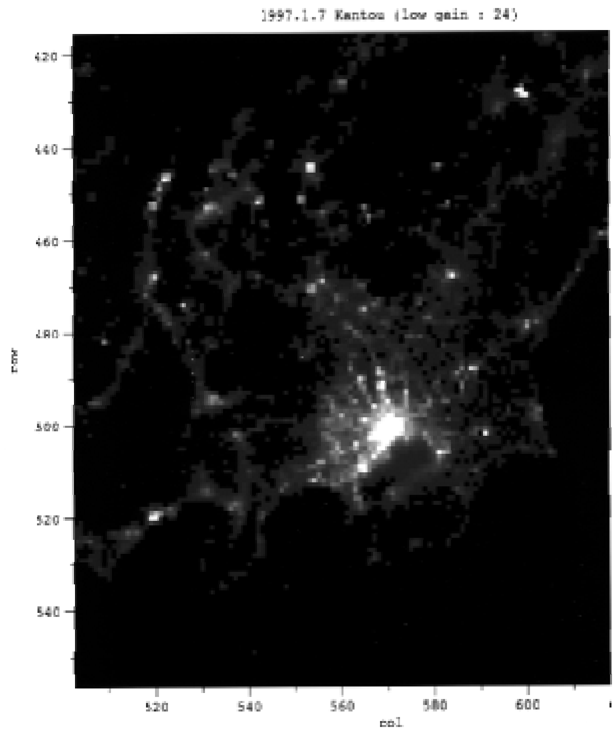


Fig. 3. A map of Kanto plain enlarged from figure 2.

coincident with each other. In future, we will measured an area to the others a where we can not find any cloud from data of different days and sum up through the country. Then, much reliable data will be obtained.

4. Conclusion

There were no monitoring methods for light pollution except an effort of some specific observatories. Now, we found from our study in this paper that data of the DMSP satellites can give a global monitoring method for light pollution. When people see they are loosing so much energy and money, I believe they will join our activities to reduce light pollution. Finally, I will say that the Japan Environmental Agency produced a guideline against light pollution in March, 1998, after two year study within a committee where I was one of the members, and is requesting to each local government to follow this guideline. I believe this is the first governmental effort in the would.

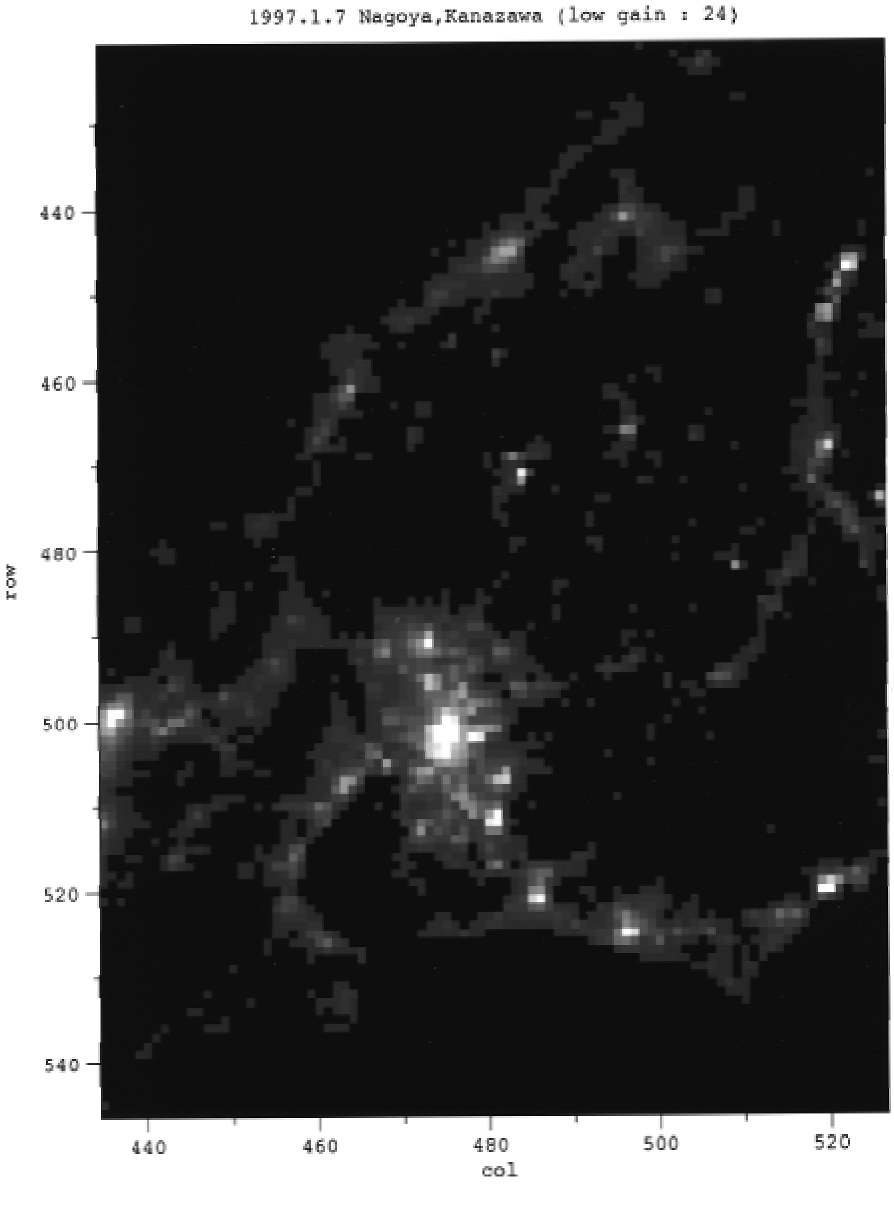
Table 1. Measured loss in energy and in yen

	Total observed energy 10^{-8}Watt/cm^2/st/μm	Total energy loss 10^{6}kW·h	Total loss in yen 100 million yen
Akita city	410	2.47	0.62
Kanto plane 1997. 1. 7			
30km×30km	1.17×10^{4}	70.2 (70.2)	17.6
60km×60km	2.46×10^{4}	147 (25.6)	36.8
90km×90km	3.15×10^{4}	189 (8.4)	47.3
120km×120km	3.40×10^{4}	204 (2.1)	51.0
150km×150km	3.41×10^{4}	213 (1.0)	53.2
Japan			
1997. 1. 7	1.38×10^{5}	826	207
1997. 1. 13	1.44×10^{5}	866	217
1997. 2. 9	1.60×10^{5}	961	240

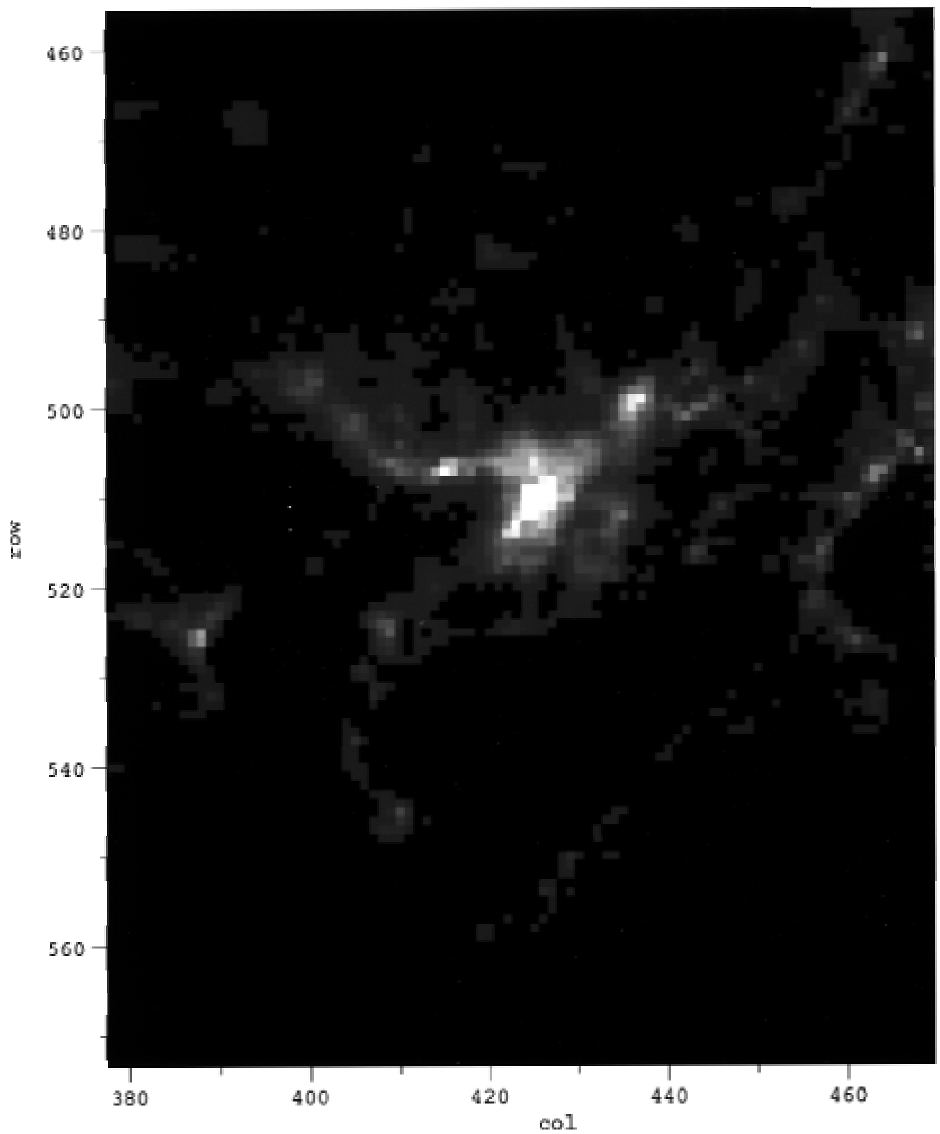
References

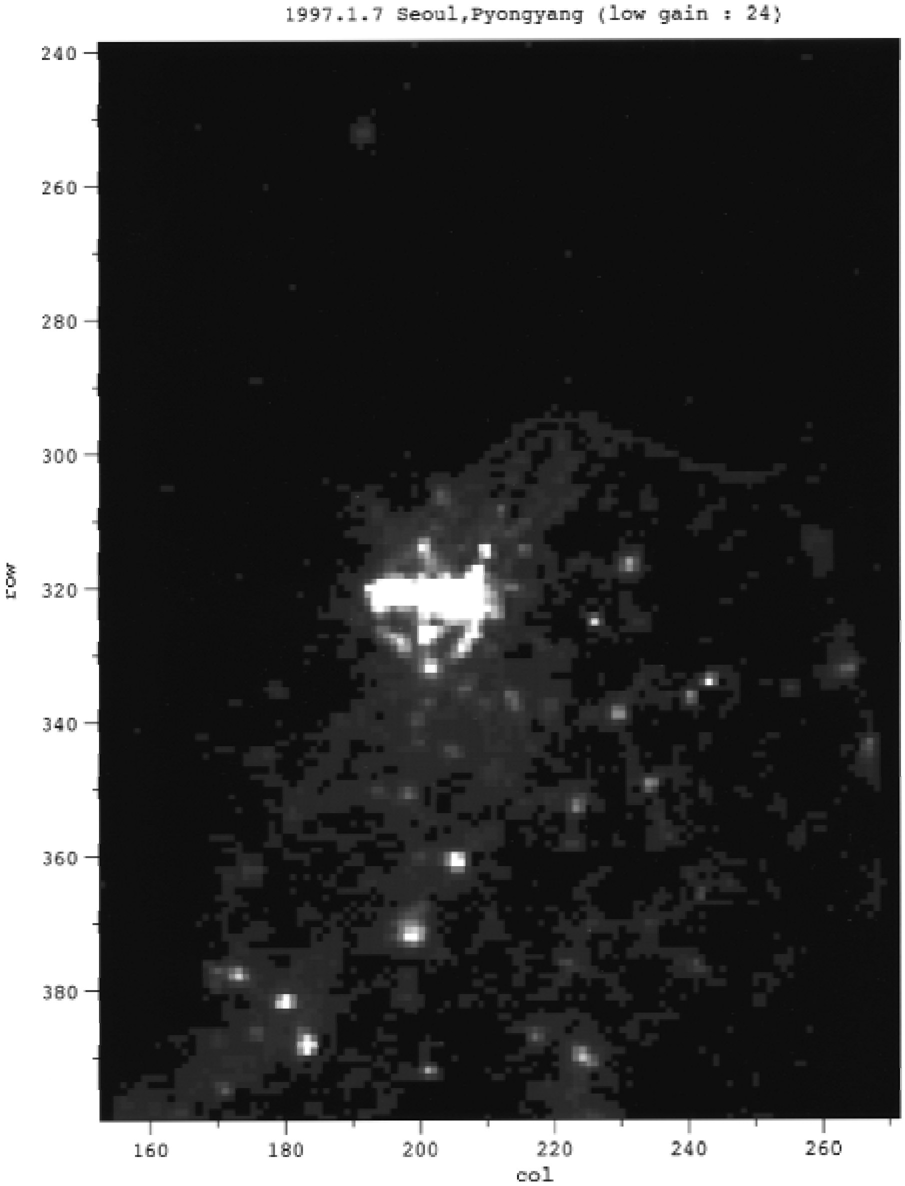
Isobe, S. 1998, Bilateral agreements, zoning, international protocol to preserve astronomical windows, in Preserving the Astronomical Windows : Astronomical Society of Pacific Conference Series, pp.119-123.

Isobe, S. and Hamamura, S. 1998, Ejected city light of Japan observed by a defense meteorological satellite program : Astronomical Society of Pacific Conference Series, pp.191-199.


1997.1.7 Nagoya,Kanazawa (low gain : 24)
row
440
460
480
500
520
540
col
440
460
480
500
520

1997.1.7 Osaka (low gain : 24)




1997.1.7 Seoul,Pyongyang (low gain : 24)
row
240
260
280
300
320
340
360
380
col
160
180
200
220
240
260

MAPS OF ARTIFICIAL SKY BRIGHTNESS AND UPWARD EMISSION IN ITALY FROM DMSP SATELLITE MEASUREMENTS

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ABSTRACT. We obtained the map of the zenith brightness of the night sky in Italy, constructing a simple model. The artificial sky brightness in each site is given by the integration of the contribution produced by each unitary area of surface obtained by applying a propagation function to the upward emission in the area. This operation is a convolution of the upward emission with the propagation function. In fact, the scattering from atmospheric particles and molecules of light emitted upward by the cities spreads the light far from the sources. In pratice, we convolved the DMSP satellite night-time images of the upward light emission in Italy with a propagation function, like the Treanor Law. We used the light emission as measured by DMSP satellite images in order to bypass errors due to differences in the output of cities of the same population arising when using population data to estimate upward flux and in order to take into account also the contribution to the sky brightness produced from cities outside the Italian boundaries. We chose the DMSP visible band images for their negligible number of saturated pixels and for cloudfree Italy as guaranteed by inspection of IR images taken at the same time.

We also evaluated the emission versus population relationship comparing the relative emissions of a number of cities of various populations. The measured emissions increase quite linearly with the city population in the range from 1000 to 400000 inhabitants. In a preliminary analysis, more populated cities seems have a lower emission per inhabitant, so that in the range from 1000 to 3000000 inhabitants the best fitting curve to the measured emission seems to be a power law with the power 0.8 of the city population. We did not find any dependence of city upward emission on the economic development of the area.

1. Introduction

The effects of artificial lighting on the brightness of the night sky in Italy were explored by Bertiau, de Graeve and Treanor in 1971 (Treanor 1971, Bertiau et al. 1973), but since then no other systematic study followed. An inquiry done by the *Commission for the study of light pollution* of Società Astronomica Italiana (Di Sora 1991, 1993) was limited to the situation of the night sky in the main Italian astronomical observatories. In the last quarter of century in Italy there was a great increase in the brightness of the night sky due to the increased number and efficiency of the lamps used for the outdoor artificial lighting (see e.g. Cinzano 1999b). As a consequence, awareness of the light pollution problem by the professional and amateur astronomical communities is greatly increased. A study was needed to evaluate the new situation. Mappings of sky brightness for extended areas were performed by Walker (1970, 1973), Albers (1998) in USA and Berry (1976) in Canada with some simple modelling. These authors used population data of cities to estimate their upward light emission and a variety of propagation laws for light pollution in order to compute sky brightness. Recently DMSP satellite images allowed direct information on the upward light emission from almost all countries around the World (Sullivan 1989,1991) and were used to study the increase of this flux with time (Isobe 1993; Isobe & Hamamura 1999).

In this paper we present a detailed map of artificial sky brightness in Italy. In order to bypass errors due to differences in the output of cities of same population arising when using population data to estimate upward flux and in order to take into account also the contribution to the sky brightness produced from cities outside the Italian boundaries, we constructed the map measuring directly the upward flux as detected in DSMP satellite night time images and we convolved it with a light pollution propagation law. We also studied the relation upward flux – city population in Italy and compared it with results obtained in other countries.

In section 2 we describe the satellite image and the analysis technique. The relation upward flux – city population is presented and discussed in section 3. In section 4 we describe and discuss the method used to construct the map of artificial sky brightness. The map is presented in section 5 together with the map of upward emission and the map of sky brightness. Section 6 contains our conclusions.

2. Observations

We studied a visual image of night time Italy obtained by the Defense Meteorological Satellite Program (DMSP) of the National Oceanic and Atmospheric Administration (NOAA). DMSP are satellites in a low altitude (830 km) sun-synchronous polar orbit with an orbital period of 101 minutes. Visible and infrared imagery from DMSP Operational Linescan System (OLS) instruments monitor twice a day, one in daytime and one in nightime, the distribution of clouds all over the world. At night the instrument for visible imagery is a Photo Multiplier Tube (PMT) sensitive to radiation from 470 nm to 940 nm (510-830 FWHM) with the highest sensitivity at 550-600 nm, where the most used lamps for external night-time lighting have the strongest emission: Mercury Vapour (545 nm and 575 nm), High Pressure Sodium (from 540 nm to 630 nm), Low Pressure Sodium (589 nm). The IR detector is sensitive to radiation from 10,0 μm to 13,4 μm (10.3-12.9 FWHM). Every fraction of a second each satellite scans a $\sim$3 km swath extending 3000 km in east-west position with a resolution varying from less than 3 km at the nadir to about 12 km at each end (Sullivan 1991). In our images each pixel is $2.70 \pm 0.02 \times 2.75 \pm 0.03$ km wide respectively in North-South and West-East directions, a mean of five by five pixels $\sim$0.56 km wide of the high-resolution original images which are not distributed. The pixel values are currently relative values rather than absolute values because instrumental gain levels are adjusted to have a constant cloud reference brightness in different lighting conditions related to the solar and lunar illumination at the time. Due to the limited dynamic range of the satellite detectors, the automatic gain normally saturates the most lit pixel of the largest cities. Sensitivity

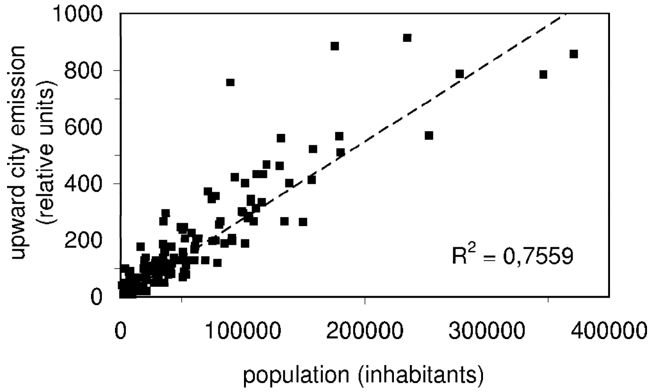

Fig. 1. Upward flux versus city population relationship for Italy in the range 1000 - 400000 inhabitants.

reaches 10^{-5} W m^{-2} sr^{-1} μm^{-1} (Elvidge et al. 1997). A few images were taken with lower gain (50-24 db) and they have only a few saturated pixels. We studied two visible band images chosen for the negligible number of saturated pixels and because Italy is almost cloudfree as guaranteed by inspection of the IR image taken at the same time. The images were taken the 13th January 1997 h20:27 from satellite F12 and the 11th March 1993 h20:37 from satellite F10 from an altitude of about 800 km.

3. Emission vs. population relationship

In order to evaluate the emission versus population relationship we chose a number of cities in cloudfree zones of the images, as seen in the corresponding IR images, and evaluated their emissions. To measure a city emission we summed the counts of all pixels pertinent to each city. So we obtained the relative emission of a number of cities of various populations. The population data were taken from the 1995 Italian census provided by Istituto Italiano di Statistica (ISTAT).

Figure 1 show our measurements for 139 cities distributed in all Italy in the range from 1000 to 400000 inhabitants from our low gain image. No sources in this plot has saturated pixels. The dashed line shows the best fit of $u \propto P$. The upward emission increase linearly with the population in the considered range.

We tried to study in deeper detail the upward flux versus city population relationship, expanding the dynamics of our data. We constructed a composite image replacing the saturated pixels in the higher gain image, useful to measure accurately low population sources, with the measurements coming from the low gain image, adequately rescaled. Results are shown in figure 2 and 3. The best fit curve to the measured emission in the range 1000-3000000 inhabitants is a power law with the power 0.8 of the city population P. These results need to be confirmed as soon as many more measurements become

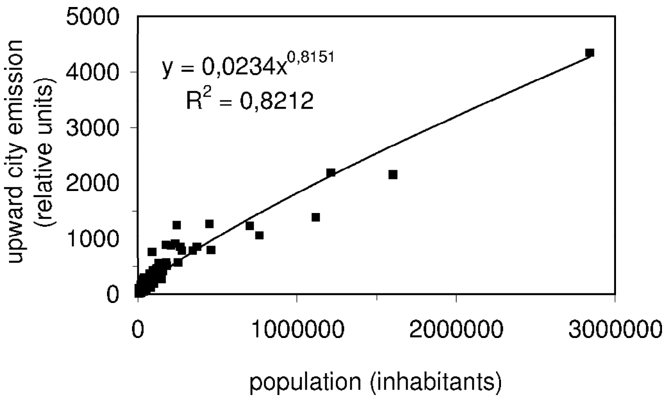

Fig. 2. Upward flux versus city population relationship for Italy in the range 1000 - 3000000 inhabitants.

available. This dependence might be due to the fact that in larger cities there are more inhabitants per unit area. In a district of high buildings there are less street lamps than in a same population district of single-family houses. This hypothesis so far was not confirmed. At the moment we cannot exclude that the exponent 0.8 be the result of the presence of saturated pixels near the center of more populated cities.

A possible source of errors is that each pixel of the distributed images is the sum of smaller pixels and we haven't any way to check if some of them were saturated. This uncertainty will be solved only when original images become available. Other main sources of error in our measurements are the uncertainties in determining the boundary of the suburbs. These errors influence mainly the measurement of the emission of the largest cities where the boundaries are less definite so that it is easier to include pixels relative to small cities in the surroundings. This causes an underestimate of the population relative to the measured emission.

Figure 4 shows the relation between upward emission and population for Italian Regions when the contribution of the biggest cities is subtracted. As expected, it is linear. In fact, excluding bigger cities, Regions are composed of a big number of sources of different populations which can be considered a statistical sample.

Even if the upward emission vs. city population function depends on the local lighting conditions, our results are in agreement with relations successifully applied or measured in other countries. Bertiau et al. (1973) used successfully a linear model (exponent equal to 1) to model light pollution in Italy, and so did Walker (1970,1973) for studies of California skies. Garstang adopted both models with $b \propto P^{1.1}$ (Garstang 1986) and with $b \propto P$ (Garstang 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993) obtaining a good fit with many observations including Walker (1977) population - distance data. Walker (1977) verified for a number of California cities the assumption of linear proportionality for street light emission only, finding a general good agreement

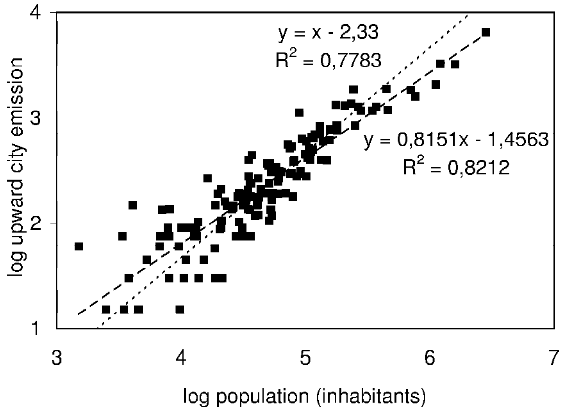

Fig. 3. Upward flux versus city population relationship for Italy in the range 1000 - 3000000 inhabitants in logarithmic scale.

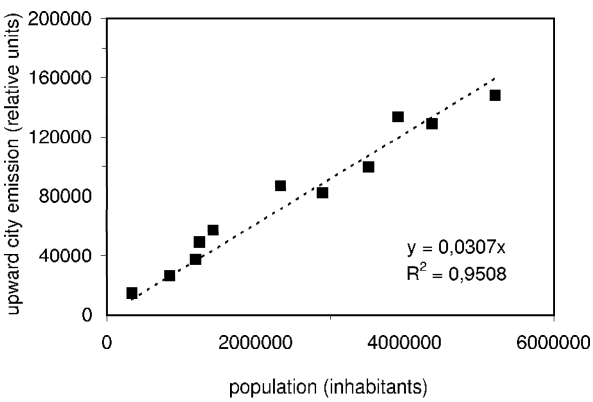

Fig. 4. Upward flux versus city population relationship for Italian Regions.

with a few departures above or below the mean depending on the industrial or residential character of the city. Walker (1977) also measured the sky illumination produced by three cities of different populations, obtaining a dependence on the power of 0.8 of their population. Berry (1976) fitted well observations of sky brightness in city centers in Ontario with a propagation law for light pollution based on the approach of Treanor (1973) but assuming $b \propto P^{0.5}$. Nevertheless Garstang's linear models fit well Berry (1976) observations suggesting that power of 0.5 found by him be produced by extinction of light emitted by outskirts of large cities in propagating to the center and does not depend on the upward flux versus population relationship (Garstang 1989a).

So far, we did not find any dependence of city upward emission on the development of the area. Cities of southern Italy have the same light output as comparable size cities of northern Italy, even if the former have an income per capita that is nearly half that of one of the latter. Bertiau et al. in the early '70 found that the city upward emission depended on its economic and commercial development, so they were forced to include in their model a development factor. There isn't any evidence in our preliminary data for the need of a similar coefficient now.

4. Light pollution mapping technique

We obtained the map of the zenith brightness of the night sky in Italy, constructing a simple model. If $b = E\ f(d)$ is a propagation law for light pollution giving the artificial sky brightness b produced at a site in (x', y') by an infinitesimal area $dS = dxdy$ with upward emission $e(x, y)$ per unit area, the total artificial sky brightness b at a site is given by:

$$b(x', y') = \int\int e(x,y) f((x-x')^2 + (y-y')^2)\ dx\ dy \qquad (1)$$

This expression is the convolution of the $e(x, y)$ with the function $f((x - x'), (y - y'))$. So our operation consists in convolving the satellite image giving the upward emission with the propagation function. The scattering from atmospheric particles and molecules of light emitted upward by the cities spreads the light far from the sources.

In pratice, we divided the surface of Italy in pixels with the same positions and dimensions as the satellite image. We assumed each area of the country defined by a pixel be a source of light pollution with an upward emission $E_{x,y}$ proportional to the measured one and we computed the sky brightness at the center of each pixel. In this case the expression (1) became:

$$b_{i,j} = \sum_h \sum_k E_{h,k} f((x_i - x_h)^2 + (y_j - y_k)^2) \qquad (2)$$

We used for $f(d)$ the Treanor law (Treanor 1973):

$$b = b_0 I_0 \left(\frac{A}{X} + \frac{B}{X^2} \right)\ e^{-kX} \qquad (3)$$

where b is the zenith artificial sky brightness and b_0 is the zenith natural sky brightness at the site considered and produced by a city with upward emission I_0 placed at a distance X. A, B and k are constants related to the scattering component, the direct beam component and the attenuation of the city light by absorption and scattering losses. All the constants were empirically determined by Bertiau et al (1973) to fit in the best way the data of the zenith luminance due to three different cities in Italy at various distances from them. In applying this law we have considered still valid the calibration of the ratio B/A and the coefficient k from Bertiau et al (1973) because these depend only on the mean conditions of the atmosphere in clear nights which we have supposed unchanged from 1973, neglecting the seasonal variations and the effects

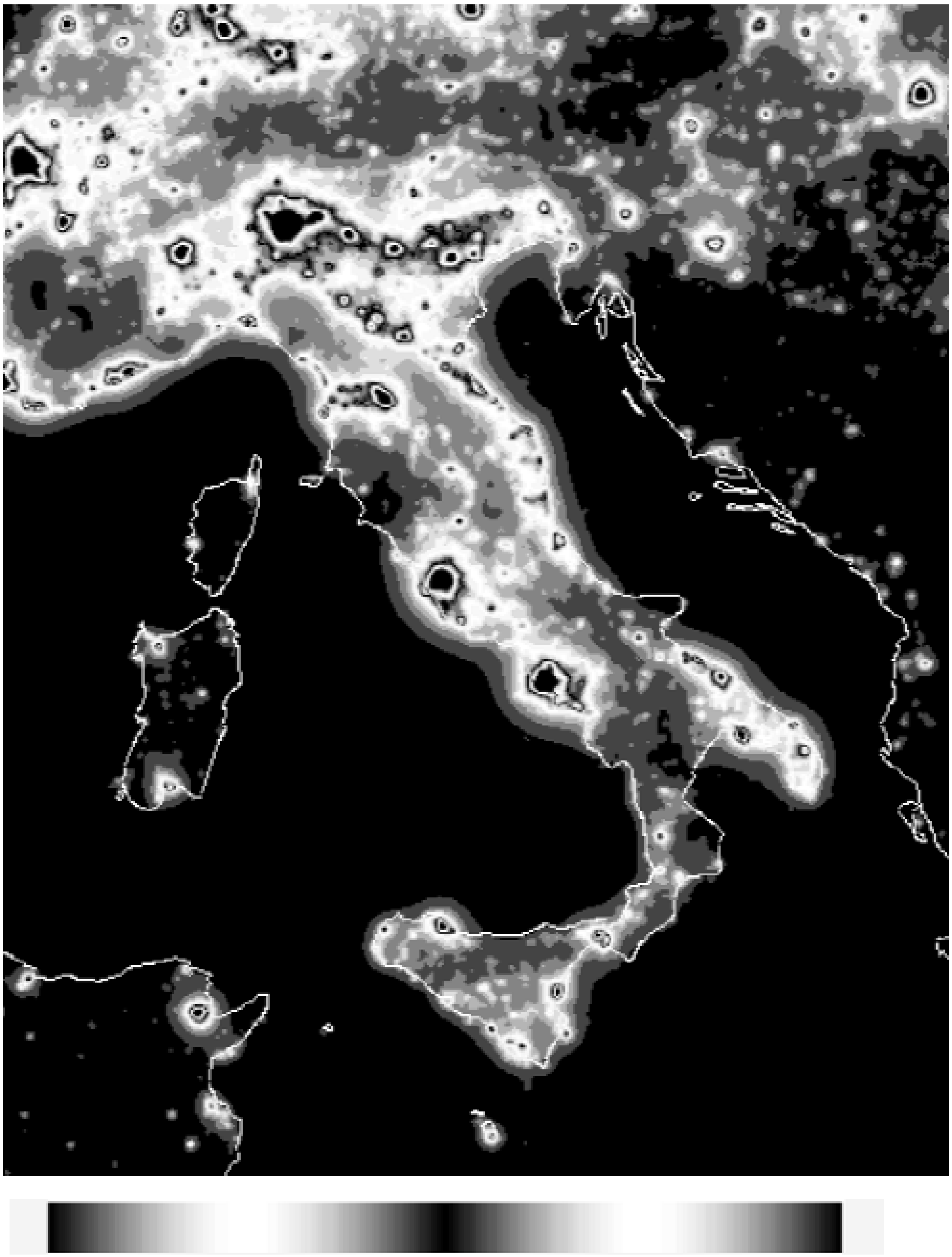

Fig. 5. Map of the artificial sky luminance in Italy. The counts from 0 to 100 are split into 25 levels displayed with a multiple gray scale (bottom) in order to better show the finest details of the luminance distribution. Greater counts are set to 100 for clearness purposes. Contours of Italy are just an indication.

of the changes in atmospheric pollution. The Treanor Law holds only for the brightness in the B band.

Using directly the upward light emission as measured in the satellite images we bypassed the possible errors due to differences in the output of cities of the same population. Using satellite images instead of the population of Italian cities we take into account also the contribution to the sky brightness produced from cities outside the Italian boundaries. This contribution was ignored by Bertiau et al. because bordering and near lands were sparsely populated mountain regions or underdeveloped countries (Albania). This approximation was far better in the early '70 than now, because of the high increase in light emission per capita since then. A source of error should be the possible presence of clouds over some cities; these clouds could hide or dim the light received by the satellite. To avoid this we searched for an image without cloud over all Italian territory. We neglected curvature of the earth in our computation. This might produce an error for isolated areas but in strongly urbanized areas it is negligible. The effect of earth curvature is about 2 percent at 50 km (Garstang 1989). In computing the sky brightness we neglected sources outside a 200 km radius from the site. This limit was chosen to exclude overestimating the contribution from far cities whose effects at 200 km are negligible due to the earth curvature. The emission coming from the same pixel for which we computed the artificial brightness was artificially taken away to 2.7 km distance. This was done because we want to compute the mean brightness in the area, not the exact brightness in a precise site which could be sensitive to the detailed distribution of nearest light sources. Moreover the Treanor Law breaks down at small distances, causing spurious high values due to the nearest sources. To get the absolute values of the brightness all over Italy we need to calibrate the map with the measured brightness of the sky in some sites. The sites should be far from bright emission sources, in order to fulfil the law used.

5. Results

The map of artificial light pollution in Italy expressed with linear scale (artificial luminance) is in figure 5. We also present in figure 6 the map of artificial light pollution in Italy expressed with magnitude scale (total sky brightness) as Garstang (1986):

$$m_{i,j} = 12.603 - 2.5\ log(b_{i,j} + b_{nat}) \tag{4}$$

where m is in V band, b is in cd/m^2 and the natural sky brightness for minimum solar activity is $b_{nat} = 200\mu cd/m^2$ (Smith 1979). Differences with Bertiau et al. (1973) due to the increase of upward emission from time and to population changes are under study (Falchi 1998). In figure 7 is shown a map of upward light emission as obtained directly from the satellite image. An enlargement of figure 5 is presented in figure 9. All the maps have been obtained from the low gain image. We are working to obtain a composite image including high gain images in order to have better sensivity to minor sources.

Satellite images are not calibrated so our upward flux measurements are only relative.

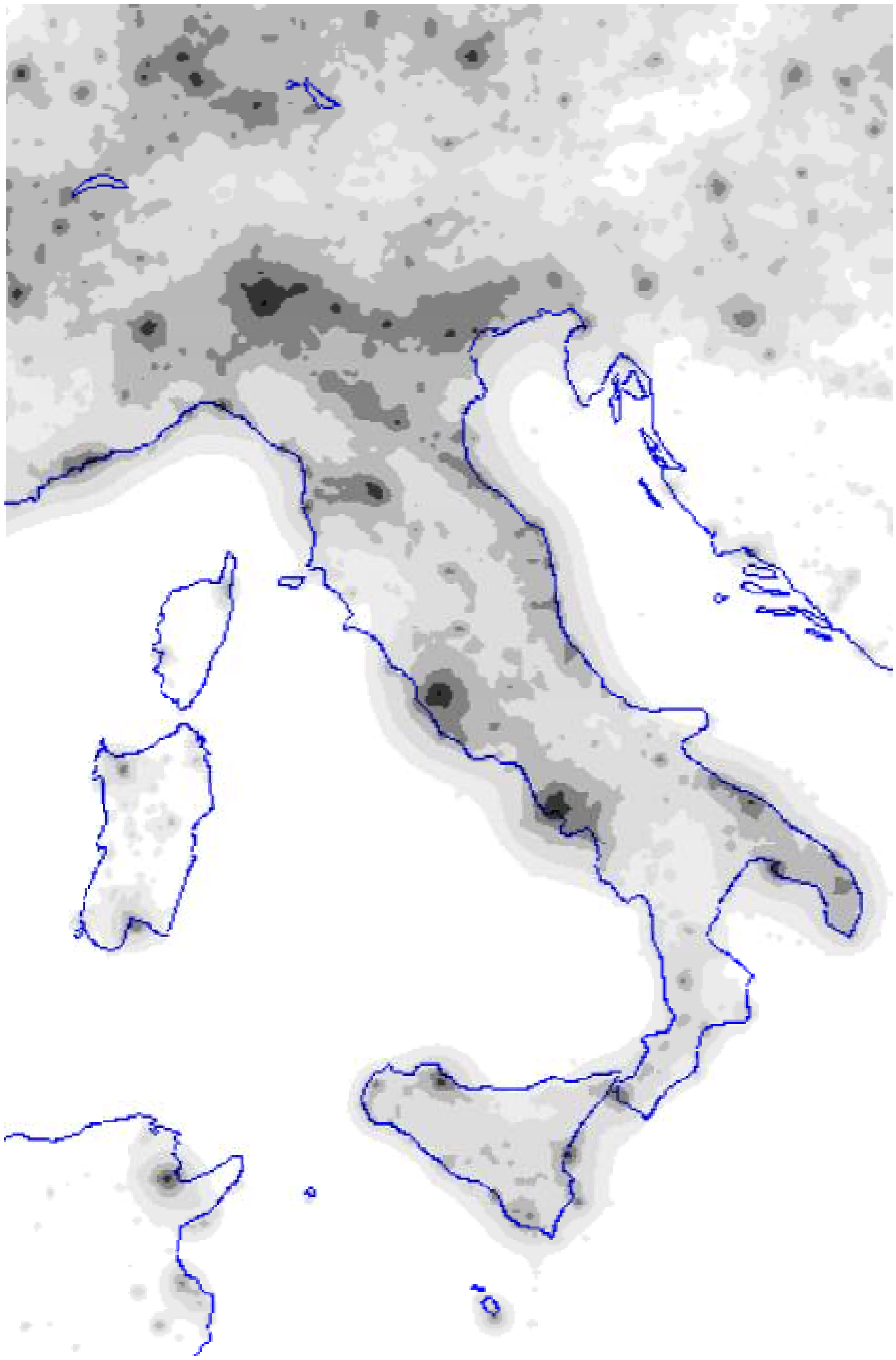

Fig. 6. Map of the sky brightness in Italy. The seven gray levels of the image correspond tentatively for 1998 to levels of <0.5, 0.5-1.1, 1.1-1.8, 1.8-2.7, 2.7-3.6, 3.6-4.6, >4.6 $mag/arcsec^2$ over the natural sky brightness. Contours of Italy are only an indication.

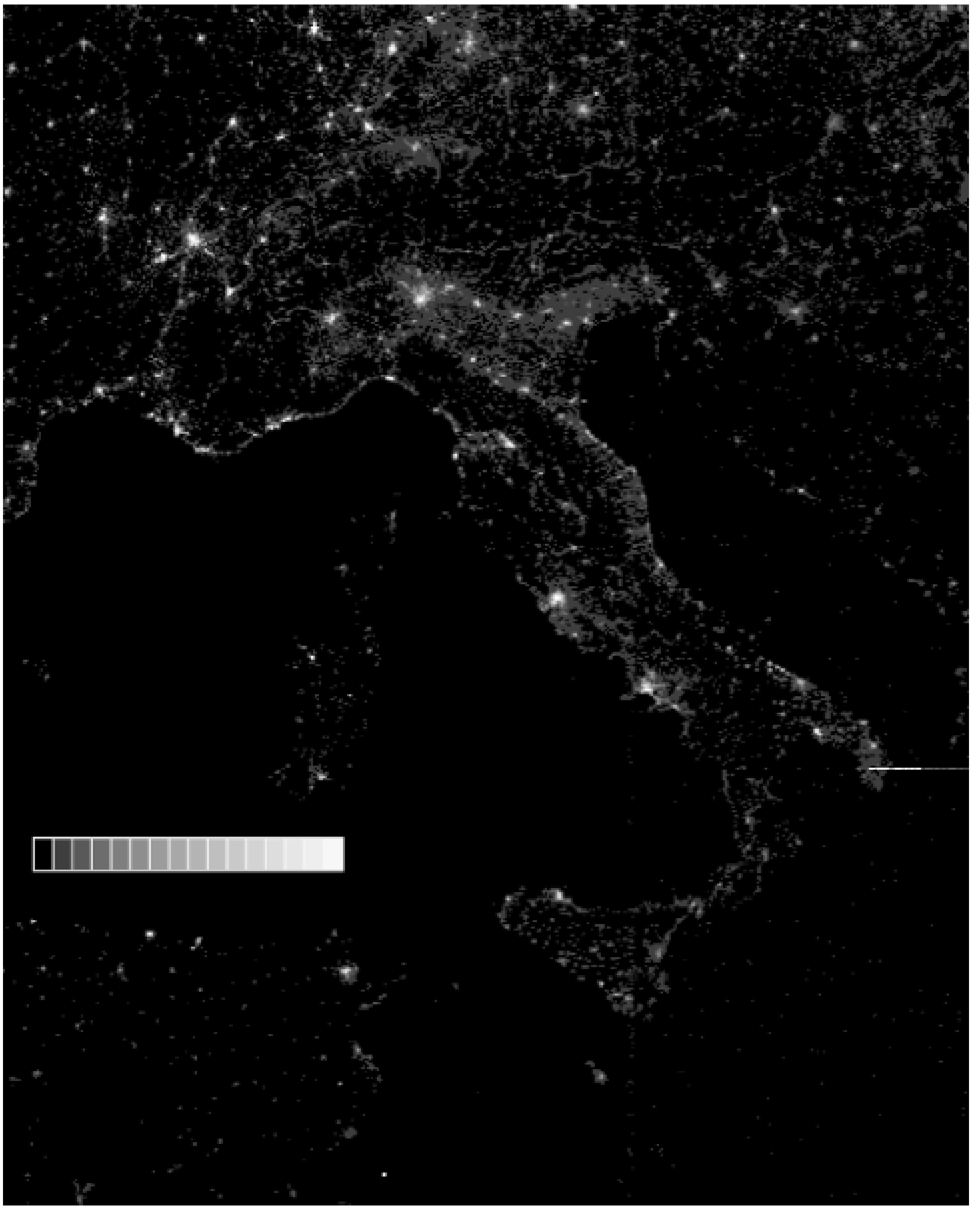

Fig. 7. Map of the upward light flux in Italy. Counts go from 0 to 171 in 16 gray levels.

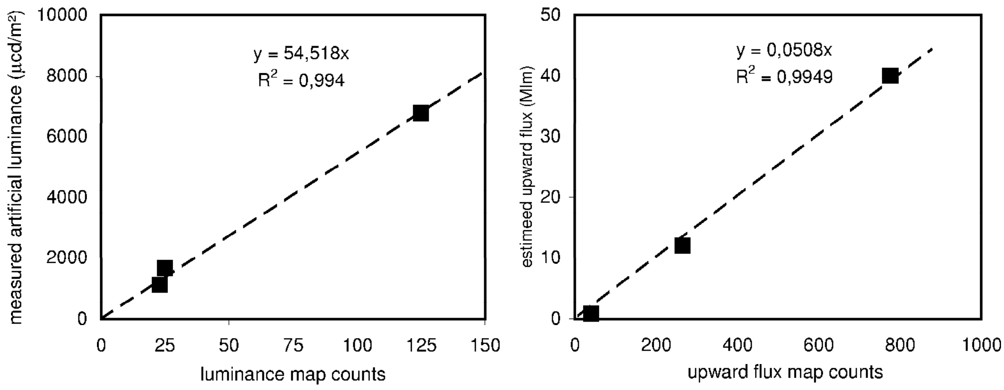

Fig. 8. Comparisons between maps and available data.

The results of the specific measurement campaign started to calibrate the sky brightness and sky luminance maps are not yet available at the time of this paper, so we tried a preliminary calibration comparing our results with available measurements of sky brightness. Given the growth of light pollution with time (Cinzano 1999a), we used only measurements taken in the last year. After transforming the measurements into luminances we subtracted the natural sky luminance (see Cinzano 1999b). The comparison is presented in figure 8 (left). Data refers respectively to Mount Ekar (taken in 1994 and scaled to 1998 as Cinzano 1999a), Collurania (Piersimoni et al. 1999), Padova (from Favero et al. (1999) scaling Padova to 2.7 km from the site with the Walker Law).

We also tried a comparison of our upward flux map with available data of upward flux. Results are shown in figure 8 (right). Data refers respectively to Asiago, Treviso (from Medusa 1999, assuming public lighting 60% of total), Padova (Favero et al. 1999). We excluded available data from the city of Torino because it has saturated pixels in all our images. At the moment the resulting calibrations have to be considered highly unconfirmed.

6. Conclusions

We obtained the maps of the zenith artificial sky luminance and zenith total sky brightness of the night sky in Italy convolving with a light pollution propagation function the upward light emission from each unitary area as measured in DMSP satellite night-time visible band images chosen for their negligible number of saturated pixels and for the cloudfree Italy. We are working to extend our mapping to other European countries. Figure 10 shows a preliminary map obtained from the high gain image of 1993. Densely populated cities in this image have saturated pixels so the map is less accurate near major cities than the other maps but it could be more accurate in less populated areas. Better results will be presented in a forthcoming paper.

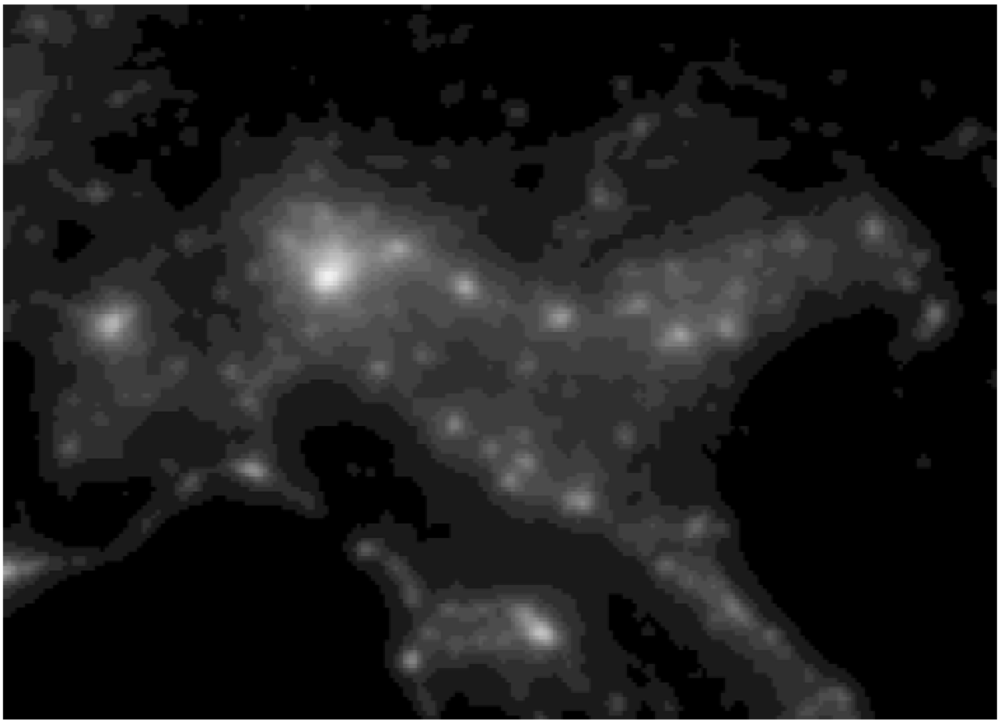

Fig. 9. Artificial sky luminance in North Italy. Enlargement of the map in Figure 5. Counts from 0 to 100 are displayed in 25 levels with a linear gray scale. Greater counts are set to 100 for clarity.

We also studied the emission versus population relationship comparing relative emission of a number of cities of various populations. The measured emission increases quite linearly with the city population in the range from 1000 to 400000 inhabitants. More populated cities seems to have a lower emission per inhabitant, so that in the range from 1000 to 3000000 inhabitants the best fitting curve to the measured emission seems to be a power law with the power 0.8 of the city population. At this stage we cannot confirm this relation. So far we did not find any dependence of city upward emission on the economic development of the area.

A better calibration obtained after a specific sky brightness measurement campaign and a comparison with the map of Bertiau et al. (1973) showing the changes in sky brightness from 1973 to 1997 will be presented soon.

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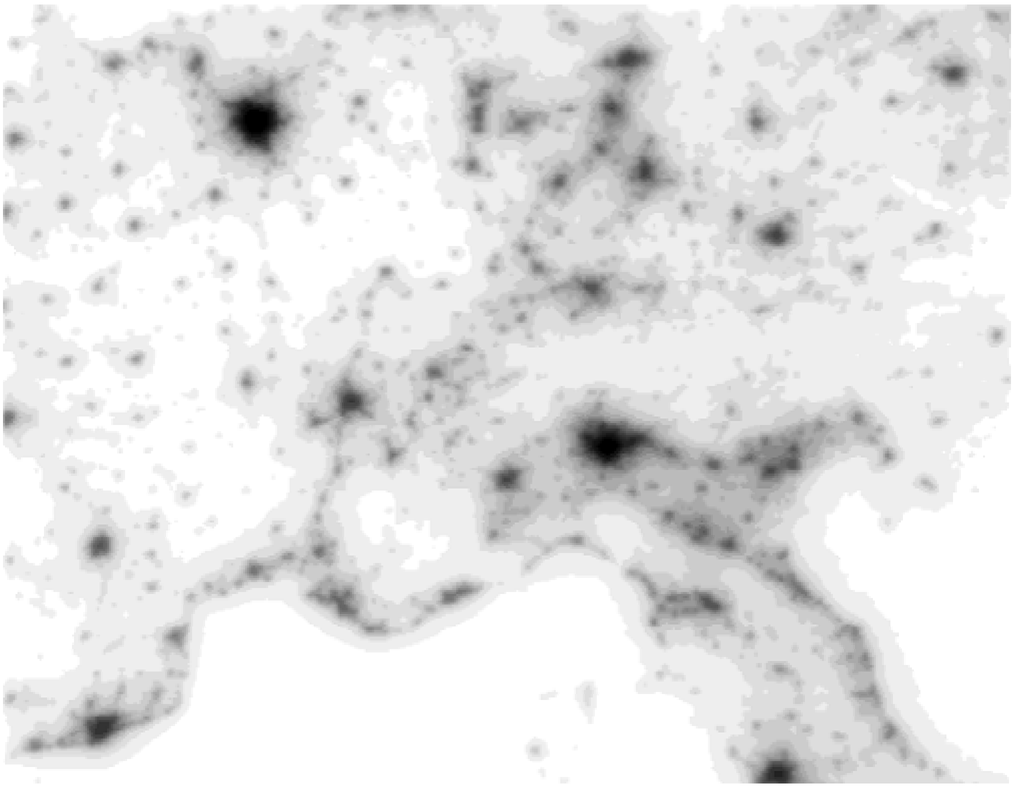

Fig. 10. Preliminary map of artificial sky luminance in parts of the European countries from an high gain satellite image. Due to saturation of more populated city this map is usefull only for a qualitative evaluation. The 16 gray levels are equispaced but the scale is not calibrated.

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References

Albers S. 1998, http://laps.fsl.noaa.gov/albers/slides/ast/places.html

Berry, R. 1976, J. Royal Astron. Soc. Canada, 70, 97-115.

Bertiau, F.C.S.J., de Graeve, E.S.J. & Treanor, P.J.S.J. 1973, Vatican Observatory Publ., 1, 4, 159-179.

Cinzano, P. 1997, Inquinamento luminoso e protezione del cielo notturno (Venezia: Istituto Veneto di Scienze, Lettere ed Arti), 224 pp.

Cinzano 1999a, in this volume.

Cinzano 1999b, in this volume.

Di Sora, M. 1991, Boll. Soc. Astron. It., 2, 12-14.

Di Sora, M. 1993, Mem. Soc. Astron. It., 64, 173-177.

Elvidge, C.D., Baugh, K.E., Kihn, E.A., Kroehl, H.W., Davis, E.R. 1997, Photogrammetric Engineering and Remote Sensing, 63, 727-734.

Falchi, F. 1999, Thesis, in prep.

Favero, G., Federici, A., Blanco, A.R., Stagni, R. 1999, in this volume.

Garstang, R.H. 1986, Publ. Astron. Soc. Pacific, 98, 364-375.

Garstang, R.H. 1987, in Identification, optimization and protection of optical observatory sites, eds. R.L. Millis, O.G. Franz, H.D. Ables & C.C. Dahn (Flagstaff: Lowell Observatory), p. 199-202.

Garstang, R.H. 1988, The Observatory, 108, 159-161.

Garstang, R.H. 1989a, Publ. Astron. Soc. Pacific, 101, 306-329.

Garstang, R.H. 1989b, Ann. Rev. Astron. Astrophys., 27, 19-40.

Garstang, R.H. 1989c, Bull. of American Astron. Soc., 21, 2, 759-760.

Garstang, R.H. 1991a, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conference Series 17, p. 56-69.

Garstang, R.H. 1991b, Publ. Astron. Soc. Pacific, 103, 1109-1116.

Garstang, R.H. 1991c, The Observatory, 111, 239-243.

Garstang, R.H. 1992, Bull. of American Astron. Soc., 24, 740.

Garstang, R.H. 1993, Bull. of American Astron. Soc., 25, 1306.

Isobe, S. 1993, Measurement of energy loss through world light distribution at night, preprint.

Isobe S. & Hamamura, S. 1998, in Preserving the Astronomical Windows, IAU JD5, ed. S. Isobe, Astron. Soc. of Pacific Conference Series 139, p. 191-199.

Medusa, C. 1998, Thesis, University of Padova (advisor L. Fellin, co-advisor P. Cinzano).

Piersimoni, A., Di Paolantonio, A., Brocato, E. 1999, in this volume.

Smith, F.G. 1979, Reports on Astronomy, IAU Trans., XVIIA, 218-222.

Sullivan, W.T., 1989, Intl. J. of remote sensing, 10, 1-5.

Sullivan, W.T. 1991, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conference Series 17, p.11-17.

Treanor, P.J.S.J. 1973, The Observatory, 93, 117-120.

Treanor, P.J.S.J. 1974, in Rapporto OAN n.3, Padova.

Walker, M.F. 1970, Publ. Astron. Soc. Pacific, 82, 672-698.

Walker, M.F. 1973, Publ. Astron. Soc. Pacific, 85, 508-519.

Walker, M.F. 1977, Publ. Astron. Soc. Pacific, 89, 405-409.

THE SITUATION OF LIGHT POLLUTION IN GERMANY

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ABSTRACT. We estimate the increase of light pollution in Osnabrück, a town of about 160.000 inhabitants located in northwestern Germany. We try to extrapolate these statistical data to Germany and discuss the reasons for increasing light pollution though the energy consumption nearly stagnates. While the climate in central Europe is not favourable for astronomical research observations in the optical region, the general public looses the unhindered sight of the starry sky. Therefore we present some activities to make the public aware of the problem (e.g. the Astronomy-Online light pollution project) and strategies for reducing artificial night lights.

1. Introduction

The central European climate is not ideal for serious astronomical observations. Though many of the old established astronomical institutes are situated in this region, modern observing facilities are built at places with more favourable climate and less light pollution. Nevertheless astronomical observatories in Germany are used for educating students, testing new equipment and some astronomical research, e.g. at Hamburg-Bergedorf, Potsdam, Bonn, Jena, Heidelberg and Munich. Some observatories are quite far away from disturbing light sources like Wendelstein (Munich), Tautenburg or Hoher List (Bonn) or have arranged reduction of light locally. However thousands of amateur astronomers and millions of other people still have to struggle with light pollution. The experience of planetarians shows that many of their visitors are excited when they see the undisturbed milky way in the planetarium, which might lead to the conclusion that they have not seen it from an unpolluted site before. So the provocative question: Are we on the way to preserve the aspect of the night sky in the planetarium just as we show extinct animals and plants in a natural science museum? Therefore we try to study the increase of light pollution and to find the reasons for this. In addition we discuss projects to make the public sensitive to the problem.

2. Estimating the increase of light pollution in Germany

The best method to measure the increase of light pollution would be measurements of the brightness of sky background. However, these are rare at Germany, even at professional observatories. An indirect method would be the monitoring of the limiting magnitude. As far as we know there exists only a long row of observations from an engaged observer of variable stars in Stuttgart, who observed an increase of the limiting magnitude from

5.6 mag in 1958 to 5.2 mag in 1971 (Marx, 1972), since then the limiting magnitude has increased by about 0.1 to 0.2 mag (Marx, private communication, 1997).
We use another approach: There are many sources that contribute to light pollution, mainly artificial light that is scattered in the atmosphere:

- direct and indirect lights for advertising seem to play a minor role in Germany, because these are restricted, mainly for traffic security reasons. However during the last years sky beamers used mainly by discotheques are increasingly disturbing. These are powerful moving spotlights that sometimes are visible over dozens of kilometers. In several cases even animals (mainly birds, but perhaps also amphibians) have been threatened by these lights.

- direct and indirect lights from private households, e.g. illuminated windows, unshielded garden lighting, continously shining security lights.

- street lighting seems to be the most important contribution, though estimates differ between 14 % (cited by Schreuder, 1991) to 50 % (Shaflik, 1997). In this context the predictions for the increase of outdoor public lighting are especially alarming (Riegel, 1973, Sullivan, 1984). This is much faster than the increase in electricity consumption because more efficient light sources are progressively used. Riegel (1973) estimated that the number ratio of vapor/incandescent lamps in 1960 was about 0.1, in 1970 1.2, afterwards increasing annually by 6 to 10 %. As there was a trend to more efficient high-pressure sodium lamps, the luminous flux increased by 23 % annually between 1967 and 1970.

We want to check if these predictions are also valid for Germany. As it was not possible to get informations about street lighting in the whole country, we have choosen the following way. We compare the relative increase of the public electricity consumption in Osnabrück (Stadtwerke Osnabrück, priv. comm.), Germany and the United States (Bundesministerium für Wirtschaft, 1996) with the values of 1950 (fig. 1). These data have to be judged with caution: electricity consumption in Osnabrück has increased faster because new suburbs are provided with energy. The reunification of Germany changed the electricity consumption in Germany since 1990 significantly. The faster increase in Germany than in the U.S.A. during the sixties might be due to deficits in Germany at that time. The data from Osnabrück and other statistical data show, that street lighting consumes about 1 % of the total electricity (2.8 10^9 kWh in 1989, alte Länder in western Germany). In the future most lamps used for lighting principal roads will be high pressure sodium lamps. Though low pressure sodium lamps would be more desirable because of their yellow emission lines and higher efficacy, these lamps have difficulties in acceptance due to their bad colour balance. In residential quarters fluorescent lamps will mainly be used, because of their better colour balance and low cost. This mix will result in an efficacy of about 100 lm/W. In figure 1 we have included the increase of night light in the US as given by Sullivan (1984). We compare this to values in Germany with a rough estimate of increasing light efficacies from about 40 lm/W in 1950 to about 90 lm/W in 1990. From this we see, that light pollution from street lighting increases, but less pronounced as the predictions by Riegel (1973), because

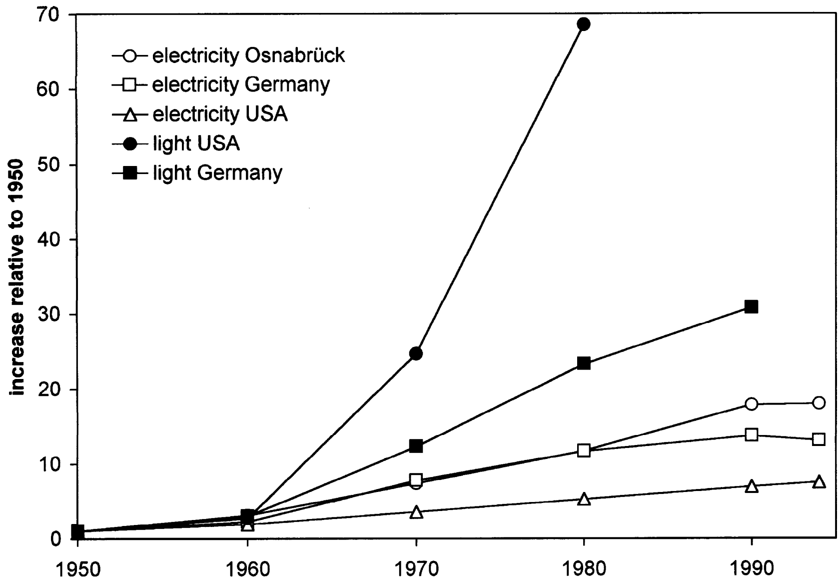

Fig. 1. Annual electricity consumption in U.S.A., Germany and Osnabrück and estimation of the emitted light in the U.S.A. and Germany, normalized to 1950 = 1

energy efficient illumination (mainly fluorescent lamps) has been used in Germany quite early.

For Osnabrück we knew the number of street lamps and the electricity consumption as provided by the local energy company (fig. 2). The number of lamps is steadily increasing, while the power supply and the consumption remain more or less constant. Assuming that during the time interval shown in the graph, the efficacy of the lamps has increased from 80 lm/W (corresponding to a mixture of 50% fluorescent lamps, 40% mercury vapour lamps and 5% sodium lamps) to 100 lm/W (50%:25%:25%), this corresponds nearly to the increase of number of luminaires of about 20%. The reason for this are new residential quarters and the quest for pretended more security through more light. To propagate the reduction of light pollution is the aim of the working group "DARK SKY", which has been formed by some amateur astronomers as a section of the national amateur association *Vereinigung der Sternfreunde*.

3. Aims for reducing light pollution in Germany

The main aim must be the information of the general public, because they are not aware of the problem and ask for more light because they suppose that this gives more security. This is done by information sheets, press releases and talks. This publicity helped to reach some success against the sky beamers. In several cities these have been prohibited, but in others they are still in use. It would be desirable that these light sources become prohibited in general.

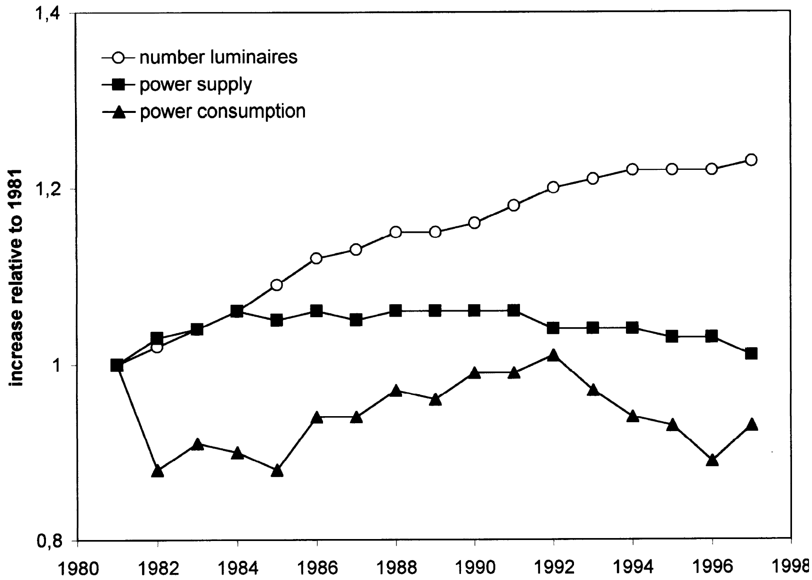

Fig. 2. Number of luminaires, power supply and annually consumed electric energy for illumination in Osnabrück, normalized to 1981 = 1

Most street lighting on main roads is well shielded against the sky. Minimal luminance levels of streets depending on type of street, width and traffic frequency are recommended in norms (Deutsche Industrie-Normen DIN 5044) and these lie between 0.3 and 2 cd/m^2. As traffic frequency reduces during night, the light of some streets is reduced by switching off every second lamp. However, this should be used on more streets. In addition, a trend towards low-pressure sodium lamps instead of high-pressure sodium lamps would also be desirable. Investigations by the Naturschutzbund Deutschland (Schanowski and Späth, 1994) showed that high-pressure mercury lamps attracted and often killed about 4 times more insects than the sodium lamps. Some of the DIN norms are however questionable: why a principal road with identical traffic and passenger frequency within and outside of the limits of a city must be brightly illuminated within these limits and not at all outside? In town centres and in residential areas often badly shielded luminaires are used, where fully shielded luminaires should be preferred. Another aim should be to sensitize the more interested public and especially the youth, which has been tried with the following project.

4. The Astronomy On-Line Project on light pollution

In 1996 the *European Southern Observatory (ESO)* and the *European Association for Astronomy Education (EAAE)* organized the Astronomy On-Line Project to demonstrate the use and advantage of the internet to young people (West and Madsen, 1997). We proposed to measure light pollution in Europe using a simple method to determine the limiting magnitude in the constellation Ursa Minor. The British Sky Glow and the American Star Watch project had inspired us. We wrote a HTML web page with a sky chart that helped to find UMi during the peak phase in November. Another chart gave magnitudes for some stars in UMi to determine the limiting magnitude, which could be reported in a web form. Due to extremely bad weather conditions during the peak phase in Europe only 25 reports mainly from the southern parts of the continent have been received. The limiting magnitude within one city varied considerably, an interesting discovery that pupils in a larger Spanish city and the Bulgarian capital made. The observations together with a weather picture have been posted on the web. Unfortunately more conclusions from the scarce material could not be drawn and it can be hoped that some actual projects in Catalonia and Greece give as interesting results as the Sky Glow project.

5. Outlook

Hunter and Crawford (1991) estimated that in 1985 58 10^9 kWh electric energy have been used for nighttime lighting in the U.S.A., of which about 15 % have been wasted towards the sky due to bad shielding. This corresponds to costs of about US$ 644,000,000. We have compared theses values to similar values for Germany and the city of Osnabrück and compiled them in table 1. Some of these values differ significantly especially between the US and Germany. For Germany and Osnabrück we assumed the same waste to the sky. The amount of the emitted CO_2 depends on the mix of the energy sources for producing the electricity. We used a conversion factor of 1 t CO_2 = 1160 kWh for Osnabrück (Umweltamt, 199?) and 1800 kWh for Germany and assumed the same value for the U.S.. Though the consumption of CO_2 for night lighting is small compared to other human sources of the greenhouse gas, it is an amount that can easily be reduced without losing much comfort. At the 1992 United Nations Conference on Environment and Development in Rio de Janeiro, most industrial nations agreed to reduce their CO_2 production to facilitate a sustainable development in future. This shall be reached with the Agenda 21 action programme. Within this framework the useless waste of nighttime light must be reduced to conserve an unspoiled dark nightsky as far as possible in our modern civilization.

Tab. 1 - Comparison data for the energy of night lighting

annual data	USA (1985)	Germany (1989)	Osnabrück (1989)
total energy consumption kWh	$2.3\ 10^{12}$	$3.9\ 10^{11}$	$7.4\ 10^{8}$
electricity for nightlight kWh	$5.8\ 10^{10}$	$2.8\ 10^{9}$	$8\ 10^{6}$
population	$2.5\ 10^{8}$	$6.2\ 10^{7}$	$1.6\ 10^{5}$
CO_2 t (see text)	$4\ 10^{7}$	$1.5\ 10^{6}$	$7\ 10^{3}$
electricity for nightlight/person kWh	232	45	50
costs US$ (1 US$ = 1.80 DM)	$4.3\ 10^{9}$	$6\ 10^{8}$	$7\ 10^{5}$
15 % wasted US$	$6.4\ 10^{8}$	$9\ 10^{7}$	$1\ 10^{5}$

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References

Bundesministerium für Wirtschaft: 1996, Energie Daten '96 (and earlier years)
Hunter, T., Crawford, D.: 1991 in *Light Pollution, Radio Interference, and Space Debris*, D.L. Crawford ed., Astr. Soc. Pac. Conf. Ser. 17, p. 89
Marx, H.: 1972, in *50 Jahre Volkssternwarte Stuttgart*, Verein Schwäbische Sternwarte ed., p. 41.
Riegel, K.: 1973, Science 179, 1285.
Schanowski, A., Späth, V.: 1994, Überbelichtet, Naturschutzbund Deutschland (NABU), Kornwestheim.
Schreuder, D.: 1991 in *Light Pollution, Radio Interference, and Space Debris*, D.L. Crawford ed., Astr. Soc. Pac. Conf. Ser. 17, p. 25
Shaflik, C.: 1997, Information sheet 125, International Dark-Sky Association, Tucson
Sullivan, W.: 1984, Sky & Telescope 67, 412
Umweltamt der Stadt Osnabrück: 199?, Betrifft CO_2
West, R., Madsen, C.: 1997, The Messenger 87, 51

THE GROWTH OF LIGHT POLLUTION IN NORTH-EASTERN ITALY FROM 1960 TO 1995

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ABSTRACT. I studied the growth rate of light pollution in the Veneto plain (Italy) analyzing archive measurements of sky brightness obtained in V, B and R bands at the Ekar Astronomical Observatory and at the Asiago Astronomical Observatory in the period 1960-1995. The light pollution in the last 35 years has increased exponentially. Assuming a constant annual increase from 1960 to 1995, the mean annual increase results of 10 percent per year. In the period 1990-1996 at the Observatory sites the strong increase of the artificial sky brightness was hidden by the decrease of the natural sky brightness due to the decrease of airglow emission produced by the sun activity going to its minimum but in the next 5 years the artificial sky brightness and the increasing airglow emission will sum producing a rapid growth of the sky brightness.

1. Introduction

The most worrying feature of light pollution is that it is rapidly growing because of its dependence on the increase of external night lighting. Nor does this tendency to increase spare astronomical sites of world interest (Garstang 1991). Monitoring of sky glow shows that an efficient limitation requires the best decoupling between the two growth rates (e.g. Hoag et al. 1973). In Italy so far no systematic measurement of sky brightness growth or upward flux growth in large areas has been carried on.

I studied the growth rate of light pollution in the Veneto plain (Italy) in the period 1960-1995 analyzing archive measurements of sky brightness obtained in V, B and R bands at two Observatory sites where the artificial sky brightness near the zenith on clear nights is due mostly to light pollution coming from more than 1200 sources in the nearby plain. I disentangled the contribution from airglow variations due to the solar activity cycle. In section 2 I describe and discuss the measurement analysis and in section 3 I present the results. My conclusions are in section 4.

2. Sky brightness measurements and their analysis

I collected the archive photometric measurements of sky brightness in B, V and R bands near the zenith at Mount Ekar Astronomical Observatory (thereafter site E) and Asiago Astrophysical Observatory (thereafter site A) obtained by many authors in the period 1960 - 1995 (see tab. 1). I corrected the measurements for the extinction of the standard stars in order to take them “under the atmosphere” (Kalinowski et al. 1975), assuming a mean extinction at one air mass of 0.25 mag in V, 0.5 mag in B and 0.1 mag in R. Then I computed in the two sites the growth curve of the ratio

$$(b_{tot} - b_0)/b_0 = (10^{-0.4(m_{tot}-m_0)}) - 1 \tag{1}$$

where m_0 is the natural sky brightness in the same photometric band. I assumed, quite conservatively, that near the zenith and for mean solar activity the natural sky brightness is 21.60 mag in V band, 22.40 mag in B band and 20.5 mag in R band. In a first approximation the ratio $(b_{tot} - b_0)/b_0$ corresponds to the ratio b_{art}/b_0 between the artificial sky brightness b_{art} and the average natural sky brightness b_0 or between the artificial sky photon radiance and the average natural sky photon radiance in that photometric band. In the case of measurements in V band it also correspond to the ratio between the artificial sky luminance and the average natural sky luminance.

Among the main error sources in the ratio b_{art}/b_0 there are the variations in the natural sky brightness m_0 depending on the solar cycle phase and due to the airglow emission. So I corrected the measurement of $(b_{tot} - b_0)/b_0$ assuming that the natural sky brightness increases or decreases depending on the solar cycle phase (Walker 1988; Cannon 1987 in Krisciunas et al. 1987) with:

$$\Delta m = -2.5 log_{10} \frac{b_{nat}}{b_0} = -0.5 \cos 2\pi \left(\frac{t - 1957.5}{11.} \right) \tag{2}$$

With this espression I corrected the eq.(1) obtaining:

$$b_{art}/b_0 \approx b_{tot}/b_0 - b_{nat}/b_0 = (10^{-0.4(m_{tot}-m_0)}) - 10^{0.2 \cos 2\pi \left(\frac{t-1957.5}{11.} \right)} \tag{3}$$

Other sources of errors for the ratio b_{art}/b_0 came from the difficulties in making an accurate estimate of the extinction and the impossibility of taking into account the changes in zodiacal light, galactic light and integrated stars light contributions, depending on the celestial coordinates of the observation point, and the decay of the airglow contribution connected to the number of hours past twilight. Nevertheless these contributions are little for the considered measurements given the high value of the artificial brightness. I computed the errorbars on the ratio b_{art}/b_0 produced by an error of ± 0.2 mag in Δm. This might be a good estimate of the incertitude in both the estinction correction and the natural sky brightness value.

3. Results for the period 1960-1995

Figure 1 shows the ratio b_{art}/b_0 between the artificial sky brightness and the natural reference brightness in V band(circles), B band (squares) and R band(triangles) obtained with eq.(1) for site A (filled symbols) and site E (open symbols). Figure 1 shows an exponential increase of the artificial sky brightness in the last 35 years. Results for B, V and R band measurements are quite similar. Scatter of values for b_{art}/b_0 arises because, as explained, the natural sky brightness oscillates around the assumed reference value m_0 because of the dependence of the airglow emission in the high atmosphere on

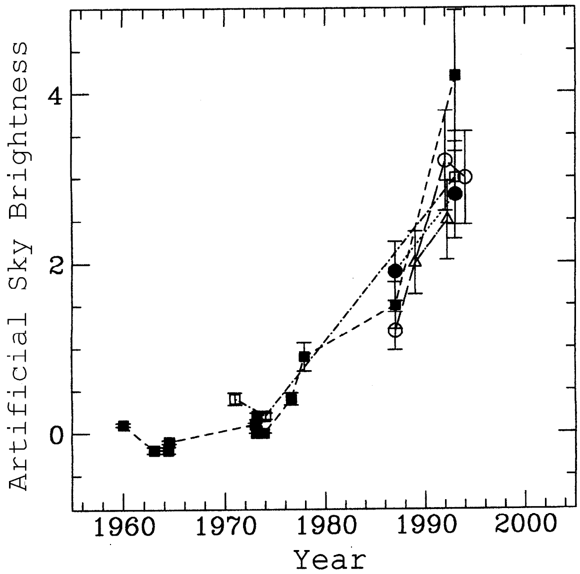

Fig. 1. The ratio between the artificial sky brightness and the natural reference brightness in V band (circles), B band (squares) and R band (triangles) for site A (filled symbols) and for site E (open symbols).

the solar activity cycle. I stress that I chose the reference natural sky brightness very conservatively so it is possible that in periods of mean solar activity it may even be lower than 0.2-0.4 mag, so the ratio between artificial brightness and natural brightness might be greater than the ratio b_{art}/b_0 even of 20-45%.

I also computed the ratio b_{art}/b_0 between the artificial sky brightness and the natural reference sky brightness in the same band corrected for the solar activity cycle with the eq. (3). Differences in the growth of the ratio b_{art}/b_0 with time between photometric bands are little so it also expresses the ratio between the artificial sky luminance and the natural reference sky luminance. Figure 2 shows its behaviour. The increase with time is well expressed by:

$$\frac{b_{art}}{b_0} = \left(\frac{b_{art}}{b_0}\right)_{t_0} (1 + x/100)^{t-t_0} \tag{4}$$

where $t_0 = 1955$, $(\frac{b_{art}}{b_0})_{t_0} \approx 0.075$ and $x \approx 10$ (dotted curve). This implies that the artificial sky luminance increases with a quite constant annual growth rate which amounts to about 10 percent per year. Given that the sources of the artificial sky luminance at the two Observatories are mainly located on the nearby plain (see Cinzano 1999) and they are a large number (more than 1200 towns inside a radius of 120 km), the annual increase is almost independent from the site and is likely roughly the same in all the venetian plain.

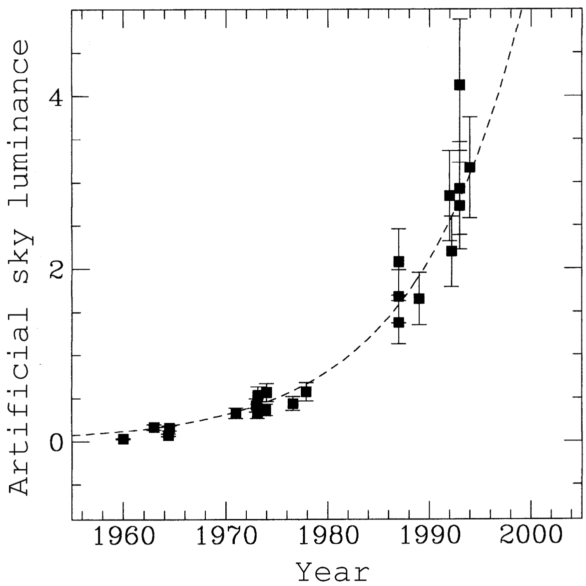

Fig. 2. The ratio between the artificial sky luminance and the natural reference luminance in both sites corrected for the solar activity.

An increase of 10 percent yearly is plausible. An analysis of the increase of compsumption of energy for external public lighting shows an annual growth rate of the order of 4.6 - 5 percent per year. Usually new fixtures use more efficient lamps than the average of the installed light park. The average efficiency in cities' lighting park increased from about 15 lm/w in the '60 to about 60-70 lm/w around 1995, which means an average annual growth rate of another 5 percent per year. Even if depending on local economic conditions, this result seems in agreement with the growth of light pollution measured in other countries. Walker (1973) presented photometric evidence that the night sky brightness in V and B bands in direction of San Jose had increased by about 5 percent per year between 1948 and 1972 and 6.2 percent per year between 1965 and 1978 (Walker 1991). Hoag et al. (1973) showed that the sky over Tucson brightened by 10-15 percent per year before the ordinance of 1972. Pike reported qualitative estimates by many observers in Southern Ontario suggesting an increase of 7 - 10 percent per year. Satellite measurements of upward emission from some cities in Japan (Isobe 1993; Isobe & Hamamura 1999) give a growth rate of about 12% per year.

In order to check the effects of solar activity on the measurements, I also plotted in figure 3 all the measurements of sky brightness in $mag/arcsec^2$, reduced to the V band from b_{art}/b_0, together with the prediction obtained from eq.(4) (continuum curve) and the prediction corrected for the effects of the solar activity on the airglow (dotted curve)

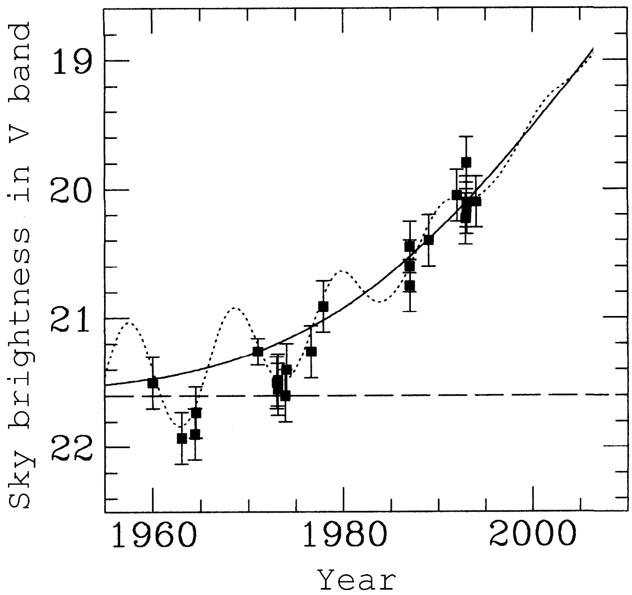

Fig. 3. All the measurements reduced to the V band (in $mag/arcsec^2$), together with the prediction obtained from (4) (continuum curve) and the prediction corrected for the effects of the solar activity (dotted curve).

assuming that the natural sky brightness depends on the solar phase by eq.(2):

$$m_{tot} = -2.5 log_{10} \left(\frac{b_{art}}{b_0} + \frac{b_{nat}}{b_0} \right) + m_0 \qquad (5)$$

The corrected prediction fits quite well the measurements. Note that the decrease in the natural sky brightness in the period 1990-1995, connected to the decrease of solar activity, hid in our measurements the strong increase in artificial sky brightness. In the next 6 years the two effects will sum producing a rapid increase of the sky brightness that will be measured at the two sites.

4. Conclusions

I studied the growth rate of light pollution in the Veneto plain (Italy) in the period 1960-1995 analyzing archive measurements of sky brightness obtained in V, B and R bands at two Observatory sites where the artificial sky brightness near the zenith on clear nights is due mostly to light pollution coming from more than 1200 sources in the plain. My conclusions are:

1. The light pollution from Veneto plain increases about 10 percent per year.
2. Differences on results for B, V and R bands are under measurement incertitudes, due to natural sky brightness subtraction.

3. The effects of solar activity on the measurements are non negligible. The prediction corrected assuming that the natural sky brightness depends on the solar phase with a simple cosine law fits quite well the measurements.
4. The decrease of the natural sky brightness in the period 1990-1995, connected to the decrease of solar activity, hid in our measurements the strong increase of the artificial sky brightness. In the next 6 years the two effects will sum producing a rapid increase of the sky brightness that will be measured at the two sites.

Levels of sky brightness measured at the two sites are a lower limit to the levels inside the plain. So we can conclude that after about '80 the finest details of the Milky Way were surely invisible from the plain. Today it is likely that the Milky Way cannot be observed other than near the zenith from everywhere in the plain, if it is visible at all.

Acknowledgements

I am indebted to Roy Garstang of JILA-University of Colorado and Sergio Ortolani of University of Padova for their kindness in reading and refereeing this paper, for their helpful suggestions and for interesting discussions.

TABLE I
Sky brightness measurements.

Year	Band	m_{obs}	m_{corr}	$\frac{b_{tot}}{b_0}$	$\frac{b_{art}}{b_0}$	m^*_{tot}	Site	Sources
1960	B	21.8	22.30	1.10	0.1	21.50	A	Capaccioli, priv. comm.
1963	B	22.13	22.63	0.81	-0.2	21.93	A	Bertola (1966)
1964.4	B	22.20	22.70	0.76	-0.2	21.90	A	Bertola (1966)
1964.5	B	22.03	22.53	0.89	-0.1	21.73	A	Bertola & Benacchio (1967)
1971	B	model	-	1.37	0.4	21.26	E	Bertiau et al. (1973)
1973	B	21.8	22.30	1.10	0.1	21.50	A	Capaccioli (1974)
1973.1	B	21.85	22.35	1.05	0.0	21.55	A	Barbon & Capaccioli (1976)
1973.15	B	21.78	22.28	1.17	0.2	21.48	A	Barbon & Capaccioli (1975)
1973.9	B	21.90	22.40	1.00	0.0	21.60	A	Barbon & Capaccioli (1975)
1974	B	21.7	22.20	1.20	0.2	21.40	E	Capaccioli, priv. comm.
1976.6	B	21.56	22.06	1.37	0.4	21.26	A	Barbon et al. (1978)
1977.9	B	21.21	21.71	1.89	0.9	20.91	A	Barbon et al. (1982)
1987	V	20.5	20.75	2.19	1.2	20.75	E	Stagni in Bianchini et al. (1993)
1987	V	20.2	20.45	2.88	1.9	20.45	A	Stagni in Bianchini et al. (1993)
1987	B	20.9	21.40	2.51	1.5	20.60	A	Stagni in Bianchini et al. (1993)
1989	R	19.2	19.30	3.02	2.0	20.40	E	Cinzano, priv. comm.
1992	V	19.8	20.05	4.17	3.2	20.05	E	Falomo et al. (1993)
1992.9	R	19.03	19.13	3.53	2.5	20.23	E	Fasano, priv. comm.
1993	V	19.9	20.15	3.80	2.8	20.15	A	Stagni in Bianchini et al. (1993)
1993	B	20.4	20.90	3.98	3.0	20.10	E	Ortolani, priv. comm.
1993	B	20.1	20.60	5.25	4.2	19.80	A	Stagni in Bianchini et al. (1993)
1994	V	19.85	20.10	3.98	3.0	20.10	E	Ortolani, priv. comm.

In the table was included also a theoretical prediction for b_{art}/b_0 computed from b_{art}/b_{nat} corrected by b_{nat}/b_0.

References

Barbon, R. & Capaccioli M. 1976, A&A, 51, 25.

Barbon, R. & Capaccioli M. 1975, A&A, 42, 103.
Barbon, R. & Capaccioli M. 1975, A&A, 42, 221.
Barbon, R. et al. 1978, A&A, 51, 25.
Barbon, R. et al. 1982, A&A, 115, 388.
Bertiau, F.C.S.J., de Graeve, E.S.J. & Treanor, P.J.S.J. 1973, Vatican Observatory Publ., 1, 4, 159-179.
Bertola, F. 1966, MSAIt, 37, 3.
Bertola, F. & Benacchio L. 1967, MSAIt, 38, 1.
Bianchini, A., Bortoletto, F., Munari, U., Ortolani, S., Salvadori, L., Ragazzoni, R. 1993, Internal Report, University of Padova.
Cinzano, P. 1999, in this volume.
Falomo, R., Cremonese, G., Munari, U., Ortolani, S. 1993, Relazione GEK, Internal Report, Astronom. Obs. Padova-Asiago.
Garstang, R.H. 1989a, Ann. Rev. Astron. Astrophys., 27, 19-40.
Garstang, R.H. 1989b, Bull. of American Astron. Soc., 21, 2, 759-760.
Hoag, A.A., Schoening, W.E. & Coucke, M. 1973, Publ. Astron. Soc. Pacific, 85, 503-507.
Isobe, S. 1993, Measurement of energy loss through world light distribution at night, preprint.
Isobe, S. & Hamamura, S. 1998, in Preserving the Astronomical Windows, IAU JD5, Astron. Soc. of Pacific Conference Series 139, p. 191-199.
Kalinowski, J.K., Roosen, R.G. & Brandt, J.C. 1975, The night sky brightness at McDonald Observatory, Publ. Astron. Soc. Pacific, 87, 869-876.
Krisciunas, K. et al. 1987, Atmospheric extintion and night-sky brightness at Mauna Kea, Publ. Astron. Soc. Pacific, 99, 887.
Pike, R. 1976, J. Royal Astron. Soc. Canada, 70, 116-126.
Walker, M.F. 1973, Publ. Astron. Soc. Pacific, 85, 508-519.
Walker, M.F. 1988, Publ. Astron. Soc. Pacific, 100, 496.
Walker, M.F. 1991, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conference Series 17, p. 52-55.

A METHOD TO MEASURE THE NIGHT SKY LUMINOSITY

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1. Introduction

The progress of knowledge has led Man to increasingly appreciate the natural resources and thus to pose the question on their better exploitation. Also in the case the electric energy used for outdoor lighting, many protests have been raised against light pollution, which is a source of waste of energy and a cause of serious damage for the cultural life of citizens who cannot enjoy the view of the starry sky.

While the evaluation of the cultural damage needs long times and is subject to different opinions, the economic damage can be evaluated through the objective measures of the artificial radiation scattered back from sky to Earth.

In 1990 the first of us decided to study the light pollution in the area of Catania, proposing to the other, at that time undergraduate student of physics, to investigate this subject in his thesis and suggested the method we are going to explain.

2. Description of the method

The procedure consisted in taking photos of the vault of heaven, with a camera on which an optical fish-eye system had been mounted, capable of widening the field of view to about 180°.

The device for the data acquisition, made by the second of us, was very simple.
1) The camera's support was made of a rigid plate, about 40-cm in diameter, with three screws and two levels for its setting (perpendicular to the vertical of the observing site). A metallic tube with a diameter of 2 cm and about 30 cm long, was mounted on the edge of the plate and perpendicular to it. On the upper end was a 0.2 x 5 cm longitudinal translucent slit, turned towards the plate's axis to which it was parallel. Inside of it a 2.5 V, 0.5 A. battery-feeded lamp was placed. The switching of the lamp was made by an external button. With respect to the plate, the lower part of the slit had the same height of the entrance pupil as that of the acquisition system being described.
2) The acquisition system consisted in a camera with a focal lenght of 50 cm on which a Kenko objective, estending the field of view to the whole emisphere towards which is directed, had been mounted. A small square, mounted at the center of the plate, allowed the camera to be mounted on it, so that its optical axis was perpendicular to the plane

of the plate itself and turned towards the emisphere over it.
3) To orientate the plate, a compass was used so that the cylinder of point (1) was directed towards North, with respect to the optical axis of the camera.

The image of the vault of heaven provided by the equipment just described, consists in a disc with a diameter of 20 mm. A Technopan 2415 film by Kodak was used to acquire it. The optical system, as we said, covered a field of about 180°, whose image resulted, on the focal plan, in the orthogonal projection of the semi-space in front of the entrance pupil of the system.

As we had to take photometric measurements on the images so obtained, we first checked that the optical devices did not alter, varying the height and azimuth of observation, the relations of luminous fluxes received. To this aim, we used an arch forming a semi-circumference with a radius of 500 mm, made of a blacken sheet-aluminum, where some holes, 7-mm in diameter, were made along its longitudinal axis, in such a way that, putting the arch in a vertical position, the centres of the holes corresponded to the zenith distances of 0, 15, 30, 45, 60, 65, 70, 72.5, 75, 77.5, 80, 81, 82, 83 degrees. Each of these holes hosted a little cylinder with inside a little lamp of 3.5 V., 0.5 A. linked to a regulated power supply. In front of the little lamp the cylinder was closed by a diffuser, which was externally shielded by a thin diaphragm with a diameter of 3 mm: this part of the cylinder had a diameter such that it tightly inserted into the holes of the aluminum arch and the external surface of the diffuser aligned with the concave side of the arch. We first set the camera so that the center of the entrance pupil of the Kenko device coincided with that of the arch; then we made the optical axis center the hole at a zenith distance of 0°, we stabilized the little lamp, and at last we performed a 1/60 sec exposure. This procedure was repeated, moving the cylinder each time to a different hole of the arch. Then we moved the azimuth of the arch by 90°, with respect to the camera and repeated the operation. The measures, made from the negatives obtained by Foti and performed with a digital 12-bit microdensitometer, showed that the transmittance of the optical system, presented deviations of about 7% with respect to the mean transmittance. Since the precision estimated for our measures was 10%, we considered the measures of intensity derived from the negatives independent from the values of height and azimuth of the sky area they referred to.

To tackle the problem of studying the light pollution in the area of Catania, we decided to exploit the town location, lying Catania in a semicircle from N-E to S-W towards West and being surrounded by the sea at East. The measures were then scheduled along the following directions: N-E, N, N-W, and S-W, starting from the center of the town coinciding with the Astrophysical Observatory on S.Sofia hill inside the University Campus. The W direction was not included due to the presence of the highway Catania-Palermo. We decided to set the surveying points along the abovementioned directions at a distance of about 8, 16, and 24 km from the center of the town (see Fig. 1).

For the observations made by Foti on moonless nights (see Tab 1.), we selected a place in each site chosen for the observations, not much disturbed by the local lights or by traffic, where we mounted the equipment. The camera with the optical system was mounted on the proper little square of the plate. This one was then put in horizonthal position and set so that the tube with the slit was oriented towards N direction with respect to the optical axis of the camera. At least two hours after the sunset or three hours after the dawn, we performed a 50 min exposure using a 2415 Kodak Technopan film. During the first 10 sec. of the exposure the slit on the tube was illuminated so that it was easy to find the North direction indicated by the image of the slit on each obtained negative. We carried out the exposures in the 13 sites using a film of the same kind on which we obtained the image of a scale of grey illuminated by a stabilized puntiform source. (It would be convenient to perform this procedure with the same film used to record the sky images, obtained in the various places).

All the negatives obtained, except that derived from the scale of grey, were scanned with the PDS of the Trieste Astronomical Observatory, using a 20x20μ window. The scale of grey and the obtained negative were measured with a digital 12-bit microdensitometer of the OACT. These measures were used to derive the caracteristic curve of emulsion. The flaws due to the emulsion's crack and to the dust deposited on the surface of the digitalized images were removed. These irregularities would have altered the real dynamics of the digitalized images. The caracteristic curve of the emulsion, as for the part comprising the range of densities found on the negatives obtained in the 13 points of surveys, was verified, with $\chi^2 = 4.521E^{-5}$, by a polynom of seventh degree, then used for the conversion into intensities of the measured densities.

Since the values of the intensities so obtained were expressed in arbitrary units, photogram by photogram, it was necessary to unify the units and then convert it in absolute units. This was performed by taking as a reference the trail of the α Bootis present in the photograms obtained in the places of survey. As we had to measure the luminosity of the sky, we did not consider the flux of the star outside the atmosphere but the flux which reached the Earth. To obtain this flux we had to determine the magnitude of α Bootis, both over and below the atmosphere, in the spectral band limited by the transmittance of the optics and by the spectral sensibility of the emulsion used. Then we determined the coefficent of atmospheric estinction in the spectral band used by us. To this aim Foti spent an entire observing night performing 11 exposures, each lasting 5 min. The first and the last three exposures were taken every 30 min., while the other were taken every 60 min.; this was done so that the observations were better distributed with respect to the masses of air respectively crossed. In this case, since the observations of the sky luminosity and the absorption coefficient were not determined simultaneously, we had to derive the latter using the trails of the star α Tauri instead of those of α Bootis, present in the photograms relative to the various places, because in the mean time, α Bootis had became visible for an insufficient period of time. However all the exposed photograms were developed contemporarly in the same process.

The images digitalized in transparency, after removing the effects of the emulsion crack and dust, were then converted into intensity through the polynomial derived from the caracteristic curve. In the IDL environment, the images were reduced to the 500x500 pixel size and after the noise has been subtracted and a smoothing of 3x3 pixel performed, the isophotes were traced. The images so obtained are shown in Figs. 2-14.

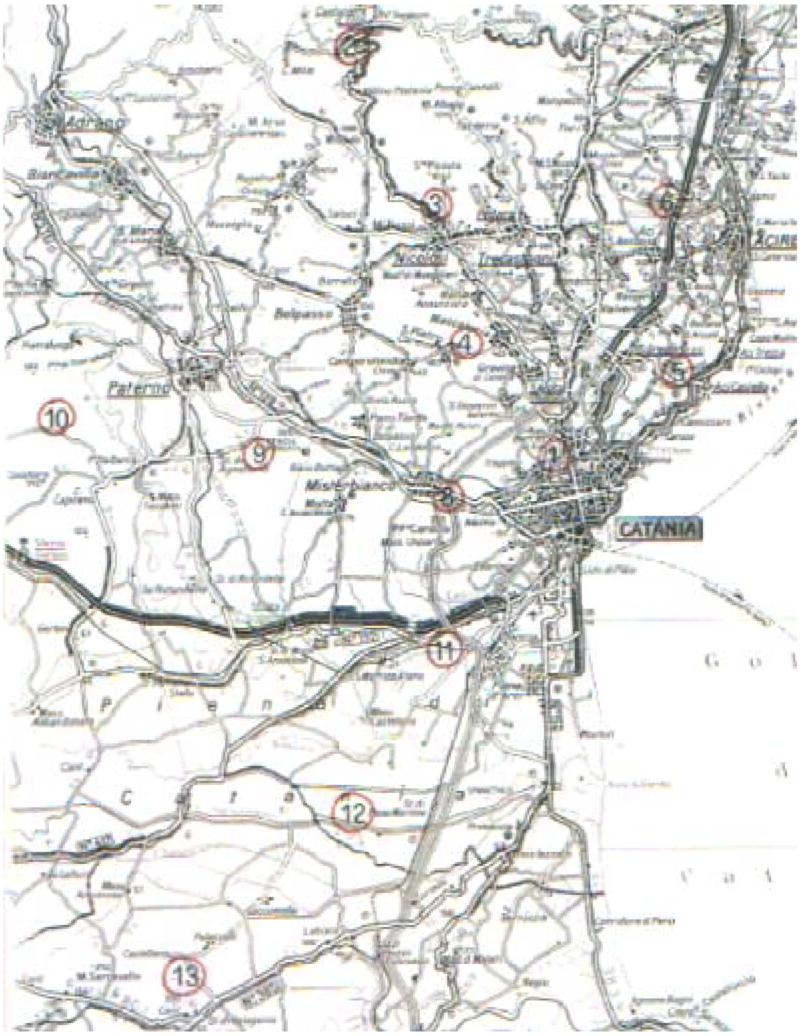

Fig. 1. Map of the region where the measurements were carried out.

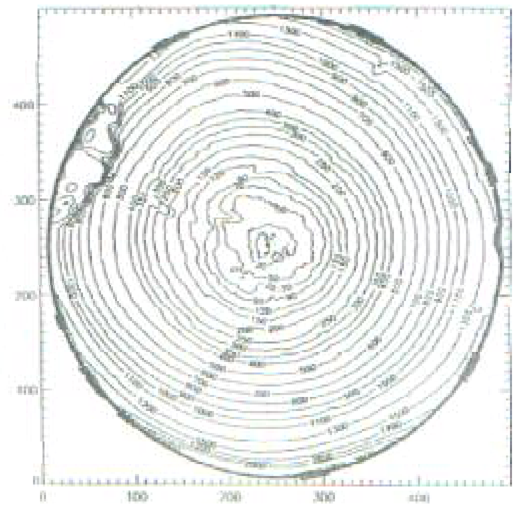

Fig. 2. 11/20/90-Catania (Univ.Campus S.Sofia).Height a.s.l. 195 m.

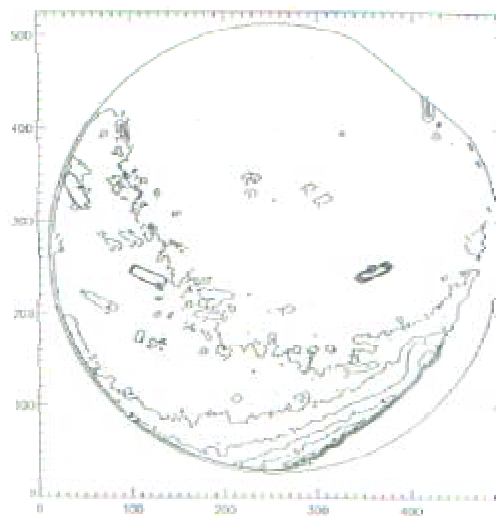

Fig. 3. 05/07/91-Serra La Nave. Height a.s.l. 1700 m.

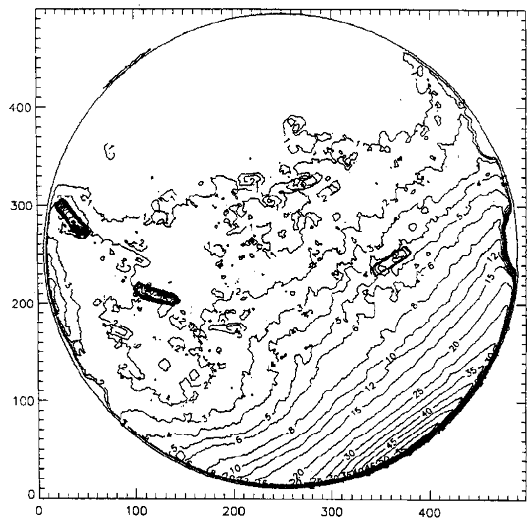

Fig. 4. 05/08/91-Mount Nocilla. Height a.s.l. 900 m.

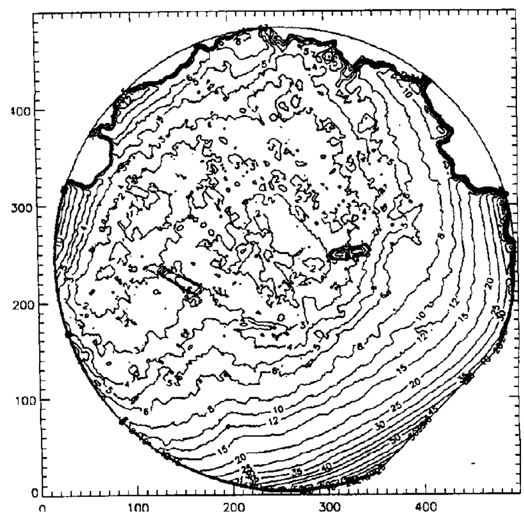

Fig. 5. 06/08/91-Schimmicci district. Height a.s.l. 390 m.

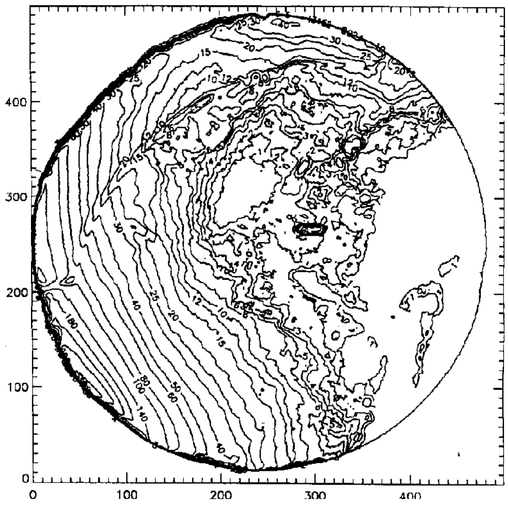

Fig. 6. 06/13/91-Reitana district. Height a.s.l. 170 m.

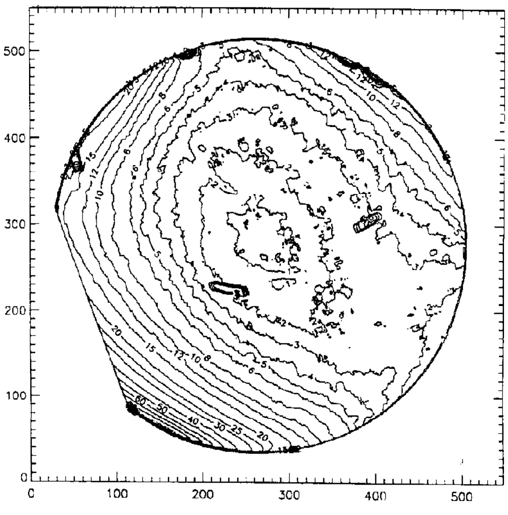

Fig. 7. 06/10/91-Ramondetta district. Height a.s.l. 350 m.

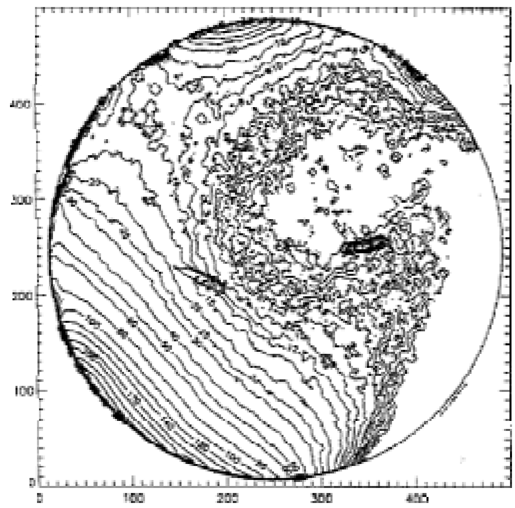

Fig. 8. 06/15/91-S. Anna district. Height a.s.l. 20 m.

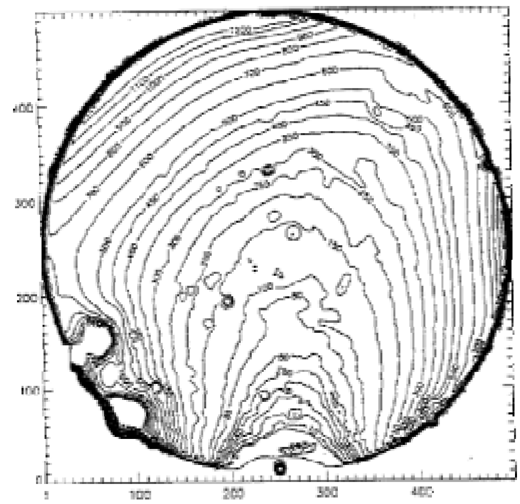

Fig. 9. 07/13/91-Misterbianco (ring-road East). Height a.s.l. 160 m.

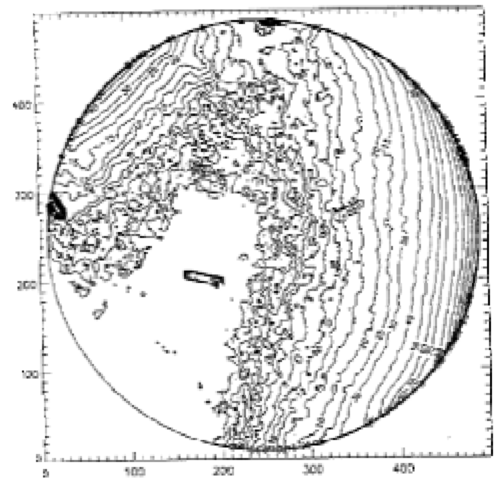

Fig. 10. 07/03/91-Bottoga district. Height a.s.l. 200 m.

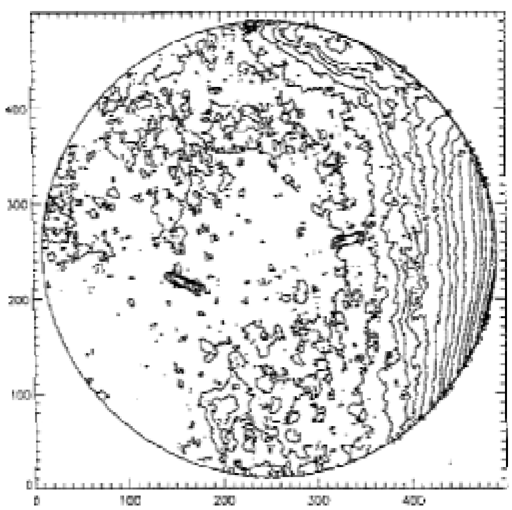

Fig. 11. 07/10/91-Irmana district. Height a.s.l. 130 m.

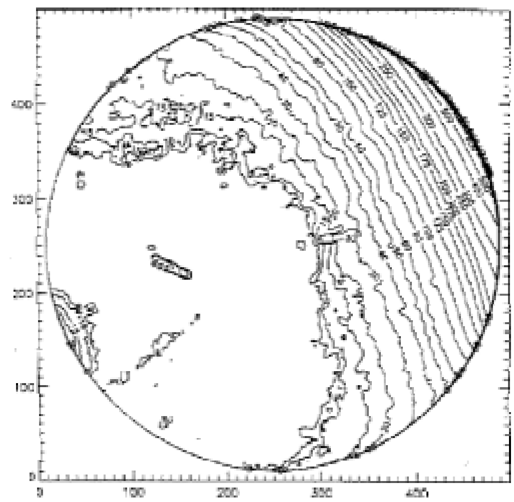

Fig. 12. 07/14/91-Gelso Bianco district. Height a.s.l. 20 m.

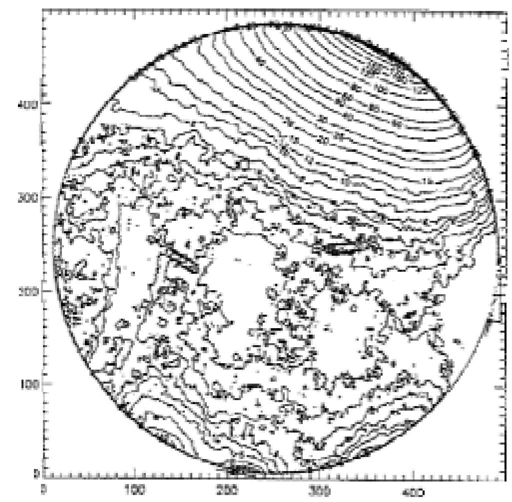

Fig. 13. 07/12/91-Robavecchia district. Height a.s.l. 15 m.

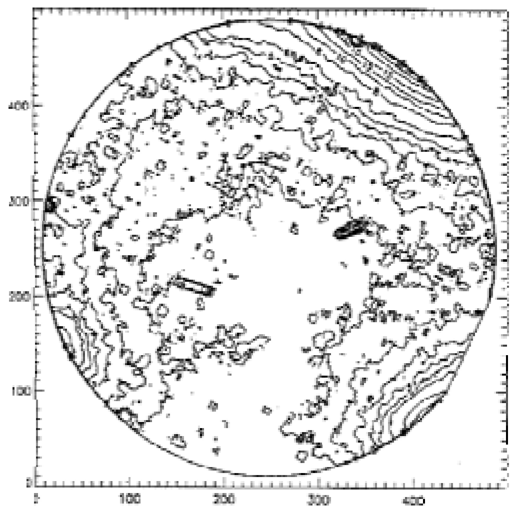

Fig. 14. 07/05/91-Catalicciardo district. Height a.s.l. 50 m.

In Figs. 2-14 the numbers reported on the isophotes show the measure at earth of the flux coming from the zone of sky in arbitrary units. For each direction considered, the trend of the intensity at the zenith relative to a unitary solid angle, is reported as a function of the distance from the center of Catania in Tabs 2-5 and Figs 15-18.

The mean fluxes measured between the two adjacent isophotes are reported in Tabs 6-17 for each place as a function of the zenith distance towards the Catania direction. These data are reported in Figs 19-30.

As we could not obtain the data relative to the power of energy provided by the electric company and to the lamps used in the various municipal lands involved in our survey, we could not take into consideration the contribution the light of each inhabited center to the pollution produced by the town of Catania. We only knew the datum of the power emitted, 7914.5 Kw, provided by Mr. Marino (Ufficio tecnico della Pubblica Illuminazione) who is kindly acknowleged. Due to above-mentioned difficulties, we decided to derive only the pollution produced in the town of Catania. We considered the measures made along the direction SW (Catania-Scordia), where there are only scarsely illuminated areas, and the scattered flux measured in this direction. In Fig 31 the logarithms of these fluxes, detected in the involved areas are reported as a function of their distance from Catania. The linear relation so derived is reported in the same figure. Using this relation we obtained the flux scattered in the circle with a radius of 0.5 km., and in the circular coronae, all 1 km wide and with radius from 1 to 28 km, centered at the Observatory.

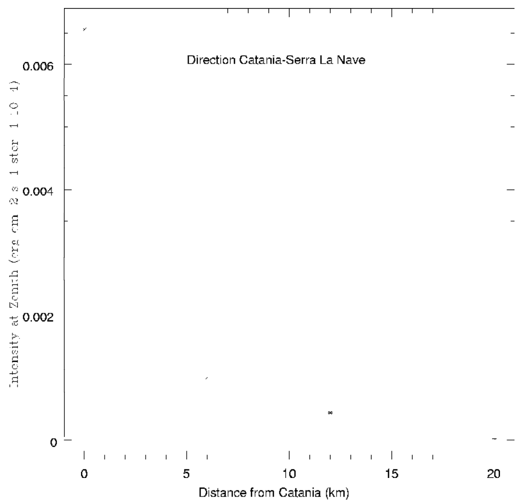

Fig. 15. Direction Catania-Serra La Nave.

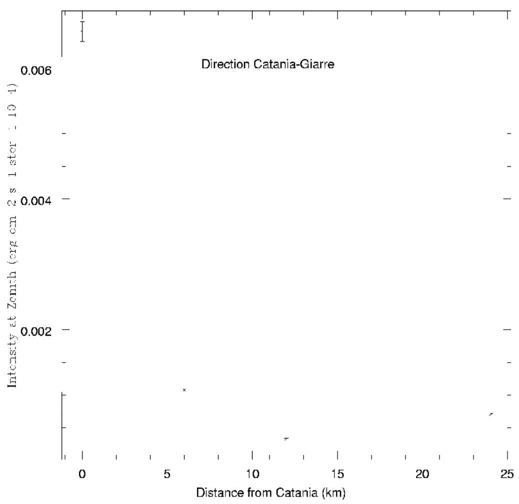

Fig. 16. Direction Catania-Giarre.

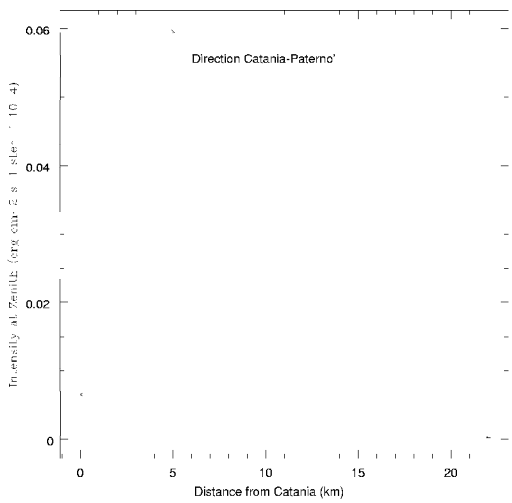

Fig. 17. Direction Catania-Patern.

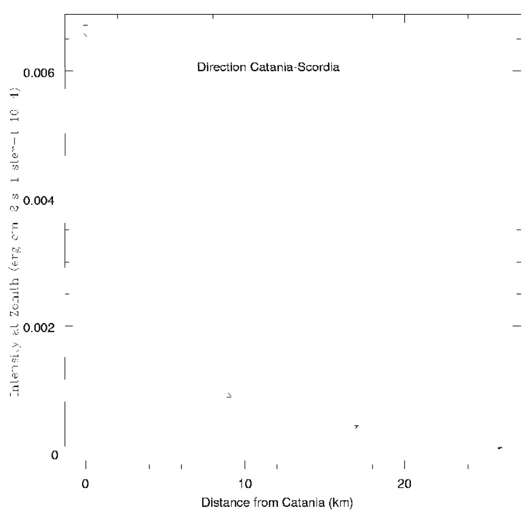

Fig. 18. Direction Catania-Scordia.

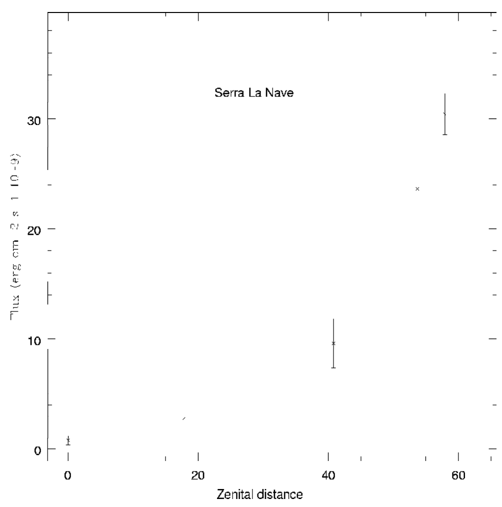

Fig. 19. Serra La Nave.

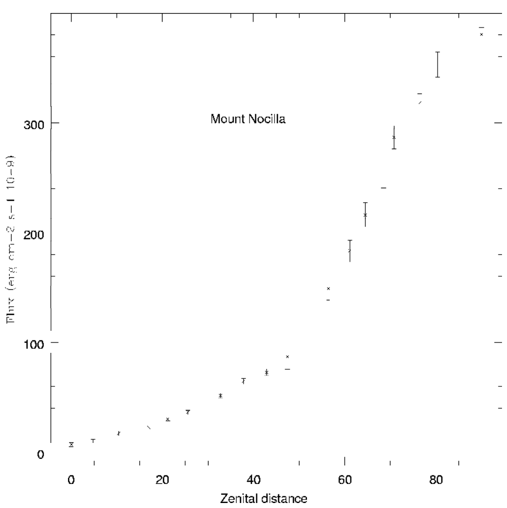

Fig. 20. Mount Nocilla.

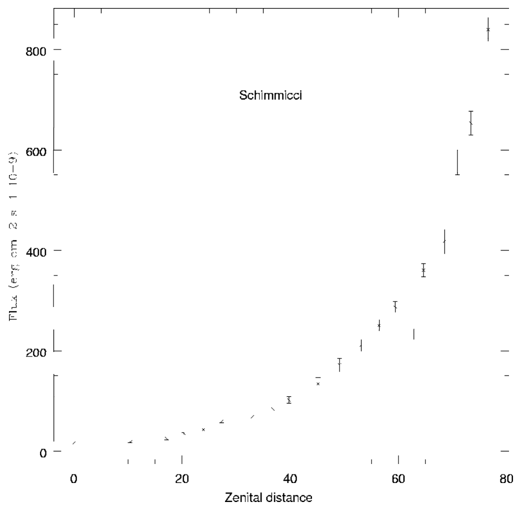

Fig. 21. Schimmicci district.

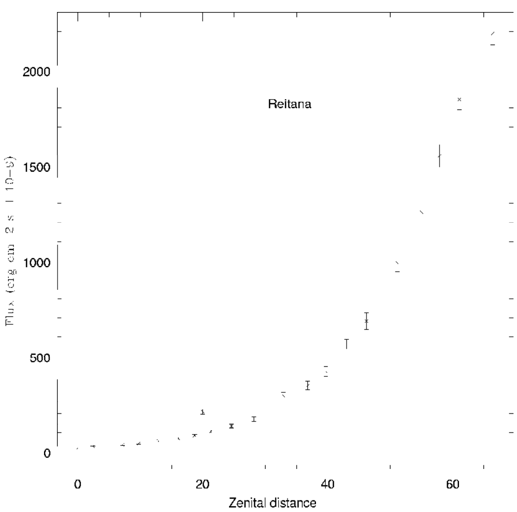

Fig. 22. Reitana district.

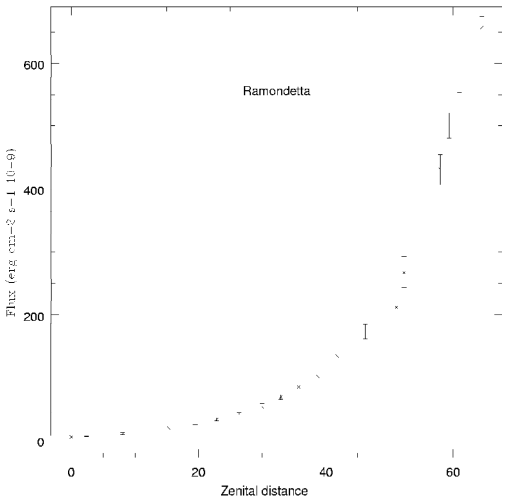

Fig. 23. Ramondetta district.

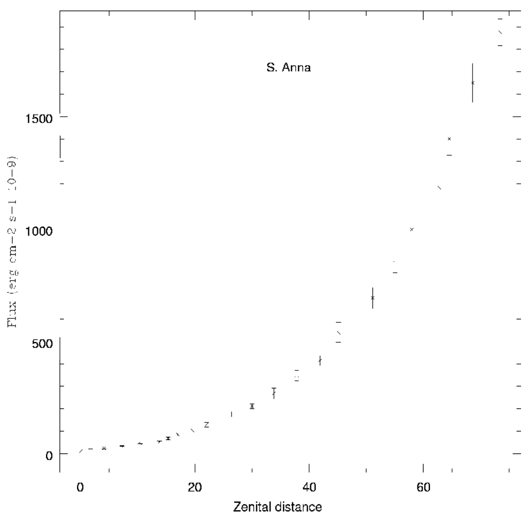

Fig. 24. S. Anna district.

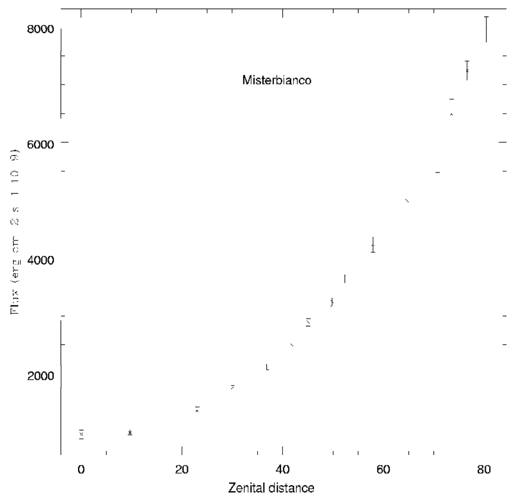

Fig. 25. Misterbianco (ring-road East)

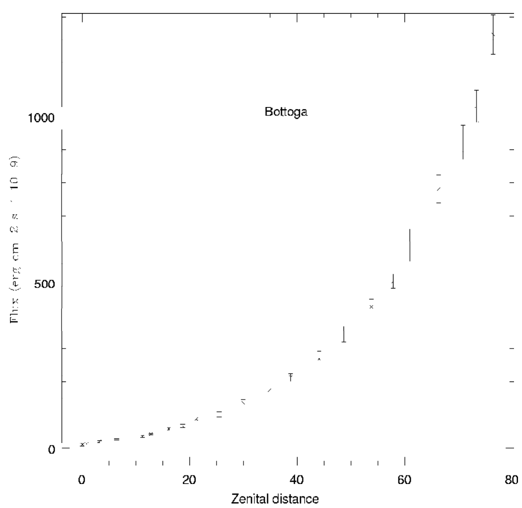

Fig. 26. Bottoga district.

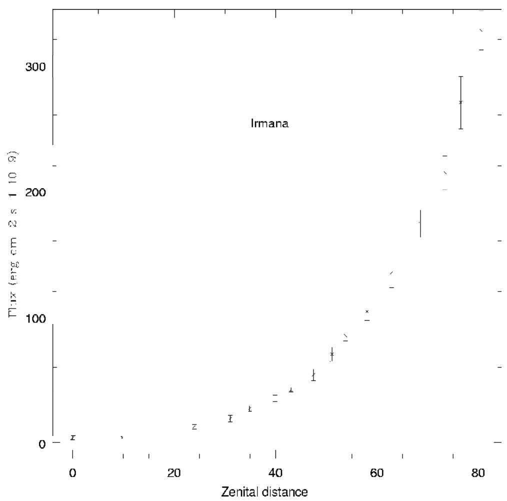

Fig. 27. Irmana district.

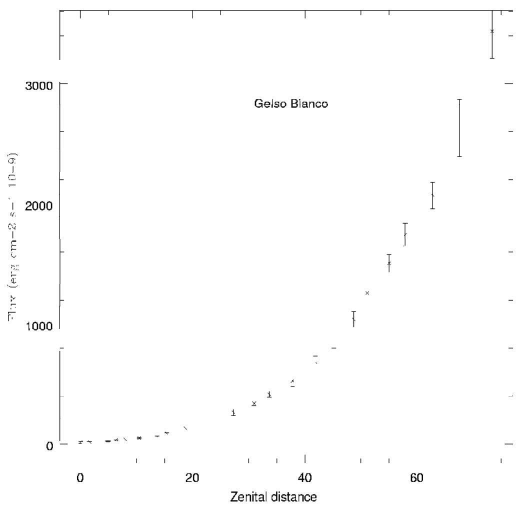

Fig. 28. Gelso Bianco district.

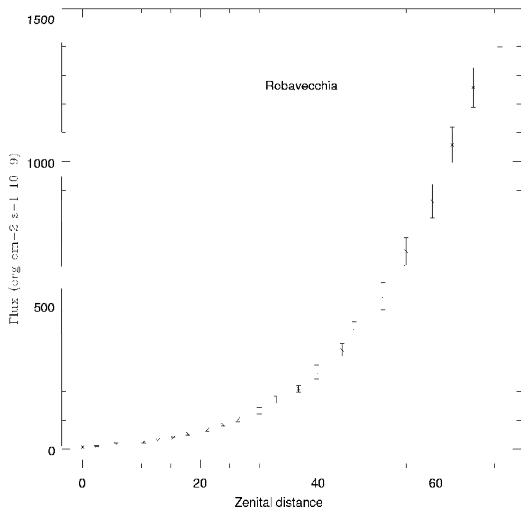

Fig. 29. Robavecchia district.

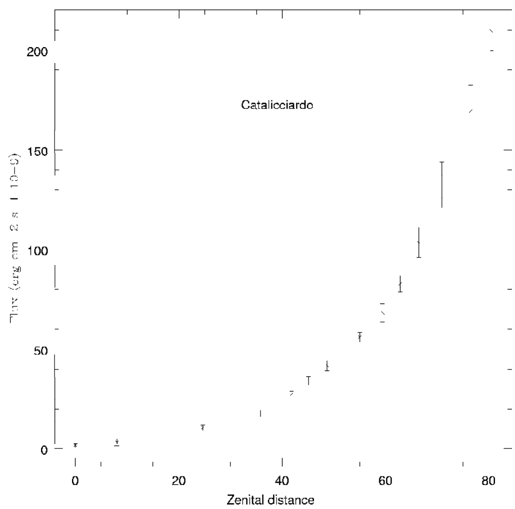

Fig. 30. Catalicciardo district.

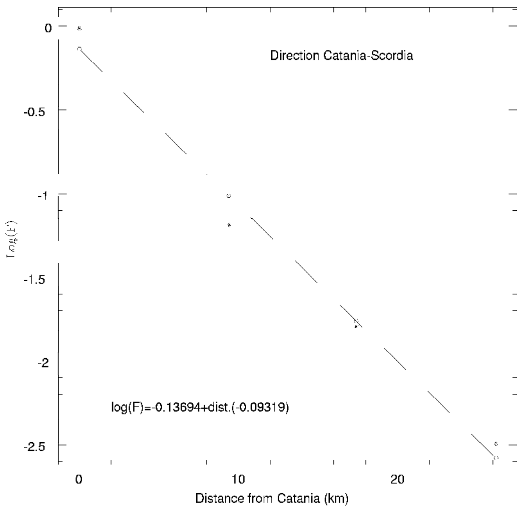

Fig. 31. Direction Catania-Scordia.

Taking the flux scattered in the Morgan and Johnson's V band, we obtained for an area having a radius of 28 km a luminous flux of 1535907 lumen, corresponding to 22573 w. To derive the radiation emitted in the upward emisphere from the lighting devices, from the measure of the artificial radiation detected at earth with the above- mentioned device, we assumed that 10% of the direct radiation towards the sky was reflected from sky to earth. Taking into account the effective power emitted in Catania (0.8% of the nominal power), the mean efficiency of the lamps mounted, corresponding to 14.1% and the scattering coefficient of 10 %, we calculated that the value of 22573 w, concerning the flux scattered in the area around Catania having a radius of 28 km, imply that 24% of the power employed for the outdoor lighting of this town is sent toward the sky. This method could be more efficient using a CCD as a detector which would simplify the acquisition and the data analysis.

By examining the graphs and tables obtained from our measurements one can note the deviation from the general trend of each graph and data, due to the local contributions to the general lighting pollution caused by the lights of Catania. The photographs of these areas would allow us to study the lighting pollution but it would be necessary to know the features of all the lighting systems of a given area.

Acknowledgements

We would like to express our thanks to the Directors of the Catania Astrophysical Observatory and Trieste Astronomical Observatory for letting us use the research facilities. We are also indebted to P. Massimino for his help in the electronic processing and D. Recupero for the English translation.

Table 1 - Places and times of the observations.

N	Place	Height.m	Dist.km	Date	C.E.M.T.
1	Univ. Campus, S.Sofia.	195	0.0	11/20/90	17 50
2	Serra La Nave.	1700	19.6	05/07/91	20 20
3	Mount Nocilla.	900	12.0	05/08/91	20 00
4	Schimmicci district.	390	6.2	06/08/91	23 00
5	Reitana district.	170	6.2	06/13/91	22 45
6	Ramondetta district.	350	12.0	06/10/91	22 45
7	S. Anna district.	20	24.0	06/15/91	22 30
8	Misterbianco.	200	5.0	07/13/91	20 45
9	Bottoga district.	200	12.6	07/03/91	21 15
10	Irmana district.	130	21.5	07/10/91	20 45
11	Gelso Bianco district.	20	9.4	07/14/91	20 45
12	Robavecchia district.	15	17.4	07/12/91	20 45
13	Catalicciardo district.	50	26.2	07/05/91	21 15

Table 2 - Intensity of the scattered radiation to the zenith along the direction Catania-Serra La Nave.

dist. (km)	I(erg cm^{-2} $s^{-1}$$ster^{-1}$ 10^{-7})	σ 10^{-7}
0.0	65573.19	1512.30
6.2	10069.62	164.04
12.0	4421.40	100.50
19.6	298.17	16.56

Table 3 - Intensity of the scattered radiation to the zenith along the direction Catania-Giarre

dist. (km)	I(erg cm^{-2} s^{-1} $ster^{-1}$ 10^{-7})	σ 10^{-7}
0.0	65573.19	1512.30
6.2	10828.65	199.68
12.0	3291.96	57.90
24.0	7022.13	218.88

Table 4 - Intensity of the scattered radiation to the zenith along the direction Catania-Paternò.

dist. (km)	I(erg cm^{-2} s^{-1} $ster^{-1}$ 10^{-7})	σ 10^{-7}
0.0	65573.19	1512.30
5.0	596290.02	3366.14
12.6	5912.98	225.81
21.5	2244.06	87.77

Table 5 - Intensity of the scattered radiation to the zenith along the direction Catania-Scordia.

dist. (km)	I(erg cm^{-2} s^{-1} $ster^{-1}$$10^{-7}$)	σ 10^{-7}
0.0	65573.19	1512.30
9.4	9288.99	414.74
17.4	4158.72	147.69
26.2	799.27	47.74

Table 6 - Serra La Nave, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	0.77	0.42
17.8	2.78	2.23
40.8	9.60	2.23
48.6	16.98	2.23
53.7	23.66	2.30
57.9	30.42	1.88
62.7	37.79	1.60

Table 7 - Mount Nocilla, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	7.10	2.01
4.8	10.52	1.54
10.4	17.29	2.21
17.0	22.65	1.54
21.2	30.28	1.94
25.6	36.38	1.94
32.8	51.59	2.01
37.8	64.32	2.55
42.9	72.76	3.08
47.4	87.10	11.46
52.3	117.58	10.85
56.4	148.87	10.25
61.1	183.31	10.12
64.5	216.21	10.99
68.5	251.58	11.06
70.8	286.69	10.72
76.5	318.38	8.11
80.4	352.82	11.52
90.0	380.29	6.03

Table 8 - Schimmicci district, scattered flux towards Catania.

Z	F(erg $cm^{-2}s^{-1}10^{-9}$)	σ 10^{-9}
0.0	16.10	3.28
10.4	18.39	2.14
17.1	24.87	2.44
20.3	35.17	1.98
23.9	42.58	2.29
27.3	58.75	3.05
32.9	68.21	4.12
36.8	83.70	4.50
39.7	102.24	6.94
45.1	134.29	11.75
49.1	171.45	12.97
53.1	210.82	11.44
56.4	250.26	11.52
59.4	286.74	11.14
62.8	323.05	10.61
64.6	360.44	12.82
68.5	417.36	24.11
70.9	575.30	25.18
73.4	652.90	23.50
76.6	839.30	23.65

Table 9 - Reitana district, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	17.36	3.99
2.4	26.34	2.00
7.2	35.33	2.38
9.7	41.32	2.84
12.9	54.22	3.84
16.1	68.43	4.76
18.7	84.10	5.38
21.3	104.60	7.30
24.6	133.94	11.67
28.2	171.96	11.29
30.0	209.20	12.60
32.9	294.91	15.36
36.8	345.83	21.81
39.7	419.79	25.27
43.0	562.25	24.27
46.2	682.98	43.78
51.1	989.57	47.62
55.0	1254.45	57.22
57.9	1548.67	58.83
61.1	1843.20	52.99
66.4	2188.80	58.83

Table 10 - Ramondetta district, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	5.25	1.16
2.4	6.10	0.54
8.1	11.27	1.62
15.3	20.30	1.00
19.5	26.79	1.93
22.9	33.58	2.08
26.4	42.61	1.62
30.0	53.73	4.79
32.9	68.63	3.94
35.7	85.07	4.63
38.8	101.06	6.64
41.8	133.56	11.04
46.2	173.08	11.81
51.1	211.45	11.73
52.3	266.96	24.24
55.1	349.02	24.47
58.0	430.54	23.55
59.4	500.87	20.00
61.0	579.00	25.09
64.5	656.41	17.45

Table 11 - S. Anna district, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	11.29	4.38
1.7	19.35	3.00
4.1	25.80	2.23
7.2	35.79	2.15
10.4	47.70	2.23
13.8	52.38	5.22
15.3	68.74	4.76
17.0	85.48	4.61
19.6	102.37	5.68
22.0	130.25	10.14
26.4	175.64	10.29
30.0	211.66	11.67
33.8	267.26	23.65
37.8	348.44	22.73
41.9	415.80	22.58
45.1	540.13	44.01
51.1	693.27	46.77
55.0	849.18	45.24
57.9	998.55	49.77
62.8	1182.95	65.28
64.5	1402.52	73.42
68.6	1651.43	87.32
73.4	1876.84	60.13

Table 12 - Misterbianco, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	949.12	76.91
9.7	982.66	45.99
23.0	1356.10	68.07
30.0	1753.23	47.22
36.8	2117.88	52.26
41.8	2495.07	53.33
45.1	2888.38	66.77
49.8	3241.80	73.50
52.3	3646.11	75.86
57.9	4234.70	128.50
64.6	4994.42	116.82
70.8	5702.80	225.53
73.5	6497.06	245.94
76.6	7242.18	168.77
80.4	7954.16	218.28

Table 13 - Bottoga district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	9.96	4.63
0.8	12.04	1.78
3.2	19.92	2.78
6.4	26.32	2.01
11.2	34.89	2.62
12.8	42.00	1.93
16.1	57.44	4.79
18.7	66.39	5.02
21.2	87.39	3.71
25.5	101.90	7.57
30.0	135.87	9.88
34.8	174.70	12.12
38.8	212.84	12.04
44.1	268.04	24.55
48.7	343.62	23.31
53.8	425.53	23.78
57.9	503.19	21.85
61.0	611.96	48.33
66.4	780.80	42.77
70.9	922.15	51.80
73.4	1030.34	47.79
76.5	1247.01	59.06

Table 14 - Irmana district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	3.72	1.78
9.7	4.18	1.47
23.9	12.46	1.78
31.0	18.89	2.48
34.8	27.01	2.24
39.8	35.06	2.55
43.0	41.95	1.86
47.4	53.72	4.33
51.1	70.05	5.34
53.8	84.75	4.02
58.0	103.95	7.12
62.8	134.99	12.00
68.5	173.76	10.84
73.4	214.24	13.47
76.5	269.74	20.90
80.5	327.32	15.56

Table 15 - Gelso Bianco district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	14.84	8.30
1.6	17.96	2.66
4.9	24.73	1.75
6.4	36.83	0.53
8.0	42.46	1.98
10.5	54.18	4.57
13.7	66.13	3.80
15.4	92.92	4.41
18.7	134.62	8.45
23.0	186.67	24.12
27.3	265.59	25.80
31.0	339.79	20.70
33.7	416.04	25.11
37.8	524.48	43.22
41.9	683.07	47.03
45.2	851.79	51.44
48.7	1041.35	62.71
51.1	1258.54	71.53
55.0	1503.51	73.13
57.9	1743.91	94.82
62.8	2071.14	109.66
67.6	2632.83	239.87
73.4	3437.58	224.27

Table 16 - Robavecchia district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	6.84	3.00
2.4	11.21	1.84
5.7	19.58	2.15
10.4	25.57	2.46
12.9	34.48	2.30
15.4	40.63	1.77
17.9	53.07	4.30
21.2	68.89	6.14
23.9	84.10	3.99
26.4	103.53	7.22
30.0	133.94	11.06
32.9	172.80	12.75
36.7	209.82	10.91
39.7	267.19	24.42
44.1	344.52	22.66
46.2	420.71	23.27
51.1	532.15	46.77
55.0	687.67	47.69
59.4	862.00	58.14
62.8	1057.84	61.36
66.4	1258.06	68.43
70.9	1457.82	59.90

Table 17 - Catalicciardo district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	1.61	1.07
8.0	3.21	1.84
24.6	10.63	1.38
35.8	17.90	1.61
41.8	27.46	1.53
45.1	34.20	2.22
48.7	41.77	2.45
55.0	55.84	2.30
59.4	68.24	4.67
62.8	82.77	4.13
66.4	103.58	7.42
70.9	132.42	11.40
76.5	169.29	13.08
80.4	209.69	10.02

Table 18 - Scattered flux from 2π ster along the direction Catania-Scordia.

dist.	F(erg cm^{-2} s^{-1} 10^{-7})	σ 10^{-7}
0.0	968.01	3.04
9.4	65.07	0.57
17.4	16.13	0.18
26.2	3.21	0.02

THE BRIGHTNESS AND COLOURS OF THE LOIANO SKY

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ABSTRACT. The sky brightness at Loiano, observing site of Osservatorio Astronomico di Bologna, was measured during moonless and clear nigths in the years 1986-1998. Most of the measures were carried out in the V and B Johnson broad photometric bands at the zenith or close to the zenith. Any conclusion about an increase of light pollution cannot be reached during these years, due to the large spread of the measurements.

The mean value of sky brightness in Loiano is about 20.2 magnitude/sq.arcsec in the visual band and 21.1 in the blue band with a standard deviation of 0.4 in both filters.

1. Introduction

During the past years man made lighting has caused an important addition to the natural light of the sky. This contribution, called sky glow, increases everyday: theoretical studies model this increasing of the sky pollution produced by the continuus expansion of the cities (Garstang 1986) and relationships have been proposed to describe the dependence among sky-brightness, increasing of the population and the distance of the cities (Walker 1977). The consequence is the progressive erosion of the dark zones (Walker 1988) endangering the activity of existing observatories. Optical observatories and the astronomical community, try to take measures for the safeguard of the sky: sky light spectra were obtained as well spectra of street lamps to study the possibility to reduce the contamination due to the lines over the astronomical spectrum (Osterbrock 1976). Long term observing campaign have been carried out at several observatories to determine the natural sky background as well as to monitor the level of sky pollution by artificial lighting (Mattila 1996, Walker 1988).

After the first study of light pollution in Italy, presented by Bertiau (Bertiau et al. 1973) and Treanor (Treanor 1973) several years ago, in the italian astronomical community realized the need to monitor the actual situation in order to find solution before reaching an irrevocable degradation of the sky.

In this paper I report a series of sky brightness measurements obtained during the past decade at the Loiano Observatory. The sky brightness values were obtained as by-product of long-term programs: monitoring of AGNs or light curves of variable stars. The observations are described in section 3, in section 4 there are the plots and the discussion of the sky brightness.

2. The site

The Loiano Observatory is the astronomical observing station of the Osservatorio Astronomico of Bologna. It is located 2 Km south of Loiano town, at an elevation of 785 m on the Appennini mountains (West Longitude= $-11^0 20'12"$, Latitude= $44^0 15'32"$).

The Loiano town is located 35 km south of Bologna. It is recheable following the Futa road (SS 65). In this site two telescopes are operating: 152 cm and 60 cm with diameter respectively. These two telescopes are surrounded by extensives areas of woods, about 23 hectare, to reduce the albedo of the ground. Nevertheless the Loiano sky is affected by the artificial light of the surrounding centers: Monghidoro, 7 Km south of Loiano, Monzuno to the West. These similar small towns, with few hundreds habitants during the winter, are summer resort places and their population can triplicate in July and August. The big city of Bologna (see figure 1) and their surrounding towns dominate the north direction.

Some limited measures have adopted in Loiano to reduce sky contamination. No limitation to the sky light pollution has been obtained in the other and most important towns.

3. Observations

To the aim of computing the Loiano sky brightness, we used an observing database with the direct images collected to study the light curve of AGN and carried out at the 152 cm of Loiano during the years 1986 to 1989. The other values are a by-product of photometric nigths allocated to study variable stars. In both cases the observations are done in the B and/or V broad band Johnson filter (Johnson 1951).

The sky magnitudes, by-product of AGN observations, are derived from CCD frames of standard fields used to calibrate the magnitudes, exposures are available in both B and V Johnson band. Only observations having air mass between 1 and 1.2 were selected. For these observations the exposure time ranges between 5 and 10 minutes. A small area close to the standard star, in the same ccd field, and free from any visible star is selected to compute the sky magnitude, the magnitude of the standards in the ccd field giving the zero point, after to have applied the mean monthly extinction coefficients . Most of the adopted standard field are open cluster. The computed sky value is a mean value of several number of sky values computed in the same frame, and the standard deviation gives the internal precision of this measurement, tipically a few percent.

The sky magnitudes derived from the observations of variable stars are from ccd frames or traditional standard photometry. In this case the standard stars were used to compute both extintion and magnitude calibration.

Table 1 lists the used night and the computed sky brightness reduced under atmosphere: the first three row show the data. The row 4 and 5 list blue sky brightness and its r.m.s. dispersion. Several sky brightness are obtained as mean value of different values computed using different frames in the same nights, in this case the computed standard deviation is reported. In the rows 6 and 7 the values for the visual band are listed. Detailed comments are reported in the following section.

Fig. 1. A map of Loiano and neightborhood.

3.1. Comments to table 1

Year 1986: the data are from standard fields obtained in a extensive survey of AGNss, selecting only observations of dark nights.

March: one night available and two observations in visual, one in blue.

May: 3 nights are available. The 10 night is somewath cloudy, the magnitude is a mean value of 3 independent values. For the 13 and 28 nights the mean value of 2 different measurements are reported.

The data of June is a mean value of 2 measurements.

Year 1987: it was a year with several failures in the telescope and only one night is available with a mean value of 6 measurements in the same frame.

Year 1988: February show the mean value of 2 independent observations.

March show a mean value from 6 measurements in the same frame. In the following months are reported the magnitudes computed as mean value of different obnservations.

Year 1989: in January the value is the mean value of several measurements in the same frame. October has single computed magnitudes.

Year 1990: the magnitude for the day 30 is from one single computed magnitude, the magnitude for the day 31 is a mean value of several values.

Year 1992: the magnitude is a mean value of several value in the same frame.

Year 1993: March data is a single value from a standard star, the April data is from a photoelectric observation.

Year 1994: the measurements of January and February are from photoelectric photometry and not from ccd, for this only B filters are done, since the B filter present the same response curve of the standard Johnson's B. The other points are from very clear photometric sky.

Year 1995: from very clear photometric sky.

Year 1998: the observation is 3 days after a snow, with the telescope pointed at west direction, were the sky is very dark. In this case it is peak up a rare very photometric night, this value is the best limit of this year.

4. Monthly sky brightness

In figure 2 are plotted the B sky brightness and the computed r.m.s., when available for independent computed values of sky brightness, as reported in table 1, vs the year. Different symbols are adopted for each observed year.

Even if the table report only observations in dark clear nights, in the plot are indicated also the local computed sky brightness values for full moon nights and for cloudy nights for the Loiano sky. It is also reported the sky brightness for one of the best astronomical sites in the world: La Silla.

Looking the figure, the scatter of the measurements larger than one magnitude is apparent. This could be explained with the different atmospherical conditions. In fact the observation of January 1988 is done tree days after a a light snow fall, faster melted; it is likely that snow did clean the local atmosphere from the aerosols.

The plotted observations are done in different positions of the sky and not in the same sky position each night: the resulting large scatter can be an indicator of the

Tab. 1 - The available data

month	day	year	Sky b	σ_b	Sky V	σ_v	Notes
3	5	1986	21.24		20.56	0.06	
4	9	1986	21.25		20.25		
5	10	1986	20.81	0.30	19.93		
5	13	1986	21.15	0.31	20.45	0.11	
5	28	1986	20.90	0.24	20.23	0.06	
6	2	1986	20.98	0.08	20.21	0.05	
7	10	1986	21.10		20.21		
8	9	1986	21.3				
5	30	1987	22.10	0.06	20.73	0.03	a)
2	21	1988	21.18	0.6			
3	25	1988	20.38	0.02	20.20	0.01	a)
7	22	1988	20.97	0.05	20.11	0.03	
7	23	1988	21.46	0.44	20.67	0.49	
9	5	1988	20.50	0.15	19.44	0.11	
9	9	1988	21.03		20.18		
11	6	1988	21.45	0.07	20.48	0.09	
12	11	1988	21.2		20.3		
1	8	1989	21.64	0.06	20.69	0.11	a)
10	5	1989	21.02		20.40		
10	6	1989	20.71		19.19		
5	30	1990	20.62		20.06		
5	31	1990	20.94	0.02	20.18	0.02	a)
5	9	1992	20.51	0.02	19.15	0.01	a)
3	29	1993			19.94		c)
4	23	1993	22.5				b)
1	31	1994	20.0				b)
2	1	1994	20.7				b) extra lights
3	18	1994	21.2				b)
4	28	1994			20.53		c)
4	30	1994			19.50		c)
5	19	1994			19.66		c)
6	15	1994			20.53		c)
6	18	1994			20.04		c)
9	12	1994	22.2				b)
12	7	1994	20.5				b)
1	3	1995			19.51		
2	6	1995			21.10		
3	7	1995			20.70		
3	22	1995			20.5		
6	6	1995			19.9		
7	22	1995	21.20	0.36	20.19	0.25	
1	17	1997	21.90				
1	31	1997			19.96	0.03	d)
2	27	1997			19.8		d)
1	28	1998	21.90	0.2	20.7	0.2	d)

a) mean value of several standards in the same ccd frame
b) from photoelectric photometry, not ccd
c) photometric sky
d) very photometric sky, after snow

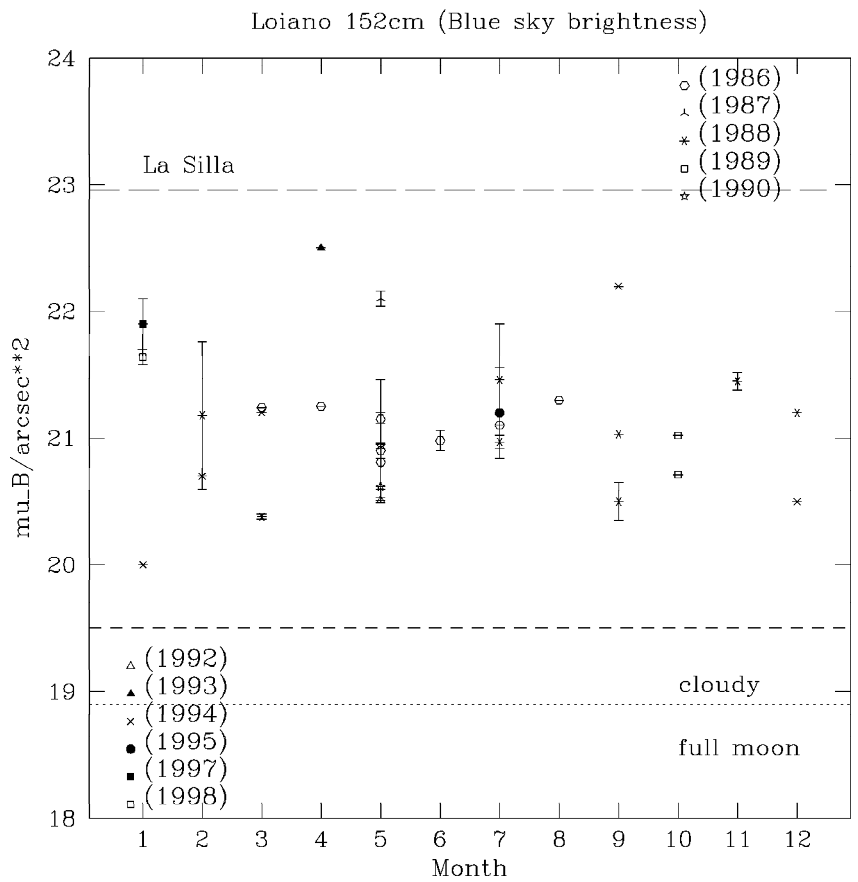

Fig. 2. The Loiano B sky brightness.

amount of the variation of the Loiano sky brightness.

The computed mean value for the B band is 21.14 with a r.m.s of 0.5 mag/sq.arcsec., starting with a mean value, for the year 1986, of 21.03.

Figures 3 shows the sky brightness in V filter.

In this filter it can be seen a marginal long term increase of the sky pollution: in fact the mean value of 20.5 in the year 1986 become the best value for the point of the year 1998, the night with the optimal atmospheric condition for the photoelectrical photometry. A few cloudy nights can affect the average sky brightness in the V band, whereas is insensitive the effect in the B band.

The computed mean value for the V band is 20.17 with a r.m.s of 0.4.

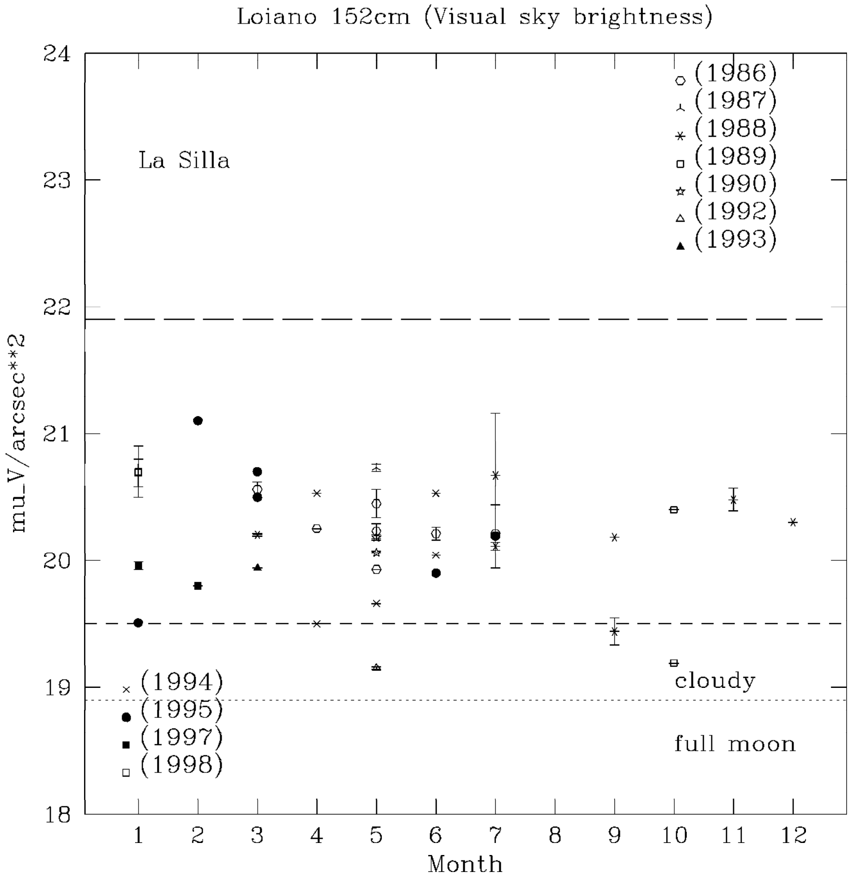

Fig. 3. The Loiano V sky brightness.

5. Annual sky brightness

The sky brightness, for the B band, as a function of the epoch is plotted in figure 4.

No clear evidence can be obtained in this B band of an increasing of light pollution during the years. The plot seems to show an increase of the brightness in the first 6 years, but this trend seems not to extended to the more recent years, where the data show an increase of the scatter. These last data are obtained as single measure for each year and not as mean value of several magnitudes. It is possible, for the last two years, to have been lucky and to have meat the very rare photometric nights (clear sky, low humidity, good seeing, etc.). Can this be a confirmation of the degradation of the sky conditions? More statistic is needed to reach any conclusion in this sense.

Figure 5 shows the same plot for the V band.

Also in this band the scatter increases after the year 1995, even if there is a marginal

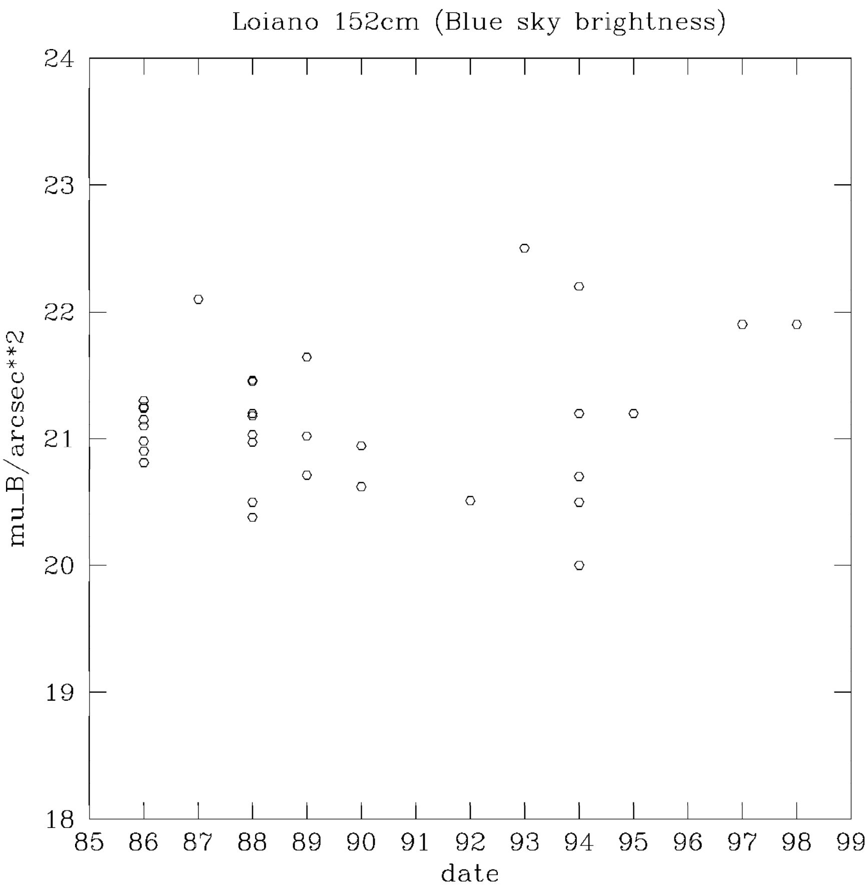

Fig. 4. The Loiano B sky brightness plotted as function of date.

evidence of a decreasing of sky brightness.

Acknowledgements

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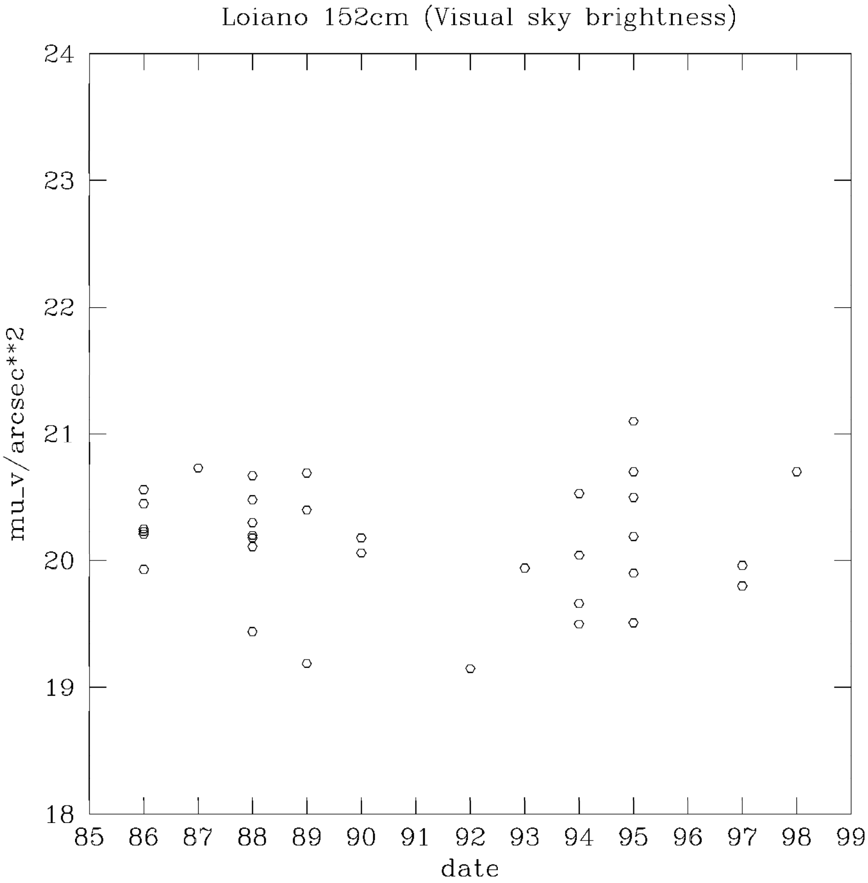

Fig. 5. The Loiano V sky brightness plotted as function of date

References

Johnson, H.,:1951, *Astron. Astrophys.* **114**, 522.

Bertiau, F.,C.,S.,J., de Graeve, E.,S.,J. and Treanor P.,J.,S.,J.: 1973, *Vatican Observatory Publ.*, 1 4 159.

Osterbrock, D.,E. et al.: 1976, *Publ. Astr. Soc. Pacific* **88**, 349.

Garstang, R.,H.: 1986, *Publ. Astr. Soc. Pacific* **98**, 364.

Treanor, P.,J.: 1973, Observatory 93 117.

Walker, W.,F.: 1977, *Publ. Astr. Soc. Pacific* **89**, 405.

Walker, W.,F.: 1988, *Publ. Astr. Soc. Pacific* **100**, 496.

Mattila, K.,P., Vaisanen P. and Appen-Schnur, v G.,F.,O. : 1996, *Astron. Astrophys. Suppl. Ser.* **119**, 153.

THE MEASUREMENT OF THE SKY BRIGHTNESS AT MERATE OBSERVATORY

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ABSTRACT. We describe the problems met using the telescopes of Merate Observatory, the branch of Brera Astronomical Observatory. From the point of view of the data analysis, we discuss how to introduce a satisfactory correction of the variable extinction coefficient, giving also some examples. We also measured the sky brightness, obtaining V=18.2 mag/arcsec^2. The light pollution is responsible for such a bright background and we present pictures showing its effects. We are limiting it trying to persuade public administrations to reduce the light scattered toward the sky by using cutoff lamps and putting out commercial searchlights. The need of a law which safeguards astronomical activities is stressed.

1. The telescopes of Merate Observatory

Since a long time, the utility of small telescopes located near to research Institutes is re–evaluated, as they can provide useful surveys of variable stars and peculiar objects, especially over a long–time baseline. This kind of survey cannot be further done at large observatories, owing to competition in dividing time at big telecopes and the closing of the small ones for budget problems.

For this reason, a constant effort was made to keep the Merate telescopes at a reasonable level of performances, in order to carry out such long–terms programs, often requiring high–precision measurements too (photometry with a precision better than 0.010 mag, for example). The 50–cm Marcon telescope is equipped with a photon–counting, single channel photometer; UBV and $uvby\beta$ filters are available. Usually, stars brighter than 9.5 mag are measured with the requested accuracy. For fainter objects, we have equipped the 102–cm Zeiss telescope with a CCD camera, allowing us to observe successfully fainter objects. Moreover, we are now substituting the optics of the Ruths telescope, replacing the old 137–cm metallic mirror with a 134–cm Astrositall one; to do that, the generous contribution of CARIPLO Foundation was of paramount importance. The substitution will be completed in late 1998; it is foreseen to automatize the movements of the telescope.

The three domes are also open to public to sightsee celestial objects in some nights each month, usually around the Moon first quarter.

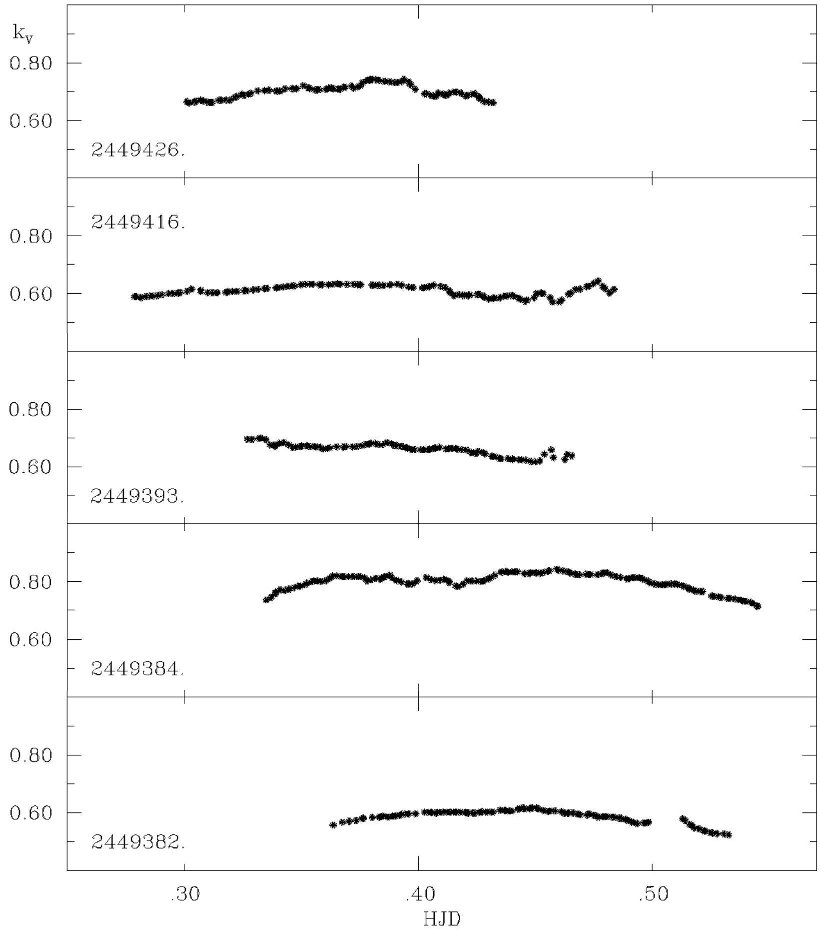

Fig. 1. Behaviour of the extinction coefficient in V light as observed at Merate Observatory on some nights in early 1994.

2. The measure of the extinction coefficient

When the measurements of the star brightness must be very accurate, it is necessary to determinate the extinction coefficient k_λ in a very reliable way.

In such a case, the usual Bouguer's line cannot be recommended since the constancy of k_λ (for the whole night in all the directions) is a constraint very hard to satisfy. As we measured a lot of times, slow variability of k_λ is a common phenomenon in a night, also in sites considered as photometric ones, as the high altitude ones (drifts of a few hundredths of mag/airmass are observed, see Poretti & Zerbi 1993a, 1993b). At lower altitude sites (Merate id 328 m above the sea level) an erratic and large amplitude (more than 0.10 mag/airmass) variability is more frequent. In general, it mimics the

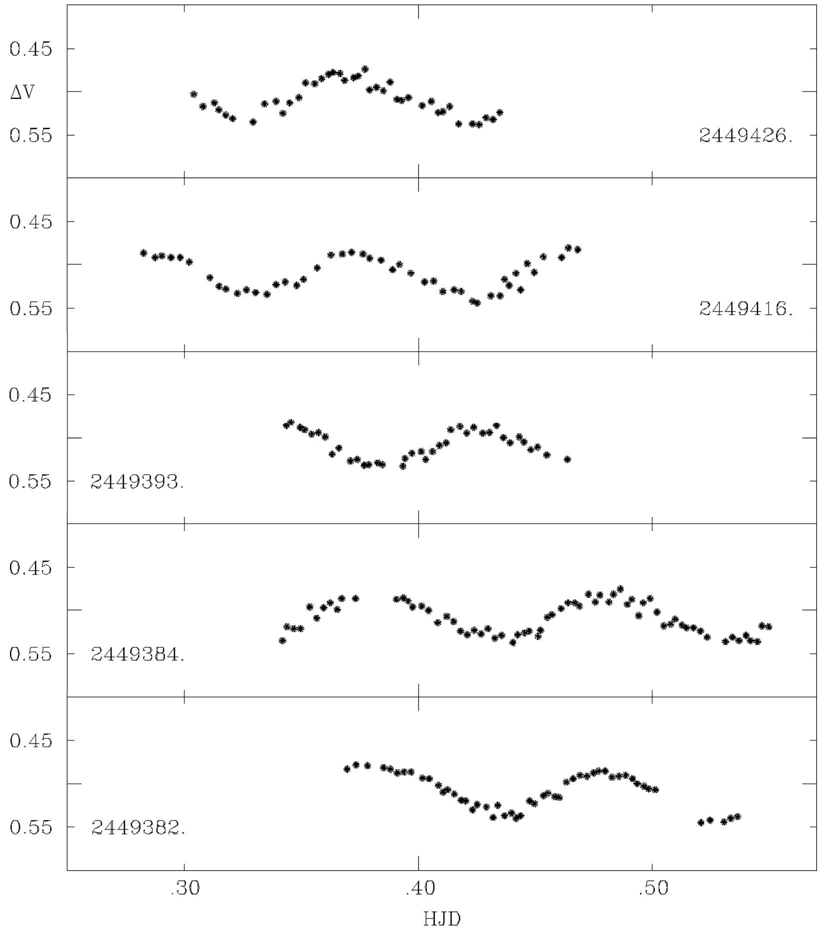

Fig. 2. Light curve of the δ Sct star AZ CMi as observed in the same nights of Fig.1: the variability of the extinction coefficient was corrected by our method and satisfactory light curves were obtained.

variations in the lower part of the atmosphere, which is influenced by the local conditions on the ground: presence of woods, lakes, industrial and urbanized areas ... Moreover, also temperature and relative humidity changes can modify the k_λ value, especially in the first hours of the night. The passage of medium altitude clouds is also responsible for long term waves in the measured flux.

In such conditions, the differential photometry is strongly recommended to minimize these effects. However, it cannot ensure the requested accuracy when the fluctuations of k_λ are large even if the comparison stars are not very far. For this reason, we developed a method allowing us to monitor continuously the transparence variations. To do that, the instrumentation is kept under a tigth control (cooled, always on, no hardware changes..);

an artificial source is inserted in the filter wheel to check at the beginning of each night if the instrumental response is the same. We always verified that within the statistical errors, confirming that a photon counting photometer can provide a high–level stability.

Our main research field is the study of short period variable stars (see Poretti & Mantegazza 1992 and references therein); the target stars and its two comparison stars are measured for all the night. In such a way, it is quite easy to build the graphs described by Poretti & Zerbi (1993a, 1993b) to calculate m_0, the *instrumental magnitude above the atmosphere* of a comparison star. Once m_0 is known, k_λ can be evaluated every time this star was measured, resolving the Bouguer formula

$$k_\lambda(t) = (m(t) - m_0)/X \quad (1)$$

where X is the airmass, $m(t)$ and m_0 are the magnitudes of the reference star inside and outside the atmosphere, respectively. Figure 1 shows some examples of the variability of the k_V coefficient as observed when measuring the δ Sct star AZ CMi at Merate Observatory (Poretti at al. 1996). As can be easily noticed, it is hard to see a constant behaviour. In the JD 2449393 night the continuous drift was of about 0.10 mag/airmass, while in the JD 2449384 night the parabola–like arc spans 0.15 mag/airmass. Note that fluctuations starting after the half of the JD 2449416 night, in a quite unpredictable way. Note also the presence of waves in the k_V curves, practically in all the nights, and the changing mean level of the k_V value, suggesting that an average value should not exist.

The method described in the quoted papers and briefly recalled here provides a satisfactory correction of the extinction since the instantaneous value can be used all the times the magnitude difference stars are calculated. Figure 2 shows the very small amplitude light curve of AZ CMi as obtained from the measurements carried out in the same nights: as can be seen, the regular cycle of variability is well described by the single points (see Poretti et al. 1996 for further details on the frequency analysis). It is important to note that its application does not require any additional measurement, i.e. no time is subtracted to the main programme.

3. The sky brightness: the procedure to measure it

To measure the sky brightness, we used the 50–cm telescope and the photon–counting instrumentation. We give here a short description of the procedure, emphasizing some methodological aspects.

To establish the relationship between counts per second and magnitude, a standard star was measured and the sky as observed near it was subtracted. Therefore, the absorption correction was applied to transform the catalogue magnitude to the measured one. If the star is very bright, the dead–time correction was also applied; Poretti (1992) describes a reliable method to determine it. Once we did that, the sky was measured in different positions. To calculate the brightness per arcsec^2, we need for the diaphragm area. The exact sizes of the diaphragms can be determinated by the crossing time of a bright star (an eyepiece allows us to see the diaphragm wheel); this procedure is suitable for larger ones, but not recommended for smaller ones. The latter values can be better established by performing some sky measurements in the same position, allowing us to obtain very accurate area ratios; once the larger areas were determined by means of the crossing times, the smaller ones can be derived. In all these measures, do not forget to subtract the value of the dark current.

4. The sky brightness: the Merate values

To check the dependence of the measured value from the position, we performed a series of measurements in different parts of the sky (September 1990). Of course, the darkest point was the zenith, where we measured V=18.2 mag/arcsec^2 in average local conditions (k_V=0.50 mag/airmass, no moon, no wind); this value was taken as a reference. Then we moved the telescope mapping the sky toward the south. Table 1 lists the observed increases in brightness: note that 40–45^o above the horizon the sky is already 1.0 mag brighter than at zenith. To yield a better evidence of this fact, Fig. 3 shows a fish–eye picture of the sky as seen from Merate observatory; the camera was pointed toward North. The pollution by the light of the neighbour towns (Merate, Milano, Lecco, Como, ...) is impressive.

Tab. 1 - Increase of the sky brightness at different declinations and hour angles. (0 h, +45^o) corresponds to the zenith value, i.e. V=18.2 mag/arcsec^2.

	Hour angle		
Decl.	– 2 h	0 h	+2 h
+ 45^o	0.08	0.00	0.09
+ 35^o	0.19	0.08	0.18
+ 25^o	0.30	0.19	0.35
+ 15^o	0.60	0.40	0.62
+ 05^o	1.02	0.61	0.95
– 05^o	1.32	0.90	1.28

5. Preserving the observational capabilities

We met a lot of problems in defending the capabilities of our observatory. Since it is located in a crowded area, there are often conflicting interests from different people. However, we did an effort to create a favourable climate of opinion about our activity, especially by means of straight contacts with local administrators. Since the results of the measurements carried out in our Observatory are regularly published in professional journals, this is a relatively easy task.

To avoid light dispersion toward the sky, we mainly try to convince them to use cutoff lights. On the basis of a collaboration plan, they ask for our approval about the lightings of large plants, even if the fulfilment of our suggestions cannot be considered as mandatory. In general, we met an attentive audience of our opinions. However, we stress the importance of a regional or national law which establishes the safeguard of astronomical sites, both from a scientific and a cultural point of view. In the lack of that, disputes can easily arise. As an example, we had a legal controversial against a

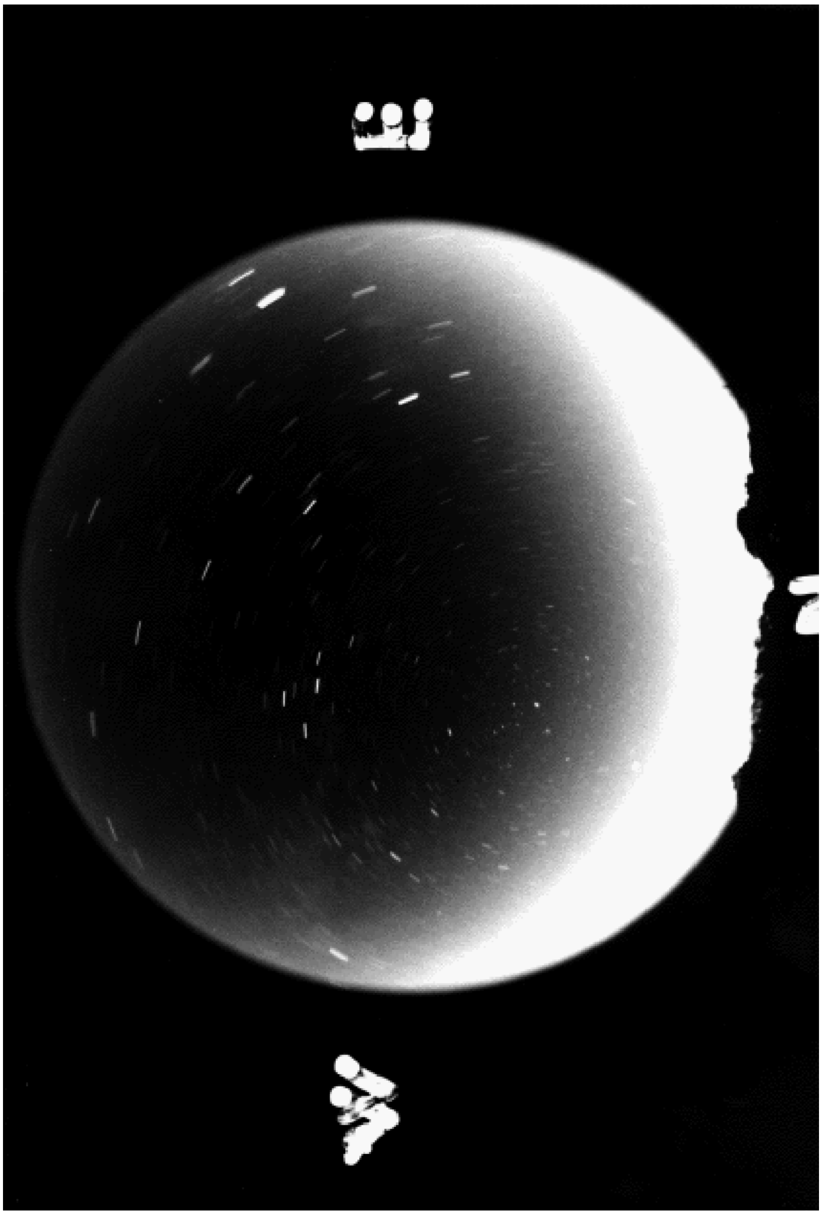

Fig. 3. Picture of the night sky taken with a fish–eye objective from Merate Observatory. Exposure time was 15 minutes, November 1990. The camera was pointed toward North.

Fig. 4. The effect of a searchlight on the sky seen from Merate Observatory. Its damage to the observational activities was demonstrated and its putting out was decided by the public authority

discotheque which placed a powerful searchlight on the roof to be seen at large distances (Fig. 4). On the basis of a collection of evidence, official institutions ordered to switch off the searchlight since its damage to the observations carried out in our institute was evident.

Acknowledgements

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References

Poretti, E.: 1992, *The Messenger* **68**, 52
Poretti, E., Mantegazza, L.: 1992, *The Messenger* **68**, 33
Poretti, E., Mantegazza, L., Bossi, M.: 1996, *Astron. Astrophys.* **312**, 912
Poretti, E., Zerbi, F.: 1993a, *Astron. Astrophys.* **268**, 368
Poretti, E., Zerbi, F.: 1993b, in *Stellar Photometry - Current Techniques and Future Developments* (IAU Colloq. 136), C.J. Butler and I. Elliott eds., Cambridge Univ. Press, p. 221

MEASUREMENTS OF THE NIGHT SKY BRIGHTNESS AT THE CATANIA ASTROPHYSICAL OBSERVATORY

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ABSTRACT. We report on measurements of the night sky brightness at the *"M. G. Fracastoro"* stellar station of the Catania Astrophysical Observatory during 3 moonless nights in February 1998. Measurements were performed in the broad band UBV filters. We compare our observed night sky zenith brightness to measurements from other sites and we also discuss the long term variations from 1980 up to now. Futhermore, we try to correlate the brightness variations both with the solar activity and with the mount Etna volcanic activity.

1. Introduction

To describe the quality of an astronomical site one of the most important parameters to take into account is the brightness of the night sky, which is due to both natural and artificial components. Among the natural components, some are extraterrestrial in origin and thus indipendent from the place on the Earth's surface in which the measurements have been done: zodiacal light, unresolved starlight, diffuse galactic light and extragalactic background light. Other natural components have their origin in the Earth's atmosphere: the airglow emission and the scattered light, for example, depend on the site and the time of the observations.

The artificial component is added to these natural components and contributes to total night sky brightness. This component is mainly due to the artificial illumination that reachs the sky.

There have been many studies of the night sky brightness at particular observatories, see for examples references in Table II. Some studies of light pollution have been made over wider geographical areas, for examples California and Arizona (Walker 1973), Southern Ontario (Berry 1976) and Italy (Bertiau et al. 1973). Berry (1976) has demonstrated an important relationship between the city center zenith sky brightness and the population of the city. Walker (1977) by using the results of his observations derived luminosity - population, brightness-distance and population-distance relationships.
Despite all these observational results, there have been few attempts to construct models to explain the observations, see for example the work performed by Berry (1976) and

Bertiau et al. (1973), who used the empirical law derived by Treanor (1973) to reproduce the zenith luminosity. An important step toward in the modelling of the night sky brightness was given by Garstang (1986, 1989). This author derived a model that, taking into account the main features of the physical situation, provided a good theoretical representation of the observed data.

With the aim of analyzing the actual situation of light pollution at the Catania Astrophysical Observatory, we have performed photometric observations during three moonless nights in February 1998. Moreover to study the long term variations we have examined a number of data collected at our site during last 20 year. The observational techniques and reduction procedures are described in Sect. 2. In Sect. 3 we report on the long term sky brightness variations and in Sect. 4 and 5 respectively, their correlation with solar and mount Etna volcanic activity. Finally, in Sect. 6 we present our summary and conclusions.

2. Observations and data reductions

The observations were carried out at the *"M. G. Fracastoro"* stellar station of the Catania Astrophysical Observatory located at $\lambda = 14° : 58.4'$ W, $\phi = 37° : 41.5'$ at the height of 1735 m on mount Etna in the south of Italy. We used the 91 cm cassegrain telescope equipped with a single channel photometer with an EMI 9893QA/350 photomultiplier, which, cooled to −15 C, produces a dark current of 1 count/s, negligible in comparison with the sky signals, which were at least several hundred counts/s. The selected diaphram gives on the focal plane an image having a diameter of 2 mm corresponding to 28.92 arc sec on the sky.

The observing technique was to get photometry of some selected points in such a way to cover as uniformly as possible the sky and avoiding in the selected area the presence of stars brighter than 20^{th} magnitude. This choice has been done to avoid the influence of the unresolved starlight. The selected points in the sky are shown in Fig. 1. The sky brightness at each point were calibrated and atmospheric extinction coefficients were determined by observing a set of standard stars extracted from the list of Landolt (1983). The measured extincion coefficients are given in Table I.

The maps shown in Fig. 2 have been realized by means of an interpolating procedure created in the IDL environment. These maps describe the trend of the night brightness expressed in mag/□". Azimuth coordinates are measured from the north point eastwards.

According to the maps, it is evident the great contribute of the artificial illumination produced in the city of Catania located close to the south. Despite the patchy structure

TABLE I
Measured extincion coefficients

	U	B	V
k(λ)	0.89 ± 0.13	0.58 ± 0.10	0.28 ± 0.10

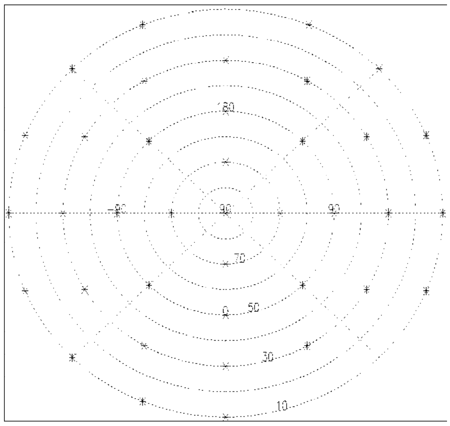

Fig. 1. Selected positions observed to realize the maps. Missing positions were not observed due to the presence of obstacles on the horizon (essentially the tops of some trees near the dome).

of the light distribution over the sky it is however possible to find out a spherical cap centered at the zenith and with a radius of about 20°, in which the brightness is essentially constant. The values of the sky magnitude in that cap have been compared with the ones measured in other important astronomical sites. The results are shown in Tab. II. As we can see, the zenith night sky brightness in our site is at least 1 magnitude brighter than at other astronomical observatories. The measured V magnitude is in good agreement with the theoretical one calculated by Cinzano (1998) for our site. Developing Garstang (1986,1989) models with K = 1, this author found 20.44 mag/□" for an epoch near solar minimum. K is a parameter related to the aereosol content in the Earth's atmosphere. According to Garstang (1986), K = 1 is the typical value for clear air at sea level.

TABLE II

Comparison of zenith sky brightness at different sites in units of mag/□". The given solar 10.7 cm flux value is in unit of 10^4 Jy.

Site	I_U	I_B	I_V	Solar flux	Reference
Catania	21.37	21.13	20.80	95	This work
ESO - La Silla	–	22.85	21.80	165	Mattila et al. (1996)
Calar Alto	–	22.51	21.79	65	Leinert et al. (1995)
CASLEO	22.10	23.30	22.70	–	Clariá & Bica (1990)
San Benito Mt.	–	23.08	22.07	77	Walker (1988)

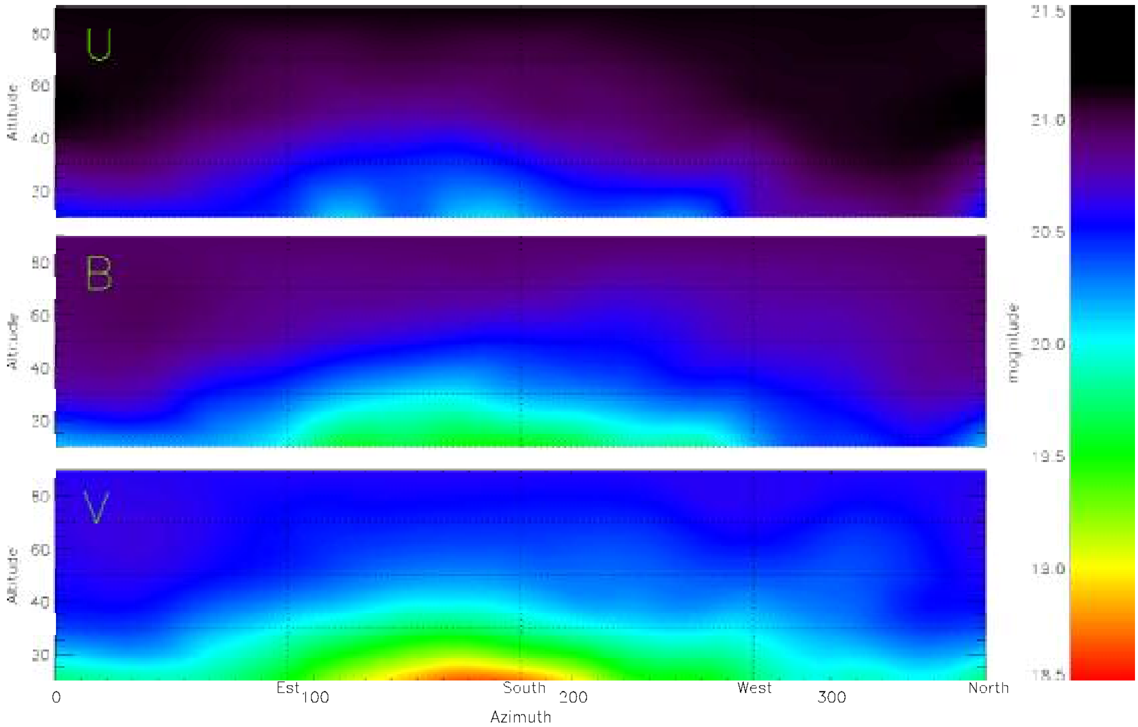

Fig. 2. UBV maps of night sky brightness at the Catania Astrophysical Observatory. The origin of azimuth coordinates is at the North point.

3. Long term variations

In the attempt to study the long term variations of the night sky brightness, we have analyzed a number of photometric observations collected at the Catania Astrophysical Observatory during the period from 1980 up to now (Catalano et al., 1998).
The selection criteria were:

- used strumentation as uniform as possible (telescope + photometer + filters + diaphram)
- position in the sky of the observed point inside a spherical cap extending up to $z = 20°$. In fact, as we can see in Fig. 2 inside that zone the brightness is pratically costant
- the photometric observations have been performed during periods without Etna's eruptions, in such a way to avoid problems with the interactions between volcanic dust and light
- and finally, the photometric observations have been carried out in moonless nights.

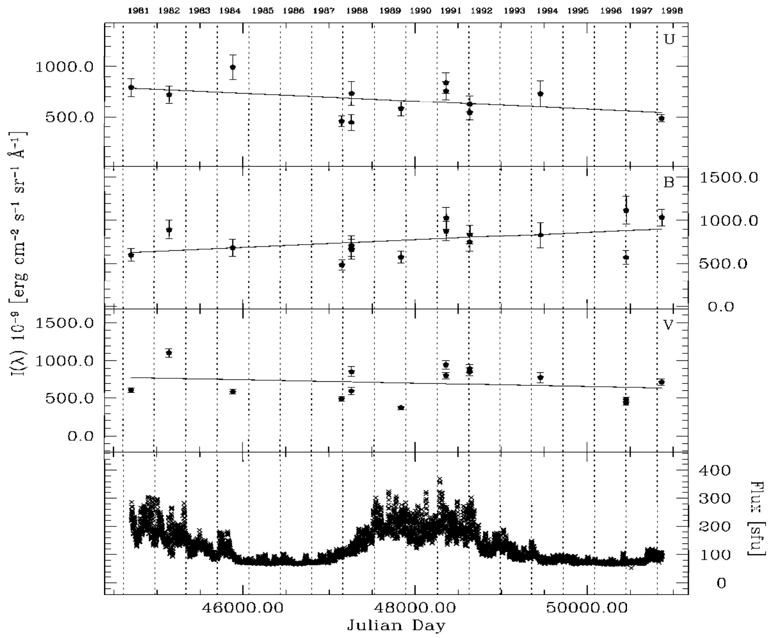

Fig. 3. Long term variations of the night sky brightness as measured during the period 1980 - 1998. The first panel represent the solar activity cycle monitored by means of the 10.7 cm flux (DRAO).

In Fig. 3 we plot the night sky brightness versus julian day for the period 1980 - 1998. To express the magnitudes in energetic units (erg · $cm^{-2}s^{-1}sr^{-1}Å^{-1}$), we first used the formula given in Leinert et al. (1995) to transform the mag/□" in S_{10} units[1]

$$I(mag/\Box'') = -2.5\log I(S_{10}) + 27.78 \tag{1}$$

then according to Leinert et al. (1998), we used the following conversion factors:

$$1\,S_{10} = \begin{cases} U: & 1.37\cdot 10^{-9} erg\cdot cm^{-2}s^{-1}sr^{-1}\mathring{A}^{-1} \\ B: & 2.17\cdot 10^{-9} erg\cdot cm^{-2}s^{-1}sr^{-1}\mathring{A}^{-1} \\ V: & 1.18\cdot 10^{-9} erg\cdot cm^{-2}s^{-1}sr^{-1}\mathring{A}^{-1} \end{cases} \tag{2}$$

As shown by the fit lines, the data seem to vary in time but in different ways in the three filters, in the sense that in the U and V bands the fluxes show a slight decrease while the flux increases in the B bands. We would like to point out that, since the component of the natural sky brightness measured at the zenith is almost constant, the total brightness can be used without any loss of generality.

[1] 1 S_{10} unit is the brightness equivalent to the flux of a star of magnitude 10 distribuited over one squared degree. It refers to A0 stars, which essentially have the same magnitude in all wavelength bands.

4. Correlation of the night sky brightness with solar activity

A correlation between the intensity of the 5557 Å OI airglow line with sunspot numbers has been already reported by Rayleigh (1928) and Rayleigh & Jones (1935). A similar correlation has been later on found for other emission lines of OII, Na, D and OH (Rosenberg & Zimmerman 1967, Walker 1988). For the period 1976 - 1987 Walker (1988) found in his mesaurements a clear evidence of correlation with the solar cycle, in the sense that the night sky brightness increased with the solar activity. Walker argued this result to be the demonstration of the validity of this kind of correlation not only for the strong lines but also for the airglow emission. A similar result has been obtained by Leinert et al. (1995), who, from photometric data carried out at the *Calar Alto Observatory* in Spain, concluded that sky night brigthness is correlated with solar activity.

In order to better investigate the correlations between the night sky brightness and the solar activity, we have plotten each night measurement against the solar 10.7 cm flux. The daily flux was measured in Ottawa (Army Research Office) at 17:00 UT until June 1991, when the program was moved to the Dominion Radio Astronomical Observatory in Penticton (Canada). The daily time of the measurements was changed to 19:30 UT for one year, then was changed to 20:00 UT as it continues today. The solar fluxes are expressed in sfu[2] and are the "observed values", i.e. not corrected to a 1 AU solar distance.

Our results are shown in Fig. 4, in which we can individuate a slight correlation between sky brightness and solar flux, but also in this case we have different slopes for the three filters. U and V bands show an encrease with solar flux while B band shows an opposite behaviour. In order to study this correlations in more detail we have calculated the correlation coefficients r and the related probability P(r,N), where N is the number of data points. The correlation coefficients, the probability and the least squares fit parameters found are shown in Tab. III.

TABLE III

Correlation of the night sky brightness with solar activity. The correlation coefficients r, the probability and the least squares fit parameters for the linear relation ($I_{sky} = a \cdot f_{sfu} + b$) are given for each colour.

Filter	a	b	r	P(r,N)
U	0.73	595.73	0.06	0.50
B	−0.80	904.35	0.24	0.68
V	0.14	641.75	0.23	0.67

In astronomical sites in which the level of light pollution is low, the observed variations due to the effect of solar activity on the airglow emission are usually about 0.4 mag for the B band and 0.5 mag for the V band (Walker 1988, Leinert et al. 1995). Thus, the poor correlation between night sky brightness and solar activity that we observed

[2] 1 sfu = 10^{-22} W m^{-2} Hz^{-1} = 10^4 Jy

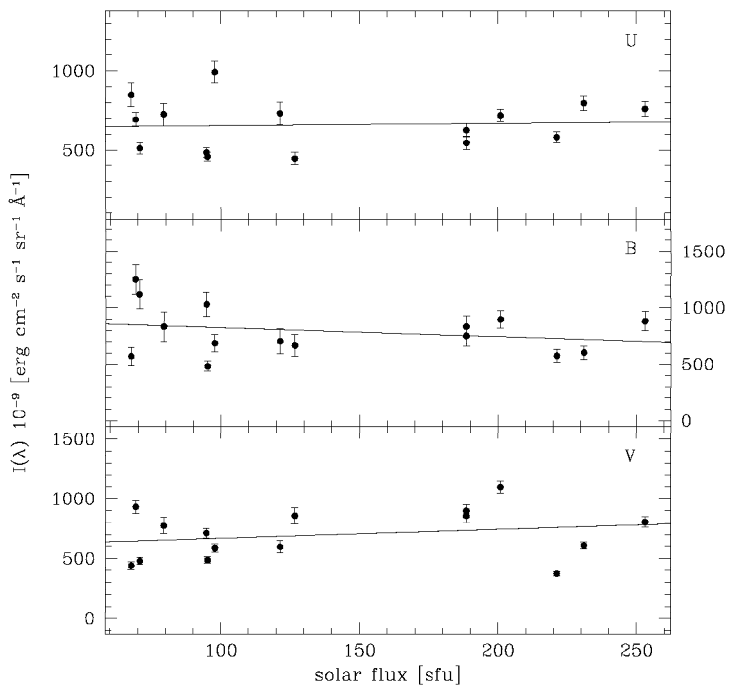

Fig. 4. The night sky brightness versus the solar 10.7 cm flux expressed in sfu units

might be related to high level of the artificial illumination, which contributes to mask the variations due to solar cycle.

5. Correlation of the night sky brightness with mount Etna volcanic activity

It has been known for many years that volcanic dust in the high atmosphere affects astronomical observations. Many studies were made on the effects of volcanic ash when a violent eruption in the Andes on 1932 April 10 left a cloud of volcanic material in the stratosphere over the Commonwealth Solar Observatory on Mount Stromlo in Australia. During that day a decrease in the intensity of the total solar radiation was observed (Rimmer, 1937).

Volcanic dust affects photometric measurements. For example, the eruption of Mount Agung in Bali, of March 1963 formed a cloud that passed over Australia and Chile which produced an excess extinction of 0.38 mag in the B band and 0.30 mag in the V band over the normal ones (Hogg, 1963). Moreno & Stock (1964) reported that the visual extinction at the Cerro Tololo Inter-American Observatory in Chile started to increase in late April 1963 from its normal value of about 0.12 mag, reached a maximum of 0.42

mag in September 1963, and subsequently decreased gradually. The maximum excess extinction due to the cloud was thus 0.30 mag. By September 1964 the excess extinction had fallen to 0.07 mag (Moreno et al., 1965). Futhermore they found that the volcanic extinction was gray.

More recently, Livingston & Lockwood (1983) studied the effect of the stratospheric cloud coming from the eruption of the volcano El Chichón, Mexico. They measured the increase in extinction and found that it was remarkably gray over the visible spectrum, but not in the infrared, where it was much less.

Theoretical works on the interaction between volcanic dust and light were performed by Garstang (1991 a,b). According to his models, Garstang (1991b) calculated the refractive index and the particle distribution function for ash particles from the El Chichón volcano. His results show that extinction and scattering are nearly grey in the visual region, that is, that the absorption has a modest dependence on wavelenght.

In the attempt to investigate the effect of the mount Etna eruptions on the night sky illumination, we have plotted the night sky brightness measured near the zenith versus the ash column produced during volcanic explosions (Coltelli, 1998). The ash column is the height at which volcanic dusts have been ejected, expressed in km above sea level, and it is a good indicator of volcanic activity.

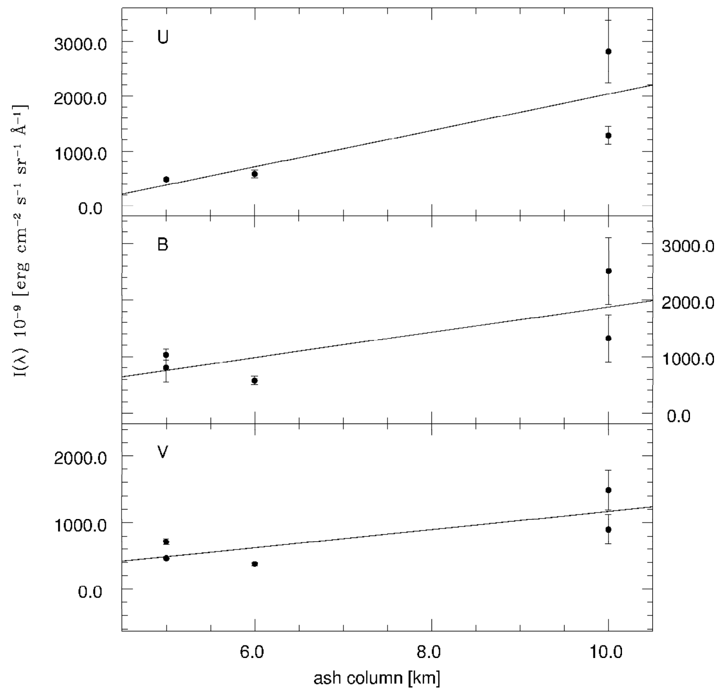

Fig. 5. The night sky brightness versus the ash column expressed in km above sea level

As can be seen from Fig. 5, a correlation between these two quantities might exist. To stress this point, we have calculated the quantities shown in Tab. IV; by means of the correlation coefficient, we estimated the probability and for all filters we obtained P(r,N) $\geq$ 0.9. Nevertheless, because we were not able to get the actual extinction factors for the three bands, we used the mean ones. So, it is possible that these effects mimic an increase of the extinction which appears as a real increase due to the presence of the dust in the atmosphere. Hence, further work is still necessary to understand the real effects of dust on the light pollution.

TABLE IV

Correlation of the night sky brightness with mount Etna volcanic activity. The correlation coefficients r and the least squares fit parameters for the linear relation ($I_{sky} = a \cdot ash\ column + b$) are given for each colour.

Filter	a	b	r
U	330.80	−1273.66	0.91
B	223.43	−367.57	0.77
V	135.79	−192.48	0.78

6. Conclusions

We have performed broad band photometry of night sky brightness during three moonless nights in February 1998 at the *"M. G. Fracastoro"* stellar station of the Catania Astrophysical Observatory with an observing technique that allows to map the luminosity of the sky. We also have investigated about the long term variations and about the correlations of the night sky brightness both with the solar activity and with the mount Etna volcanic activity.

Our main conclusion are the following:

1. there is a spherical cap centered at the zenith and with a radius of about 20° in which the sky brightness is almost constant;
2. the zenith sky brightness at our site is at least 1 magnitude brighter than at other observatories;
3. our V band measurament is in good agreement with theoretical calculation performed by Cinzano (1998) for our site;
4. during the last 20 years the long term variations show different type of variation in the three band;
5. the night sky brightness is slightly correlated with the solar activity cycle measured by means of 10.7 cm flux;
6. the night sky brightness seems to show a strong correlation with the mount Etna activity monitored by using the ash column ejected in the atmosphere during the eruptions.

We will continue our observations both to better understand the previous points and also to check the presence of seasonal variations.

Acknowledgements

We wish to express our sincere gratitude to drs. S. Catalano, E. Marilli and A. Frasca for putting at our disposal their unpublished data of sky brightness measurements. We also thank dr. P. Cinzano for its comments useful to improve our paper.

References

Berry R. L. 1976, *J. R. A. S. Canada* **70**, 97
Bertiau F. C., de Graeve E., Treanor P. J. *Vatican Obs. Pub.* **1**, 159
Catalano S., Marilli E., Frasca A. 1998, unpublished results (private comm.)
Cinzano P. 1998, private comm.
Coltelli M. 1998, private comm.
Clariá, Bica 1990, home page of the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina
Garstang R. H. 1986, *Publ. Astr. Soc. Pacific* **98**, 364
Garstang R. H. 1989, *Publ. Astr. Soc. Pacific* **101**, 306
Garstang R. H. 1991a, *Publ. Astr. Soc. Pacific* **103**, 1109
Garstang R. H. 1991b, *The Observatory*
Hogg A. R. 1963, *Aust. J. Sci.* **26**, 119
Landolt A. U. 1983, *Astron. J.* **88**, 439
Leinert Ch., Väisänen P., Mattila K., Lehtinen K. 1995, *Astron. Astrophys. Suppl. Ser.* **112**, 99
Leinert Ch., Bowyer S., Haikala L. K., Hanner M. S. et al. 1998, *Astron. Astrophys. Suppl. Ser.* **127**, 1
Livingston W., Lockwood G. W. 1983, *Science* **220**, 300
Mattila K., Väisänen P., v. Appen-Schnur G. F. O. 1996, *Astron. Astrophys. Suppl. Ser.* **119**, 153
Moreno H., Stock J. 1964, *Publ. Astr. Soc. Pacific* **76**, 55
Moreno H., Sanduleak N., Stock J. 1965, *Science* **148**, 364
Rayleigh IV, Lord (R. J. Strutt) 1928, *Proc. Roy. Soc. London* **A119**, 11
Rayleigh IV, Lord (R. J. Strutt), Jones H. S. 1935, *Proc. Roy. Soc. London* **A151**, 22
Rimmer W. B. 1937, *Gerlands Beitr. Geophys.* **50**, 388
Rosenberg N., Zimmerman S. P., 1967, *Planet. Space Sci.* **15**, 863
Treanor P. J. 1973, *Observatory* **93**, 117
Walker M. F. 1973, *Publ. Astr. Soc. Pacific* **85**, 508
Walker M. F. 1977, *Publ. Astr. Soc. Pacific* **89**, 405
Walker M. F. 1988, *Publ. Astr. Soc. Pacific* **100**, 496

SKY BRIGHTNESS AT TERAMO OBSERVATORY

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ABSTRACT. Recent CCD measurements of the sky brightness, giving a mean value $V = 19.25 mag/arcsec^2$ and $B = 19.60 mag/arcsec^2$ near the zenith, are presented. A brighter background is, of course, measured toward the town due to the light pollution.

1. The telescope of Teramo Observatory

The telescope in use at Teramo Observatory is a 72 cm equipped with a Tektronics CCD 512×512 (UBVRI system) or a photoelectric photometer (UBV). It became available since 1995 and from that epoch several papers based on observations collected at that telescope have been published concerning variability of both pulsating stars and peculiar objects (Brocato & Stiavelli (1997), Nesci et al. (1997), Castellani et al. (1998)). This is , if necessary, a further demonstration of the utility of small telescopes in long-time baseline researches. Although the sky brightness put severe constraints to the limiting magnitude, particularly in the direction of the town which is on the north-west of the Observatory, accurate differential photometry is possible down to $V = (16 - 17) mag$.

2. The sky brightness

To derive an estimate of the sky brightness we used the data collected during several photometric nights, from February to June 1998, devoted to calibrate the comparison stars of our program targets. During these nights all coefficients required for the calibration were derived, included the extinction coefficients, through the observation of several standard stars (Landolt 1992).
In the following table we report sky brightness estimates in both B and V filters and the extinction coefficients for each observing night. The measurements reported in table 1 are corrected for the extinction of the standard stars used as comparison, thus they have to be considered 'inside' the atmosphere at the given zenital distance z and hour angle HA. It is easy to verify that the sky brightness increases at positive hour angles (that is in the town direction) with a rate that can't be explained with the airmass contribution. Thus while the absolute values of the sky brightness for each night are quite large and meaningless (specially in B), let us to stress that an estimate of about 0.5 mag for the increase of the sky brightness going from the South to the West is a rather robuste evidence.

By averaging the data on table 1 one gets for a mean sky brightness (outside the atmosphere) the values $V = 19.25 mag/arcsec^2$ and $B = 19.60 mag/arcsec^2$ near the zenith.

Tab. 1 - Sky brightness measurements at different positions

Night	V_{sky}	k_V	B_{sky}	k_B	z	HA
18-02-1998	19.50	0.10	19.82	0.25	40^o	$\simeq 0^h$
18-02-1998	18.92		19.45		55^o	$+3^h$
20-04-1998	19.62	0.17	20.50	0.29	36^o	$\simeq 0^h$
20-04-1998	18.89		19.64		64^o	$+4^h$
21-04-1998	19.09	0.24	20.20	0.50	42^o	$\simeq 0^h$
21-04-1998	18.24		19.54		63^o	$+5^h$
29-06-1998	19.75	0.26	19.77	0.35	34^o	$\simeq 0^h$
29-06-1998	19.42		19.68		47^o	$\simeq +2^h$

References

Brocato, E. , Stiavelli, M.: 1997, IAUC 6729

Castellani, V. , Di Paolantonio, A., Piersimoni, A. , Ripepi, V.: 1998, *Astron. Astrophys.* **333**, 918

Landolt, A.: 1992, *Astron. J.* **104**, 340

Nesci,R., D'Alessio, F., Maesano, Massaro,E. Montagni, F.: 1997, *Mem. Soc. Astron. It.* **68**, 205

MEASUREMENTS OF LIGHT POLLUTION OF PADUA

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ABSTRACT. We present the results of the Padua sky brightness measurement obtained in 1998 with CCD photometry. The average night-sky zenith brightness results 17.53 ± 0.03 $m_V/arcsec^2$. On the basis of the results of a Garstang model kindly provided by P. Cinzano we disentangled the contribution of the city of Padua from that of the hinterland and we calculated the light flux sent toward the sky from the city of Padua which resulted of about 255 *lumens* per head.

1. Introduction

Padua is one of the cities included in the "Urban Lighting Plans" of the Veneto Region's Law n.22 of the 27 June 1997, the first against the light pollution in Italy, being Padua the observation site of the Observatory "Giuseppe Colombo".

With this work we want to start a program to monitor night-sky brightness in Padua to evaluate the future variation.

In the following sections we describe the methods used to observe and reduce the photometry for the sky brightness, as well as the calculation used to estimate the total light flux sent from Padua toward the sky.

2. Observations and reductions

Photometry for the sky brightness is done using the CCD observations obtained with a PXL-211 CCD camera attached to the Newtonian focus of the 0.35-m f/5.6 reflector at the "Guido Ruggieri" private Observatory. This Observatory (East Longitude: $+11°$ $53'20''$; Latitude: $+45°$ $25'10''$; Height (m.s.l.): 50 m) is located inside the city of Padua, 3 km North from the center of the old city. The PXL-211 CCD camera, made by Pixel (Oakland, USA), incorporate a Texas Instruments TC211 chip, which is a full-frame CCD sensor arranged in 192x165 pixel, each pixel being 13.75 μm by 16 μm. At the focus of the telescope, the scale is 105.24 arcsec mm^{-1}. Thus, 1 pixel of CCD subtends 1.45 x 1.68 arsec and the total field of view is 4.63 x 4.63 arcmin. The spectral sensitivity measured by Favero of the chip TC211, is shown in figure 1. The CCD camera is cooled by a thermoelectric element with forced ventilation to remove heat from the hot side and equipped with a 12 bit converter. No mechanical shutter is avaible. The sensitivity across

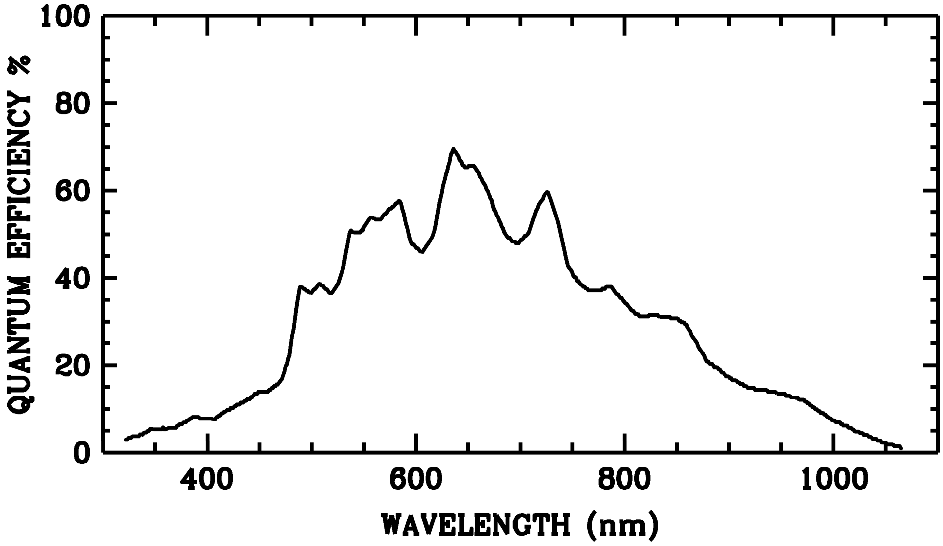

Fig. 1. The measured spectral sensitivity of the chip TC211.

the chip results very uniform and it has very little imperfections (1.4 ADUs Standard Deviation). This fact makes unimportant the correction of the image for the flat field.

The filter set used during the observations are:

Bandpasses	Filter (thickness mm)
B	BG12(2)+BG39(1)+GG385(1)
V	GG495(2)+BG39(2)
R	OG570(2)+KG3(2)
I	RG9(2)+WG280(2)

This filter set and CCD combination resulted in rather small coefficients when transforming the instrumental magnitudes to the standard Johnson-Cousins system. By observing standard stars, the photometric repeatibility of the system results to have a precision better than 1% from night to night.

A total of 3 nights of observations has been collected for the determination of night-sky brightness. All sky measurements have been taken in the V band. The magnitudes of the stars used to calibrate the CCD images are selected by the list of bright stars of "the Astronomical Almanac for the year 1998".

It is important to note that for the exact determination of sky brightness it is necessary to know the magnitude of the standard star inside the atmosphere. This involves the determination of the extinction coefficients every night.

Tab. 1 - Observations of the night-sky brightness of Padua

UT h m	z °	A °	Brightness $m_V/arcsec^2$	n	Flamsteed/Bayer Star Designation			V	Spectral Type
February 18, 1998 - Extiction coefficient: $k_V = 0.47$									
20 42	72	184	16.28	2	25	δ	CMa	1.84	F8 Ia
20 56	43	204	17.14	2	12		Mon	5.83	K0 III
21 01	29	192	17.34	2	54	λ	Gem	3.58	A4 IV
21 16	11	70	17.77	2	9	ι	UMa	3.14	A7 IVn
February 19, 1998 - Extiction coefficient: $k_V = 0.79$									
20 15	71	177	15.31	3	28	ω	CMa	3.85	B2 IV-Ve
20 24	39	195	16.55	4	13		Mon	4.50	A0 Ib-II
20 37	29	182	16.68	3	54	λ	Gem	3.58	A4 IV
20 48	17	173	16.95	4	75	δ	Gem	4.28	K1 III
20 59	7	30	17.18	4	27		Lyn	4.84	A1 Va
March 26, 1998 - Average extiction coefficient: $k_V = 0.48$									
20 12	64	94	16.62	3	5	υ	Boo	4.06	K5.5 III
20 17	40	99	17.25	3	15	γ	Com	4.35	K1 III Fe 0.5
20 20	24	72	17.59	3	63	χ	UMa	3.71	K0.5 IIIb
20 26	9	102	17.52	3	33	λ	UMa	3.45	A1 IV
20 33	5	244	17.47	2	36		Lyn	5.32	B8p Mn III
20 55	63	159	16.22	3	12	δ	Crt	3.56	G9 IIIb CH 0.2
20 52	43	148	16.82	3	77	σ	Leo	4.05	A0 III$^+$
20 49	29	145	17.15	3	60		Leo	4.42	A0.5m A3 V
20 46	11	160	17.44	3	21		LMi	4.48	A7 V
20 40	5	149	17.46	3	19		LMi	5.14	F5 V
20 59	60	183	16.21	3	39	υ^1	Hya	4.12	G8.5 IIIa
21 02	47	189	16.69	3	35	ι	Hya	3.91	K2.5 III
21 06	22	195	17.06	2	15	ϵ	Leo	2.98	G1 II
21 10	10	188	17.23	3	21		LMi	4.48	A7 V
21 15	3	188	17.31	3	33	λ	UMa	3.45	A1 IV
21 29	49	219	16.81	3	5	σ	Hya	4.44	K1 III
21 33	36	230	17.20	3	47	δ	Cnc	3.94	K0 IIIb
21 38	16	241	17.51	3	10	SU	LMi	4.55	G7.5 III Fe-0.5
21 42	6	247	17.54	3	33	λ	UMa	3.45	A1 IV
21 57	57	280	17.12	3	44	κ	Aur	4.35	G9 IIIb
22 03	47	268	17.17	3	60	ι	Gem	3.79	G9 IIIb
22 07	30	281	17.56	3	31		Lyn	4.25	K4.5 III
22 11	15	280	17.70	3	HR	N°3881		5.09	G0.5 Va
22 21	65	304	16.90	3	10	η	Aur	3.17	B3 V
22 26	44	330	16.49	3	HR	N°2209		4.80	A0 IV$^+$ nn
22 29	25	326	17.64	3	23		UMa	3.67	F0 IV
22 43	23	299	17.49	3	26		UMa	4.50	A1 Va
22 48	8	267	17.22	2	52	ψ	UMa	3.01	K1 III
22 51	3	327	17.58	3	63	χ	UMa	3.71	K0.5 IIIb
23 01	24	353	17.47	2	1	λ	Dra	3.84	M0 III Ca-1
23 14	44	5	17.43	1	23	δ	UMi	4.36	A1 Van
23 21	35	48	15.50	3	13	θ	Dra	4.01	F8 IV-V
23 26	23	26	17.53	3	11	α	Dra	3.65	A0 III
23 31	4	325	17.76	3	3		CVn	5.29	M1$^+$ IIIab

To prevent the CCD saturation for the bright standard stars, each stellar image has been blurred, placing it slighty out the focus. In this way it was possible to do safely exposures from five to thirty seconds, depending on the magnitude of the star. Consequently, to determine the ADUs values with the computer program, simulating a fixed aperture photometer, square areas of 30x30, 35x35 or even 53x53 pixels were measured. The same apertures were applied to measure star+sky and then sky alone.

To do the photometric reductions, it has been used the SpectraSource Instruments LYNXX PC program, version 1.04b Dec 15 1990. From each exposure it has been subtracted the relative dark, acquired after each exposure with the same exposure time.

The CCD flat field can be considered quite uniform, having worked out blurred images that occupied several pixels.

For the determination of the extinction coefficient, the measurements have been made for several standard stars, at zenith distance for six meridians all around the sky. Then, it has been possible to calculate the k_V atmospheric extinction coefficient, plotting the apparent magnitude *versus* the air mass (Bouguer's function method). Given that $m = m_\circ + k\ sec\ z$ and $m = C$ -2.5 log [star ADU] where $m_\circ$ is the catalogue magnitude and z the zenith distance, the sky magnitude is otained by the formula:
μ_{sky} = -2.5 log (sky ADU/star ADU) + ($m_\circ + k\ sec\ z$)

3. Results

The observations of the night-sky brightness obtained for every night are given in the fourth column of Table 1. The remaining columns report in the order: (1) the mean UT of observations, (2) the zenith distance and (3) azimuth of the observed standard star, (5) the number n of the images taken for every star and (6)(7)(8) the features of the standard stars used for the night-sky brightness determination. For every night, the measured extinction coefficient k_V is also reported. To verify the reliability of these measurements for every standard star we calculated the photometric costant
C = 2.5 log [star ADU] + $m_\circ + k\ sec\ z$ with an error smaller than 0.3%.

Figure 2 shows the behaviour of the sky brightness values reported on Table 1 versus the zenith distances. The continuous line is the fit of these values of the sky brightness with a polynomial of the second degree for the night of March the 26^{th}. From this line fitting we obtained the zenith sky brightness over the observation site, which resulted $17.53 \pm 0.03\ m_V/arcsec^2$. The atmospheric and photometric conditions during the same night allowed us to get measurements of the sky brightness for different meridians and zenith distances. Fitting again the brighteness values with a polynomial of the second degree, separately for each individuated meridian (0°-180°, 45°-225°, 80°-260°, 100°-280°, 130°-310° , 150°-330°) it has been possible to construct the sky's isophots for values of 16.0 ,16.5, 17.0 and 17.5 $m_V/arcsec^2$ (Fig. 3). In the same figure the points used for the fit are also reported. The orientation of the figure is the following: 0° North, 90° East. The asymmetry course of the isophots reflects the town's planimetry whose center is 3 km South. The average color indices of the night-sky of Padua near the zenith for the night of March the 26th were found to be B-V=1.11, V-R=0.06, V-I=0.38, with an error of about 1%.

4. Calculation of the upward Flux

With the sky brightness measurements of March the 26^{th} it has been possible to estimate the total light flux emitted toward the sky from the city of Padua. We transformed the brightness in luminance using the Garstang's formula valid in the V band, reported by Cinzano (1997,p.112): b [cd/m^2] = $10^{-0.4(V-12.603)}$.

In order to separate the light flux of Padua from that of the hinterland, we used a Garstang's model (Garstang 1986) kindly provided by P. Cinzano. The model has been used to estimate both the sky brightness produced by the city of Padua alone

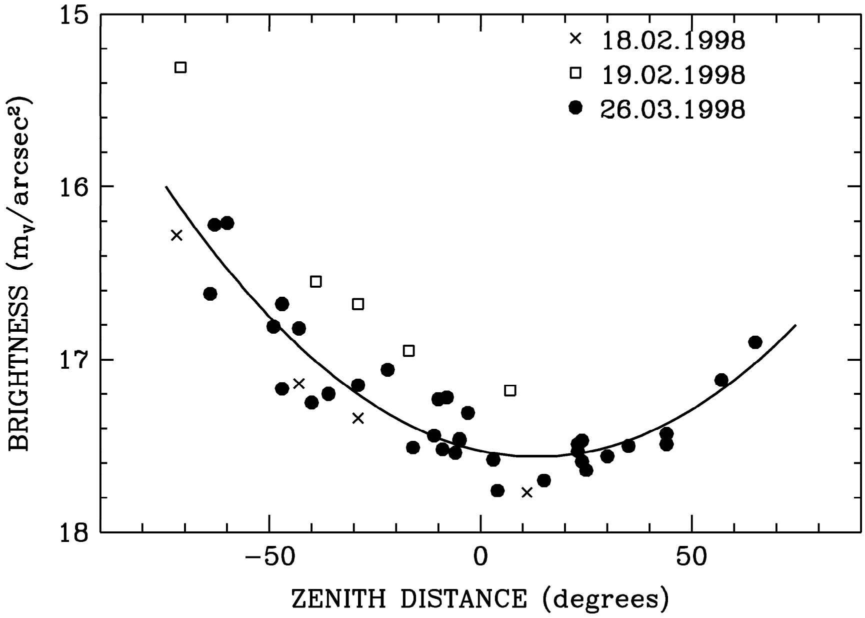

Fig. 2. Dots are sky brightness along six meridians trough downtown Padua for March the 26^{th}. Continous line is the fit of dots with a polynomial of the second degree. Crosses and squares are sky brightness for February the 18^{th} and 19^{th} respectively. Zenith distance is negative toward Padua city-center.

and that produced by of all sources in a territory of 120 km around Padua: it refers to clean atmosphere as defined by Garstang (1986). We obtained the artificial luminance produced by Padova alone, first subtracting the natural sky brightness estimed by the model, and then multiplying each measurement of artificial luminance by the ratio

$$r = \frac{(b_{Pd})_{calc}}{(b_{tot})_{calc}} \tag{1}$$

obtained from the models. The ratio r increase if sky is less clean: in this case the contribution from higher distances decrease due at stronger extinction. The ratio r also depends on the assumed light emission function of the city: if the emission toward the zenith of cities is lower than assumed in respect to the emission at higher zenith distances, the ratio is lower (see Cinzano 1999 for details on modelling). Then we determined the artificial sky luminosity $L_\circ$ produced by Padova alone in the observation site integrating the luminance in function of the zenith distance and of the azimut along the six meridians previously specified (see section 3).

In order to obtain the luminosity L respect to the Padua's city-center we assumed in first approximation that the sky luminosity L follows a Walker-like law (Walker 1997)

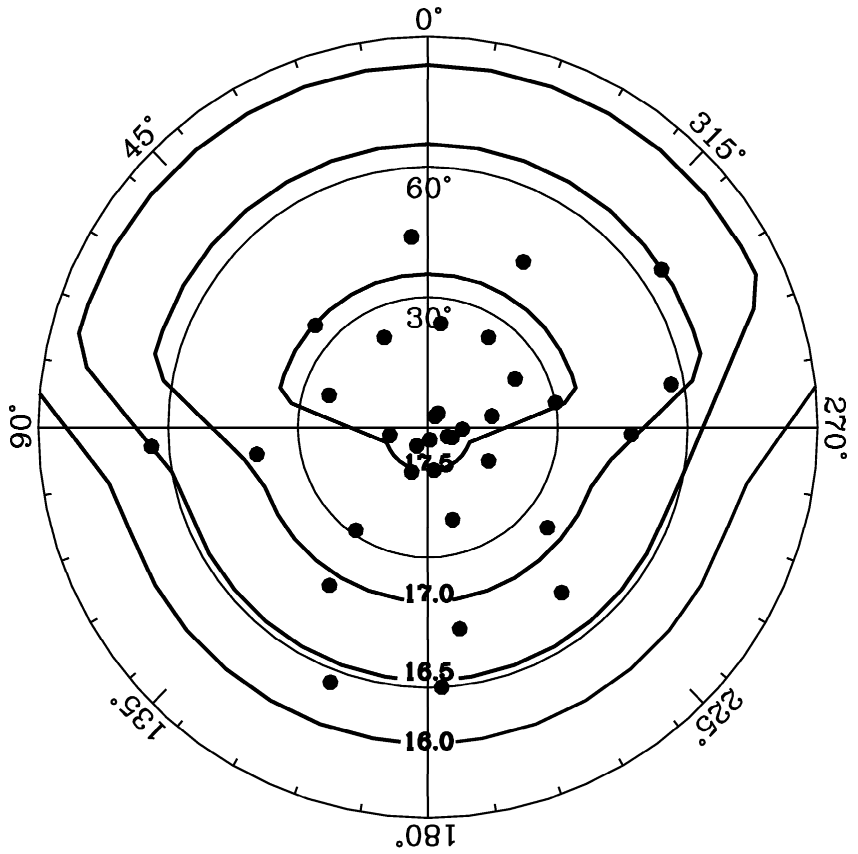

Fig. 3. Isophots of Padua's sky from "Guido Ruggieri" Observatory. South (180°) is toward Padua city-center. Dots are observed data of March 26, 1998.

like the brightness: from this hypothesis it follows that $L = c \cdot r^{-2.5}$, where r is the distance from the city-center and c a proportionality constant.

According to this relation the light flux emitted by Padua and reflected down by the atmosphere is:

$$F' = \int \int_S L dS = \int_0^\infty c \cdot r^{-2.5} \cdot 2\pi r dr \qquad (2)$$

Assuming that for a distance from the city-center $r \leq D$ the luminosity remains con-

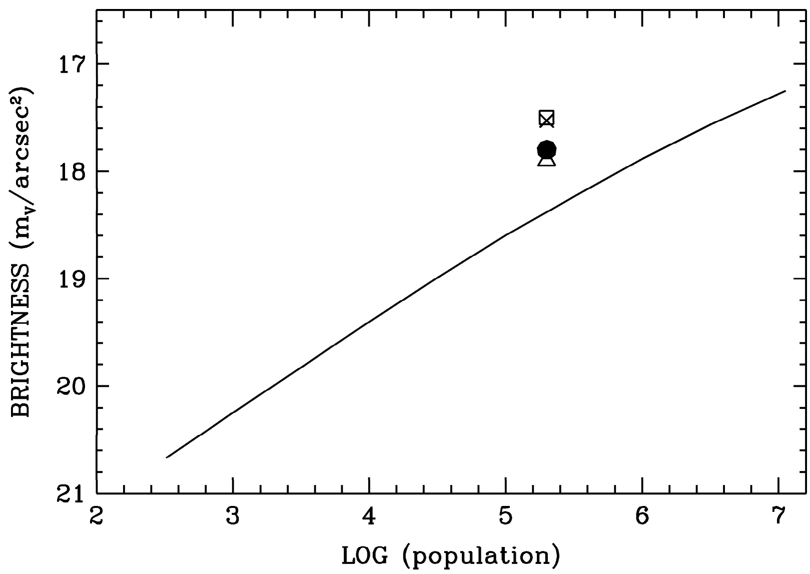

Fig. 4. City-center zenith brightness as function of population. Solid line is a model for very clean atmosphere (Garstang 1986). Theoretical dot is the prediction for Padua alone in 1998 and for standard clean atmosphere (Cinzano 1999). Square is the datum by the same Cinzano's model of Padua plus hinterland in 1998. Cross is the observed datum of March 26, 1998 and triangle is the datum corrected with r for Padua alone.

stant, we obtained:

$$F' = \int_0^D c \cdot r^{-2.5} \cdot 2\pi r dr + \int_D^\infty c \cdot r^{-2.5} \cdot 2\pi r dr \qquad (3)$$

where $c = L_\circ / r_\circ^{-2.5}$, $L_\circ \simeq 1.80 \cdot 10^{-2} lm/m^2$ and $r_\circ = 3\ km$ the distance of "Guido Ruggieri" Observatory from the city-center. Calculating the integral we obtained, for $D = 1\ km$, $F' \simeq 5.36 \cdot 10^6$ *lumens* In the hypothesis that a clear sky reflects 10% of the incident light, according to Cristaldi (1992), the total light flux that Padua send toward the sky is: $F_{up} \simeq 5.36 \cdot 10^7$ lumens.

According to an estimation of 1998, the population in Padua amounts to about $2.1 \cdot 10^5$ inhabitants; then the light flux emitted toward the sky in 1998 is nearly of 255 *lumens* per head. A comparison with a measurement of sky brightness in Padua in 1986 by G. Favero giving *under the atmosphere* $18.5 \pm 0.2\ mag/(arcsec)^2$ in V, where the incertitude depends on extinction indetermination, suggest an increase of the total artificial light flux of about $8.0^{+1.2}_{-2.1}$ percent per year in the last twelve years. The total installed flux by public street lighting in Padua in 1994 was of 719 lumens per head (Roman 1995). Likely public street lighting is responsible only of about 60% of the total public and private installed flux. So a reasonable value of total installed flux in 1994 is about 1200 lumens per head. Assuming an average true efficiency of luminaires of 60%, the total flux emitted would be of the order of 700 lumens per head. Scaling our upward flux measurement to the 1994, it result about 25% of the total emitted flux.

5. City-Center Zenith Brightness-Population Relation

With the city-center zenith brightness-population relation (fig.4) in Garstang's version (Garstang 1986) we can forecast that a city like Padua of $2.1 \cdot 10^5$ inhabitants has a zenith brightness of the order of 18.4 $m_V/arcsec^2$. This relation is valid only for very clean atmosphere.

The Garstang model provided by Cinzano for standard clean atmosphere and specifically done for Padua plus hinterland predict a zenith sky brightness at "G. Ruggeri" Observatory of 17.5 $m_V/arcsec^2$ for 1998 in good agreement with observations.

6. Conclusions

After measuring night-sky brightness and calculating the relative luminosity, we can assert that Padua's sky is about sixty times more luminous than a natural one. In 1998, about 25% of the total light flux emitted by public and private lighting installations was sent toward the sky. This waste of energetic resources, heavily comprimises astronomical researches at "Giuseppe Colombo" Observatory. The authors will keep under examination Padua's sky to verify if the application of the Veneto Region's law n.22 of the 27 June 1997, and the installation of cut-off fixtures, will be able to reduce, or at least to halt, the increase of the light flux sent toward the Padua's sky.

Acknowledgements

We appreciate advice, encouragement, and information received by prof. S. Ortolani. Thanks are due to R. Cariolato and A. Salmaso of the "Giuseppe Colombo" Observatory for the use of the facilities for data's reductions. We are indebted with P. Cinzano for interesting suggestions, for kindly revising this paper and providing the results of his models of artificial sky brightness.

References

Cinzano, P.: 1999, in this volume.
Cinzano, P.: 1997, Mem. Ist. Veneto Scienze, Lettere ed Arti, Venezia, v. 38.
Cristaldi, S.: 1992, private comunication.
Garstang, R. H.: 1986, *Publ. Astr. Soc. Pacific* **98**, 364.
Roman, A.: 1995, Thesis, University of Padova.
Walker, M.F. : 1977, *Publ. Astr. Soc. Pacific* **89**, 405.

THE COLORS OF THE SKY GLOW

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ABSTRACT. We present preliminary results on the behaviour of the B-V color index with the distance from polluting sources. Predictions obtained with models of light pollution propagation are compared with available measurements of color index in Italy.

1. Introduction

The colors of sky glow depends mainly on (1) how light of different wavelength propagates through the atmosphere, (2) the emission curve of the polluting sources, (3) the relative intensity of artificial and natural sky brightness and (4) the color of this last. Garstang (1993) studied with detailed models the changes with time of the colors of the sky connected with relative changes of the color of the light emitted by polluting cities due to the evolution of lighting technology.

In this paper we study the relation between the color index $B-V$ and the distance from a polluting source. In section 2 we present a comparison between predicted $B-V$ color index and available measurement in Italy and we discuss the results. In section 3 we shortly outline our preliminary conclusions.

2. Models, Observations and Results

We computed the $B-V$ color index of the artificial sky glow for increasing distances from a source with detailed models for light pollution propagation developed by Garstang (1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999) and recently applied in Italy by Cinzano (1999a, 1999b, 1999c). For a description of the modelling technique the readers is referred to the cited papers and, in particular, to Cinzano (1999a). The models allow the determination of the illuminance produced by a city on each infinitesimal volume of atmosphere along the line-of-sight of the observer taking in account extinction along light paths and both direct light and light scattered once from aerosols and molecules. The models take also in account the height o.s.l. of the observer and the polluting city, the aerosol content of the atmosphere and the ratio between upward emissions of the source in B band and in V band. An integration of the light scattered toward the observer by particles and molecules in the infinitesimal volumes along the line-of-sight allow us to obtain the sky brightness.

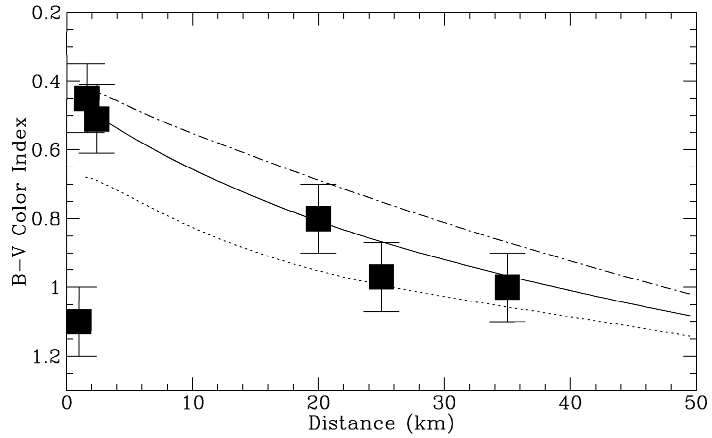

Fig. 1. $B-V$ color index and models predictions. Solid line is a model for an height of 1.000 m o.s.l. of the observer and zero height o.s.l. of the source computed for standard clean atmosphere. Dotted line and dashed line are models for zero height o.s.l. of both the observer and the source computed respectively for standard clean atmosphere and very clean atmosphere.

In figure 1 we show the measurements of $B-V$ color index near zenith in some Italian observatories collected from literature together with prediction of our model. Solid line is a model computed for an height of 1.000 m o.s.l. of the observer, zero height o.s.l. of the source and standard clean atmosphere as defined by Garstang (1986). For comparison, dotted line and dashed line are models computed for zero height o.s.l. of both the observer and the source, and respectively for standard clean atmosphere and very clean atmosphere. Models assume a V/B photon ratio of 2.3 at the source. This parameter does not affect the shape of the curves but shifts them along the vertical axis and it was chosen to optimize the fit of the first model (solid line) to observations. Measurements are done respectively at "G. Ruggieri" Observatory inside Padova (Favero et al. 1999), Collurania Astronomical Observatory (Piersimoni et al. 1999), Asiago Astrophysical Observatory (Cinzano 1999d), Mount Ekar Observatory (Cinzano 1999d), Bologna University Observatory in Loiano(Zitelli 1999) and Catania Observatory Stellar Station in Serra La Nave (Catanzaro et al. 1999). Measurements are *under the atmosphere*, i.e. catalogue magnitudes of the standard stars used in calibration have been corrected for the extinction of the light along its path to the telescope. The contribution of natural sky brightness to the measured color indexes, unknown, was not subtracted. Only for dark sites, where the artificial brightness is not prominent, the color index depends on the relative strength of the artificial and the natural sky brightness ($B-V \approx 1.1$ in dependence of direction of observation and airglow contribution) and is higher than the color index of the artificial brightness. Distances are average distances from the main polluting cities or areas. Errorbars are an estimate of the incertitude in the extinction.

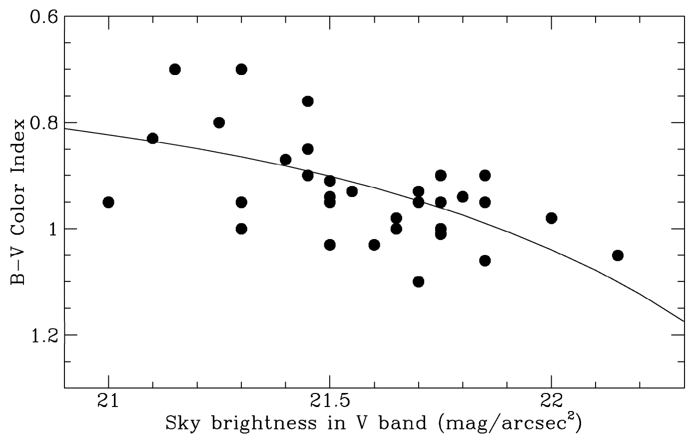

Fig. 2. Measurements of $B-V$ color index at Crimean Astrophysical Observatory and predictions as discussed in the text.

3. Conclusions

Measurements and models show that sky becomes redder as the observer move away from the sources. The redder color with increasing distance is produced by the stronger extinction of B wavelengths due at the λ^{-1} dependence of aerosol scattering and λ^{-4} dependence of Rayleigh scattering from molecules. The redder color index measured at "G.Ruggieri" Observatory inside Padova (the square at the lower left in figure 1) is likely produced by the greater aerosol content and by the greater V/B photon ratio at the source due at the great number of high pressure sodium lamps.

Our results might explain the correlation found by Lyutyi and Sharov (1982) at Crimean Astrophysical Observatory between sky brightness in V band and $B-V$ color index. If the artificial brightness from the nearby cities, increasing in mean of 0.03 mag per year from 1965 to 1980 (as shown in fig. 4 of the cited paper), change in dependence of the atmospheric conditions near the cities, then likely the color index varies in the range between its natural value and the artificial one. In this case the color index is:

$$B-V = 0.52 - 2.5log_{10}\frac{10^{\frac{0.52-(B-V)_a}{2.5}}\left(10^{\frac{41.44-V}{2.5}} - 10^{\frac{41.44-V_0}{2.5}}\right) + 10^{\frac{41.96-B_0}{2.5}}}{10^{\frac{41.44-V}{2.5}}} \quad (1)$$

where B_0 is the natural sky brightness in B band, V_0 is the natural sky brightness in V band and $(B-V)_a$ is the color index of artificial sky brightness. The numeric coefficients are computed from Garstang (1989) conversion formulae from magnitudes ($mag/arcsec^2$) to photon counts ($ph\ cm^{-1}\ s^{-1}\ sr^{-1}$). The fit of this equation to Lyutyi and Sharov (1982) measurements *under the atmosphere* (from their table I) is showed in figure 2 for $V_0 = 22.15$, $B_0 = 23.25$ and $(B-V)_a = 0.7$.

Acknowledgements

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References

Catanzaro, G., Catalano, F.A. 1999,in this volume.
Cinzano, P. 1999a, in this volume.
Cinzano, P. 1999b, in this volume.
Cinzano, P. 1999c, in this volume.
Cinzano, P. 1999d, in this volume.
Favero, G., Federici, A., Blanco, A.R., Stagni, R. 1999, in this volume.
Garstang, R.H. 1984, Publ. Astron. Soc. Pacific, 96,788.
Garstang, R.H. 1986, Publ. Astron. Soc. Pacific, 98, 364-375.
Garstang, R.H. 1987, in Identification, optimization and protection of optical observatory sites, eds. R.L. Millis, O.G. Franz, H.D. Ables & C.C. Dahn (Flagstaff: Lowell Observatory), p. 199-202.
Garstang, R.H. 1988, The Observatory, 108, 159-161.
Garstang, R.H. 1989a, Publ. Astron. Soc. Pacific, 101, 306-329.
Garstang, R.H. 1989b, Ann. Rev. Astron. Astrophys., 27, 19-40.
Garstang, R.H. 1989c, Bull. of American Astron. Soc., 21, 2, 759-760.
Garstang, R.H. 1991a, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conf. Series 17, p. 56-69.
Garstang, R.H. 1991b, Publ. Astron. Soc. Pacific, 103, 1109-1116.
Garstang, R.H. 1991c, The Observatory, 111, 239-243.
Garstang, R.H. 1992, Bull. of American Astron. Soc., 24, 740.
Garstang, R.H. 1993, Bull. of American Astron. Soc., 25, 1306.
Garstang, R.H. 1999, in this volume.
Lyutyi, V.M., Sharov, A.S. 1982, Soviet Astron., 26(1), 105-109.
Piersimoni, A., Di Paolantonio, A., Brocato, E. 1999, in this volume.
Zitelli, V. 1999, in this volume.

PROPOSAL OF A SPECTROSCOPIC MAP OF ASTRONOMICAL SITES

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ABSTRACT. We propose to both professionals and amateurs to carry out spectroscopical mapping of the sky i.e. the determination of the spectroscopical map $I(\alpha, z, \lambda)$ where I is the sky brightness in the direction of azimuth α and zenith distance z. Its knowledge would allow, among other things, (i) a better study of the propagation of light pollution at the different wavelength; (ii) the determination with a simple integration of the sky brightness in every direction and in every band or filter's bandpass even if non standard; (iii) the determination of the spectral emission function of the sources (cities); (iv) the monitoring of their changes with the time.

In order to obtain usable results this kind of research requires much care, preliminar studies, the preparation of a capable equipment and some work to be applied correctly. Nevertheless we think that it could be within every advanced amateurs reach.

This research note summarizes the main points of the methode we proposed (Rosoni 1997). Details will be discussed in forthcoming papers.

1. Introduction

In order to better control light pollution it is necessary to better know it and its behaviour.

Common measurements pratices consist of a mapping of the sky brightness in one or few photometrical bands. It is also common pratice in some branch of astronomy to obtain spectra of the sky background but the works so far published are restricted to the study of spectra taken only in one or few directions of the sky (Jenkins & Unger 1991; Louistisserand et al. 1987; Massey & Gronwall 1989; Massey et al. 1990; Osterbrock et al. 1976; Osterbrock & Martel 1992; Turnrose 1974).

Here we propose to both professionals and amateurs to carry out a spectroscopical mapping of the sky. The determination of the spectroscopical map $I(\alpha, z, \lambda)$, where I is the specific sky brightness at wavelength λ in the direction of azimuth α and zenith distance z, would allow, among other things, (i) a better study of the propagation of light pollution at the different wavelength; (ii) the determination with a simple integration of the sky brightness in every direction and in every band or filter's bandpass $F(\lambda)$ even if non standard:

$$b(\alpha, z) = \int_{band} F(\lambda) I(\alpha, z, \lambda) d\lambda \tag{1}$$

(iii) the determination of the spectral emission function of the sources (cities) which is not necessarily equal to the integrated spectrum of all its lamps due to the spectral

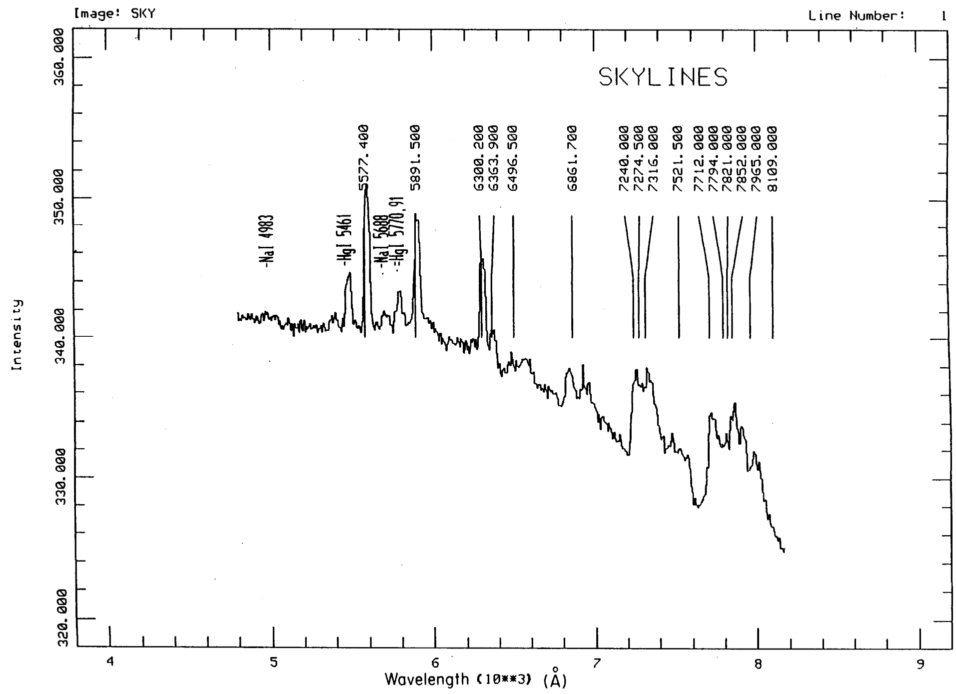

Fig. 1. A spectrum of the night sky at the Mount Ekar Observatory from 4800Å to 8200Å taken in 1990 by Pierantonio Cinzano and kindly provided to us. Natural sky lines and lines from artificial lighting are shown.

response of the reflecting surfaces still unknown; (iv) the monitoring of the changes with the time.

This kind of work is quite difficult because it needs to be done very accurately in order to obtain usable results. This research note summarizes the main points of the methode we proposed (Rosoni 1997). Details will be discussed in forecoming papers.

2. Instruments and procedure.

The spectroscopical map $I(\alpha, z, \lambda)$ can be obtained as a discrete sequence of spectra taken in a set of directions of the sky (es. the sequence proposed by Matsushima (1964)) and can easily be stored electronically as a tridimensional array.

The spectra can be taken as CCD images or photographic images on the focal plane of a spectrograph. In the second case, more difficult, it is necessary a calibration of the plates or the film with a spectrosensitometer which expose sequences of spot of known intensity with light of different wavelenght or a sequence of spectra of a spectrophotometric standard source. This allows to obtain the response curve of the plate or the film at the different wavelength. Moreover, film or plates need to be scanned with a microdensitometer or other adequate devices.

Prisms and diffraction gratings are not difficult to find so that a spectroscope it is nowadays available also to amateurs.

Spectra needs two kind of calibration:

1. A calibration in wavelength allows to associate to each position along the spectrum its wavelenght. It requires one or two comparison spectra, at the sides of the scientific spectrum, obtained with a short exposure of a known spectroscopic standard source and with some optical devices able to send the images in the proper position.
2. A calibration in intensity allows to determinate the absolute value of the incoming flux. A calibration using a comparison spectra of a spectrophotometric standard star would require the knowledge of the estinction at the various wavelength in order to obtain the flux "under the atmosphere" which is of interest in studies of light pollution. The spectral extinction is rapidly variable with atmospheric conditions and not easy to determinate. A calibration for comparison with natural sky lines is uncertain due to their possible variability. The best thing would be to have a spectroscopical standard source at the ground not far from the telescope. This point is under study by the author.

3. Conclusions

Even if spectroscopical mapping require much care, preliminar studies, the preparation of a capable equipment and some work to be applied correctly, we think that it could be within every advanced amateurs reach.

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References

Fletcher, J.M. & Crampton, D. 1973, An astronomical view of high-pressure sodium lamps, Publ. Astron. Soc. Pacific, 85, 1-3.

Jenkins, C. & Unger, S. 1991, The night sky spectrum from La Palma, ING-La Palma Technical Note No. 82.

Louistisserand, S., Bucher, A., Koutchmy, S. & Lamy, P. 1987, Night sky optical spectrum from a high altitude observatory, Astron. Astrophys. Suppl. Ser., 68, 539-543.

Massey, P. & Gronwall, C. 1989, Spectrophotometry of the Kitt Peak night sky, Bull. of American Astron. Soc., 21,4,1067.

Massey, P., Gronwall, C. & Pilachowski, C.A. 1990, The spectrum of the Kitt Peak Night Sky, Publ. Astron. Soc. Pacific, 102, 1046-1051.

Matsushima, S. 1964, Site selection for a small observatory in the midwest, Publ. Astron. Soc. Pacific, 76, 224-230.

Osterbrock, D.E., Walker, M.F. & Koski A.T. 1976, The spectrum of light pollution at Mount Hamilton, Publ. Astron. Soc. Pacific, 88, 349-352.

Osterbrock, D.E. & Martel A. 1992, Sky spectra at a Light-Polluted Site and the use of Atomic and OH sky Emission lines for wavelenght calibration, Publ. Astron. Soc. Pacific, 104, 76-82.

Rosoni, S. 1997, Giornale di Astronomia Soc. Astron. It., 23, 3, 38-44.

Turnrose, B.E. 1974, Absolute spectral energy distribution of the night sky at Palomar and Mount Wilson Observatories, Publ. Astron. Soc. Pacific, 86, 545-551.

MODELLING LIGHT POLLUTION FROM SEARCHLIGHTS

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ABSTRACT. I analyzed with a simple double scattering model the artificial sky luminance produced by the Light Pollution coming from an advertising searchlight. I evaluated both the artificial luminance produced by direct illuminance of atmospheric particles and molecules on the line-of-sight and that produced by light scattered once. I take in account the height above sea level of the observing site and the orientation of the beam.

1. Introduction

The night sky is a world heritage. The increasing concern of the astronomical community for the growth of the sky brightness due to artificial lighting was expressed in a number of official documents and positions, as the Resolutions of the International Astronomical Union General Assembly (Resolution XVI/9 1976; Resolution XIX/B6 1985; Resolution XX/A2 1988; Resolution 1997) and the positions of many national astronomical societies and organizations (e.g. the American Astronomical Society; the XXXIV Assembly of the Societá Astronomica Italiana). The Commission Internationale de l'Eclairage (CIE) itself undertakes to give consideration to this concern.

Nevertheless, in some countries to the diffuse sky glow produced by outdoor night lighting and big billboards joins the light pollution produced by advertising searchlights. They light directly the sky to get attention of people and to signal the presence of some commercial activity. Not rarely they are installed even in the nearby of an astronomical observatory. Where laws or regulations against light pollution exist, they are prohibited or strictly regulated. As an example, the City of San Diego outdoor lighting control ordinance prohibits operation of searchlights for advertising purposes between 11:00 pm and sunrise, Tucson and Pima County Arizona Outdoor Lighting Control Ordinance (1987) prohibits the use of Laser source light or any similar high intensity light for outdoor advertising or entertainment when projected above the horizontal. Law of the Kingdom of Spain in protection of Canary Island Observatories states that exterior lightings, except those necessary to guarantee aerial navigation, should avoid emission above the horizon. In Italy the Law n.22 1998 of Veneto Region prohibits light beams towards the sky inside 25 km from the protected professional observatories and prescribes that they have to be oriented at least at 90 degrees from the directions of the observatories in the range from 25 km to 50 km. The Law n.17 1998 of regione Valle d'Aosta states that beams oriented upward are prohibited everywhere in side the territory of the Region. Many cities ordinances prohibit advertising searchlights in compliance with Road Code because they can distract car drivers.

The light scattered by searchlights was studied by many authors in order to determine optical characteristics of atmospheric aerosols or the vertical distribution of atmospheric components and from late thirties to the introduction of modern lidar sensing techniques it constituted an important way to study our atmosphere (e.g. Hulburt 1937, 1941, 1946; Johnson et al. 1939; Romantzov and Khvostikov 1946; Mikhailin and Khvostikov 1946; Smirnov 1946; Elterman 1954, 1962, 1964, 1966; Gordon et al. 1975). These authors, nevertheless, were mainly interested to observe the light scattered once by particles inside the beam and considered high order scattering as a disturbance to their determinations. Furthermore, they were interested to measure the brightness only along the axis of the beam and not in the sky near the beam (but see Hulburt 1941). Some theoretical works were also developed (e.g. Hunt 1968; Rybicki 1971; Romanova 1971, 1973).

The Light Pollution produced by light wasted by outdoor night lighting was studied in good detail in the last 25 years. From the theoretical point of view, studies started with the seminal work of Treanor (1973) and evolved in the following years (e.g. Pike 1976; Berry 1976; Yoke *et al.* 1986; Garstang 1984, 1986, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999; Joseph *et al.* 1991). A review is in Garstang (1991a). All these authors studied the artificial sky luminance produced by composed sources like the lighting system of a city or an industrial installation, not the pollution produced by a single fixture. In this paper I apply a simple double-scattering model based partly on the approach of Garstang (1986, 1989a, 1991b) to predict the artificial sky luminance produced by an advertising searchlight in order to determinate its disturbance to the astronomical observations. In section 2 the radiative-transfer model is described and discussed. In section 3 results are presented. Section 4 summarizes the conclusions.

2. Model description.

The beam is assumed to be emitted from a point source C at a height H_C above the sea level and at a distance D from the observing site O at a height H_O above the sea level. In order to became simple the beam is assumed to produce an output flux for unit of solid angle $F(\theta)$, where θ is the angular distance from the axis of the beam, given by:

$$F(\theta) = \frac{P \times \eta}{\Delta} \qquad \theta \leq \theta_0 \qquad\qquad F(\theta) = 0 \qquad \theta > \theta_0 \tag{1}$$

where Δ is the angular area of the beam in units of solid angle (assumed to be little), P is the power of the searchlight and η is the efficiency of the system lamp+fixture in the adopted photometric band. When available, the use of the true distribution of luminous intensity of the luminaire would be preferable. The orientation of the beam axis is determined by its azimut γ_b and its altitude α_b. I modelled the Light Pollution produced by the searchlight using the Garstang (1986) approach and neglecting Earth curvature. The effect of curvature is to produce a more rapid fall-off of sky luminance with distance at large distances but applications in this paper are limited inside 50 km from the observing sites where the effect of curvature is less than 2% (Garstang 1989a).

A telescope of area $\frac{\pi d^2}{4}$ situated in the observing site O collect from within a section $dV = \left(\pi\epsilon^2 u^2 du\right)$ of the cone of angle 2ϵ around the line-of-sight with thickness du at a distance u, a luminous flux $d\Phi$ given by:

$$d\Phi = \frac{\pi d^2}{4}\frac{1}{u^2}M_s(u)\xi_1(u)\left(\pi\epsilon^2 u^2 du\right) \tag{2}$$

where $M_S(u)$ is the luminous flux scattered toward the observer from particles of aerosol and molecules inside a unitary volume at the distance u along the line of sight. $\xi_1(u)$ is the extinction of the light during the path to the telescope:

$$\xi_1(u) = exp\left(-\int_0^u (N_m(x\sin\alpha)\sigma_m + N_a(x\sin\alpha)\sigma_a)\, dx \quad cosec\ \alpha\right) \tag{3}$$

where $N_M(h)$ and $N_a(h)$ are the vertical number densities of molecules and aerosols, and σ_m and σ_a are their scattering sections and α is the altitude of the line-of-sight.

The artificial sky luminance b, expressed as total flux for units of area of the telescope and for units of solid angle is found integrating the eq. 2:

$$b = \int_0^\infty M_s(u)\xi_1(u)du \tag{4}$$

The average illuminance of the element of the cone is the sum of the direct illuminance from the source and that produced by the light which reaches the element after some intermediate scattering events, estimated as below. The luminous flux for units of solid angle coming *directly* from the beam and scattered toward the observer from a unitary volume along the line of sight is:

$$M'_S(u) = (N_m(u\sin\alpha)\sigma_m(\psi) + N_a(u\sin\alpha)\sigma_a(\psi)) \times \left(\frac{F(\theta)}{s^2}\xi_2(s)\right) \tag{5}$$

where the angles ψ, θ and the distance s of the section from the source depend from the distance D, the azimuth and altitude of the line-of-sight (α, γ) and of the beam axis (α_b, γ_b), and the distance u along the line of sight through geometrical relations. The extinction $\xi_2(s)$ between the source site and the considered section is:

$$\xi_2(s) = exp\left(-\int_0^s (N_m(x\sin\gamma_b)\sigma_m + N_a(x\sin\gamma_b)\sigma_a)\, dx \quad cosec\ \gamma_b\right) \tag{6}$$

A single scattering model is not sufficient to describe the sky luminance produced by a searchlight. In a real atmosphere several scatterings may occur during the travel of a photon from the source to the telescope. Moreover, it is possible to estimate the sky luminance in directions for which the line-of-sight does not intersect the beam only taking into account at least two scatterings. The optical thickness $\tau = \int kdr$, where k is an attenuation coefficient, determines how important secondary and higher scattering is.

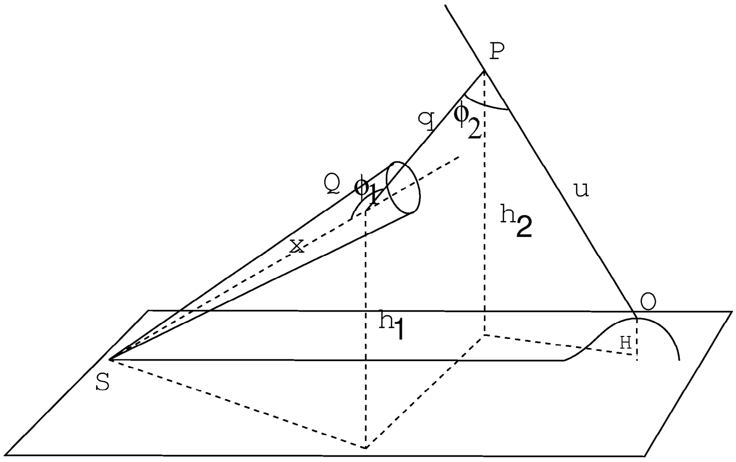

Fig. 1. Geometrical relationships for double scattering.

If $\tau >> 1$ (thick layer) multiple scattering is dominant. The fraction of incident radiation which has been scattered once is $(1 - e^{-\tau})$ and the fraction which it is scattered again is of order $(1 - e^{-\tau})^2$. If $(1 - e^{-\tau})$ is sufficiently small, which happens when τ is small, secondary and higher order scattering can be neglected. In absence of aerosol the optical thickness of the atmosphere at wavelength of 0.55 μm is about 0.1 (Twomey 1977). The aerosol optical thickness can be 0.05 in cleaner regions of the globe, but it can grow to higher values, even in dependence of seasonal changes (Garstang 1988). Then single scattering is the major contributor to scattered radiation but secondary scattering is not negligible. A double scattering model give only an approximation of the searchlight pollution and the error in neglecting third and higher order scattering can be significant for optical thickness higher than about 0.5. In order to take in account at least two scatterings, I computed, for each infinitesimal volume dV along the line of sight, the illumination coming from light scattered there by particles and molecules inside the beam. From it I obtained the luminous flux for units of solid angle scattered toward the observer from a unitary volume along the line of sight and coming from light scattered there from particles and molecules inside the beam:

$$M''_S(u) = \int_x \beta(h_1, \phi_1)\beta(h_2, \phi_2)\xi_a(q)\frac{F(\theta')}{q^2}\xi_b(x)dx \qquad (7)$$

where $\beta(h, \phi) = N_m(h)\sigma_m(\phi) + N_a(h)\sigma_a(\phi)$. The angles ϕ_1, ϕ_2, θ', the altitudes h_1, h_2 and the distance q depend from the distance D, the azimuth and altitude of the line-of-sight (α, γ) and of the beam axis (α_b, γ_b), the distance u along the line of sight and the integration variable x through geometrical relations. Figure 1 show the geometrical behaviour. The functions ξ_a and ξ_b are the extinctions of the light respectively between QP and SQ with expressions like (3) and (6).

I adopted the same model for the vertical distribution of molecules and aerosols as Garstang (1986) and the optical characteristics like the angular scattering coefficients

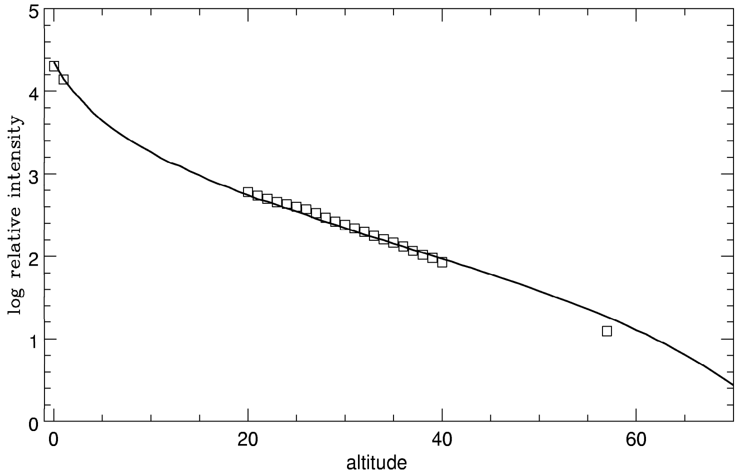

Fig. 2. Comparison between Eltermann(1966) measurement (squares) and model predictions (solid curve).

and scattering sections from Garstang (1986, 1991b), They already were successfully used in models for sky brightness in Italy (Cinzano 1999a,1999b). I calculated the natural night–sky luminance adopting the model described in Garstang (1989a) in the flat-Earth limit. It assumes that 40% of the light comes from the faint star background and a fraction of 60% comes from airglow emission by a van Rhijn layer at a height of 130 km above the ground, as found by Roach and Meinel (1955). The light which reaches the telescope is assumed to be made up of the contribution of the direct transmitted light and the light scattered from the whole sky by molecules and aerosols calculated taking in account double scattering. I assumed the solar activity near the minimum.

Sky brightness in V band can be obtained from sky luminance with Garstang (1986, 1989) formulae. Adopting the proper scattering sections and searchlight efficiency, the sky brightness in other photometric bands can be also computed.

I tested the models with the observations of a searchlight in April 1964 by Elterman (1966) at Sacramento Peak (New Mexico). I adopted $N_a\sigma_a = 9.5\ 10^{-3} km^{-1}$ and $N_m\sigma_m = 8.852\ 10^{-3} km^{-1}$ at the altitude of the beam source (1390 m over the sea level) and an aerosol scale altitude $c = 0.132 km^{-1}$, as inferred by Elterman 's measurements. Dividing the relative intensity measured by Elterman (1966) by the angular area of the searchlight as observed with Elterman 's collector telescope, I obtained a mean luminance distribution with elevation that I compared in figure 2 with the distribution of the luminance predicted by the model along the beam axis. They are in good agreement.

The model of the natural sky luminance was tested by Garstang (1989) comparing his results with measures obtained by Walker (1973) at Junipero Serra Peak. I compared the natural sky luminance predicted by my set of models at Sacramento Peak for the same atmospheric parameters used in Eltermann test with the measurements of Schneeberger

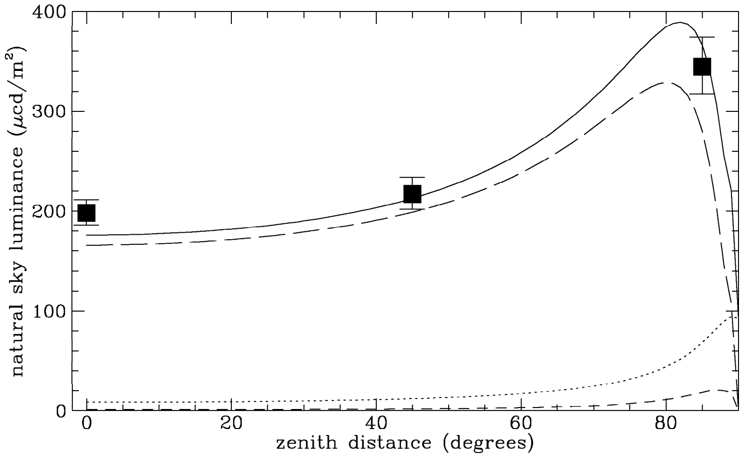

Fig. 3. Natural sky luminance as measured by Schneeberger et al.(1966) at Sacramento Peak(squares) and model predictions (solid curve). Also plotted are the contributions from direct light (long-dashed curve), aerosol scattering (short-dashed curve) and Rayleigh scattering from molecules (dotted curve).

et al.(1979) at zenithal angles 0 °, 45 °, 85 °. I trasformed its sky brightness measurements in V band from magnitudes to cd/m^2 with Garstang (1986) formulae. Results are in good agreement as shown in figure 3. Measures are annual average excluding June (which the authors considered particularly bright) and in Northeast direction (where no light pollution was detected) from table I of Schneeberger et al.(1979). Errorbars are not measurements errors but the standard deviation of the measurements along an year, related also to atmospheric fluctuations. A better fit can be achieved assuming that both natural sky brightness outside the atmosphere and aerosol content are slightly higher.

3. Results.

I computed the artificial sky luminance produced by a searchlight emitting a light flux of 150000 lm. With a mean lamp efficiency of about 90 lumens/watt and a fixture efficiency of the order of 80 percent, this flux would require a lamp with a power of about 2 kw. I assumed a beam aperture semiangle of 2°. High power advertising searchlights with carbon arc lamps have intensities even 8 times stronger than this searchlight (up to 10^9 candlepower). Results can be scaled to other emitted fluxes but other beam apertures require models be recomputed. I assumed a clean atmosphere as defined by Garstang (1986). In order to be simple I also assumed here both source and observer at sea level but other choices are possible.

Figure 4 shows the artificial sky luminance produced by the searchlight at increasing distances. Dotted and dot-dashed curves show respectively the luminance at 30°and 45°elevation for a vertical beam (inclination 90°). Dashed and long-dashed curves show

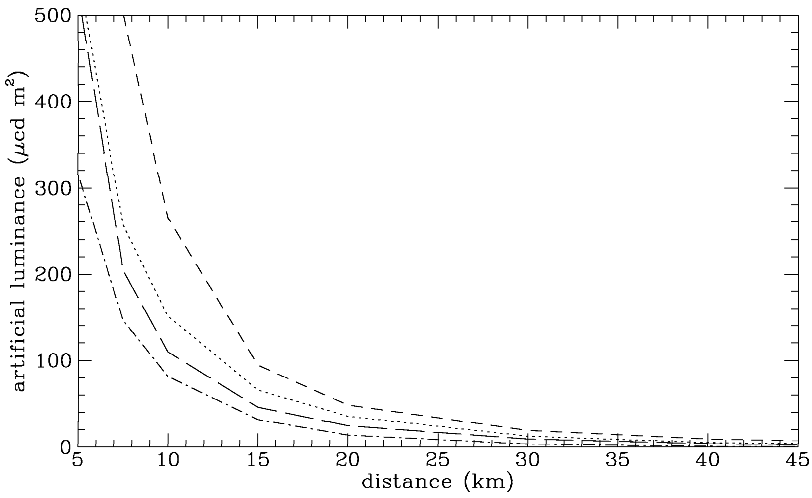

Fig. 4. Artificial sky luminance produced by the searchlight at increasing distances. Dotted and dot-dashed curves show respectively the luminance at 30°and 45°elevation for a vertical beam. Dashed and long-dashed curves show respectively the luminance at 30°and 45°elevation for a beam inclined at 45°toward the observer.

respectively the luminance at 30°and 45°elevation for a beam inclined at 45°toward the observer. The computations were done at distances of 5, 7.5, 10, 15, 20, 30, 40, 50 km and results are interpolated linearly in the figures. The figure shows the dramatic exponential increase of luminance with decreasing distance of the source. Already from this figure readers can notice that a distance of about 25 km is necessary in order that the contribution of this searchlight be lower than 10 percent of natural sky luminance ($\sim$ 200 10^{-6} cd/m^2), which is the limit requested by the recommendation 1 of the IAU Commission 50 (Smith 1979): *the increase in sky brightness at 45° elevation due to artificial light scattered from clear sky should not exceed 10% of the lowest natural level in any part of the spectrum between wavelengths 3000Å and 10000Å.*

However, the disturbance produced by searchlights to astronomical measurements may be even more relevant than the disturbance produced by diffuse glow with the same luminance. Frequently, to call more attention, advertising searchlights orientation has a random motion. This imply not only that the sky area disturbed by the searchlight is more extended than the beam area, but also that the motion of the beam produces a rapid and random varying background luminance. A beam interposing in the telescope field of view would produce a variable increase of photon counts resulting in an additional error on the measurement. Sky limited photometric observations of faint objects can be done down to level of the order of 1/100 of the background sky luminance with errors of 1 percent and probably require a lower limit than 10% on the sky brightness increase produced by the searchlight. The evaluation of this kind of disturbance, together with effects of changes in the spectrum of sky background, is left to subsequent papers.

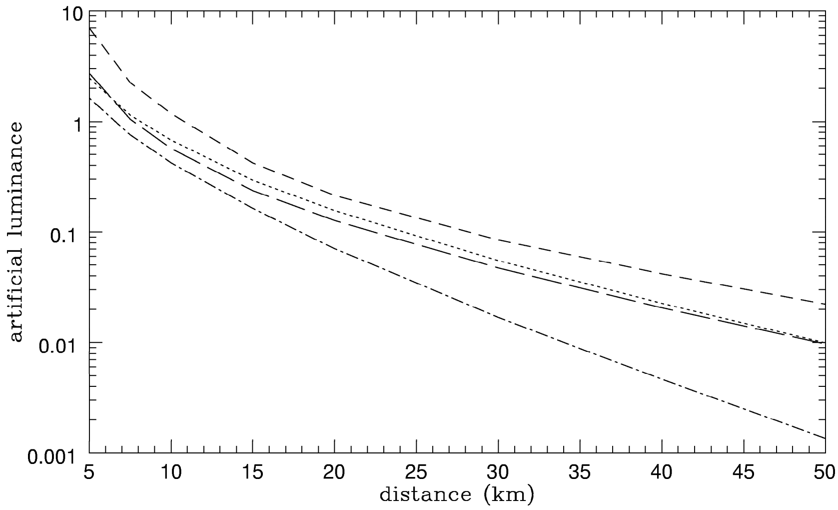

Fig. 5. Artificial luminance produced by the beam in logarithmic scale. Dotted and dot-dashed curves are respectively the luminance at 30°and 45°elevation for a vertical beam. Dashed and long-dashed curves show respectively the luminance at 30°and 45°elevation for a beam inclined at 45°toward the observer.

To these effects must also be added the reflection of the searchlight beam on dense aerosol layers which might be present at random positions and altitudes in dependence of atmospheric conditions. This phenomenon can produce very bright spots and can be another important source of errors which deserves to be studied in detail.

Figure 5 shows the artificial luminance produced by the beam in logarithmic scale. Curves symbology is the same as in figure 4. The figure shows that more than 30 km are necessary in order that over 30°of elevation the artificial luminance does not exceed 1/10 of the natural sky luminance. It can be estimated that more than 60 km are required for this purpose for an high power searchlight with an intensity 8 times higher, but if the beam is vertical only 35 km are necessary. The figure also show that in a moderately polluted site where, as an example, the sky brightness is 3 times the natural value, about 20 km are necessary to avoid a further increase of 10% of the sky luminance in the case of the modelled searchlight but it can be estimeed that about 50 km would be necessary in order to protect the observations from an high power searchlight 8 times more powerful. Only 25 km would be necessary if the beam would be vertical. At least for the considered searchlight powers and beam apertures, these results support the prescription of Law n. 22 1998 of Regione Veneto which prohibite light beams toward the sky inside 25 km from Mount Ekar Observatory and prescribe that they have to be oriented at least at 90 degrees from the direction of the Observatory in the range from 25 km to 50 km.

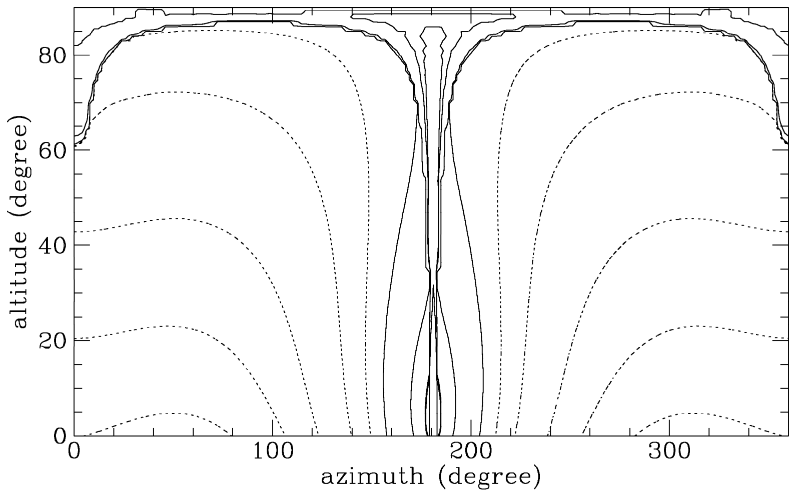

Fig. 6. Artificial sky luminance distribution produced by the searchlight at a distance of 10 km inclined 45°toward the observer. Azimuth 180°is towards the searchlight. Solid isophotes show levels of 2, 10, 50, 57, 200 $\mu cd/m^2$. Dotted isophotes show levels of 0.05, 0.1, .2, .5, 1 $\mu cd/m^2$ which are likely to be important for lower distances and higher powers.

Tab. 1 - Sky luminances along the beam axis

From 0°to 88°zenith distance in step of 2°($\mu cd/m^2$)								
0°	2°	4°	6°	8°	10°	12°	14°	16°
54	55	56	57	58	61	61	60	64
18°	20°	22°	24°	26°	28°	30°	32°	34°
62	64	65	66	70	70	73	73	77
36°	38°	40°	42°	44°	46°	48°	50°	52°
80	85	89	95	100	109	117	131	141
54°	56°	58°	60°	62°	64°	66°	68°	70°
159	176	203	233	274	322	386	493	587
72°	74°	76°	78°	80°	82°	84°	86°	88°
763	997	1262	1938	2664	3731	5887	10548	26100

Figure 6 shows the artificial sky luminance distribution produced by the searchlight at a distance of 10 km when inclined of 45°toward the observer. The effects of second scatter are clearly visible and it can be noted that the area of sky polluted is much larger than the beam area. Solid isophotes show the range under the natural sky luminance, at levels of 2, 10, 50, 57, 200 $\mu cd/m^2$. The level of the natural sky brightness is reached at an elevation of ∼32°along the beam. Higher level are reached below this elevation. Dotted isophotes show low levels of 0.05, 0.1, .2, .5, 1 $\mu cd/m^2$ which are likely to be important for lower distances and higher powers. Table 1 shows the sky luminances along the beam axis from 0°to 88°of zenith distance with step of 2°.

The total upward light emission, direct and reflected, from public lighting alone in the italian city of Treviso, computed from a detailed analysis of its fixtures, many of which are flat-glass shelded luminaires poorly polluting, resulted in 90 lm per inhabitant[1] (Medusa 1998). So the upward emission of the considered searchlight (with a power of $\sim$2 kw) is of the order of the upward emission of public lighting of a small town of about 1700 inhabitants.

4. Conclusions

In this paper I apply a simple double-scattering model based partly on the approach of Garstang (1986, 1989a, 1991b) to predict the artificial sky luminance produced by an advertising searchlight in order to determinate its disturbance to the astronomical observations. Main conclusions are:

1. In clear atmospheric conditions, a searchlight emitting 150000 lm with 2°aperture angle and inclined no more than 45°toward the observer produces a sky luminance greater than the 10 percent of the lowest natural level over 45°of elevation (recommendation 1 of the IAU Commission 50 (Smith 1979)) at a distance smaller than 25 km and over 30°at a distance smaller than 30 km.
2. An high power searchlight with an intensity 8 times higher would produce an increase greater than the 10 percent over 30°of elevation at a distance smaller than 60 km.
3. Boundary distance reduces when background sky luminance at the site increases. As an example, if background luminance is three times the natural value, boundary distances to avoid a further increase of 10% of the sky luminance reduces to about 20 km in the case of the modelled searchlight and at about 50 km in the case of an high power searchlight 8 times more powerful.
4. Results support the prescription of Law n. 22 1998 of Regione Veneto, at least for the considered searchlight powers and beam apertures. Higher emitted fluxes or more concentrated beams would require larger protection zones.
5. The polluted area of sky is not restricted to the beam area due to the effects of the second (and higher) scattering.

The effects of (i) the random interposition of the beam on the telescope field of view, (ii) the related changes in the spectrum of sky background, and (iii) the bright spots due at transient denser aerosols layers, deserves further studies to be quantified according to specific kinds of astronomical mesurements.

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[1] The mean total city upward emission per inhabitant in Italy is even more than three times stronger (e.g. Cinzano 1999a,b).

References

Berry, R. 1976, J. Royal Astron. Soc. Canada, 70, 97-115.

Bertiau, F.C.S.J., de Graeve, E.S.J. & Treanor, P.J.S.J. 1973, Vatican Observatory Publ., 1, 4, 159-179.

Cinzano, P. 1997, Inquinamento luminoso e protezione del cielo notturno (Venezia: Istituto Veneto di Scienze, Lettere ed Arti), 224 pp.

Cinzano, P. 1999a, in this volume.

Cinzano, P. 1999b, in this volume.

Elterman, L. 1954, J. Geophys. Res., 59,3.

Elterman, L. 1962 in Encyclopaedic Dictionary of Physics, ed. J. Thewlis (Pergamon Press: London).

Elterman, L. 1964, Applied Optics, 3, 745-749.

Elterman, L. 1966, Applied Optics, 5, 1769-1776.

Garstang, R.H. 1984, The Observatory, 104, 196-197.

Garstang, R.H. 1986, Publ. Astron. Soc. Pacific, 98, 364-375.

Garstang, R.H. 1988, The Observatory, 108, 159-161.

Garstang, R.H. 1989a, Publ. Astron. Soc. Pacific, 101, 306-329.

Garstang, R.H. 1989b, Ann. Rev. Astron. Astrophys., 27, 19-40.

Garstang, R.H. 1989c, Bull. of American Astron. Soc., 21, 2, 759-760.

Garstang, R.H. 1991a, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conf. Series 17, p. 56-69.

Garstang, R.H. 1991b, Publ. Astron. Soc. Pacific, 103, 1109-1116.

Garstang, R.H. 1991c, The Observatory, 111, 239-243.

Garstang, R.H. 1992, Bull. of American Astron. Soc., 24, 740.

Garstang, R.H. 1993, Bull. of American Astron. Soc., 25, 1306.

Garstang, R.H. 1999, in this volume.

Gordon, J.I., Edgerton, C.F. & Duntley, S.Q. 1975, J. Opt. Soc. Am., 65, 111-118.

Hulburt, E. O. 1937, J. Opt. Soc. Am, 27, 377-382.

Hulburt, E. O. 1941, J. Opt. Soc. Am, 31, 467-476.

Hulburt, E. O. 1946, J. Opt. Soc. Am, 36, 483-491.

Hunt, G.E. 1968 J. Appl. Math., 16, 228.

Joseph, J.H., Kaufman, Y.J. & Mekler, Y 1991, Appl. Opt., 30, 3047-3058.

Johnson, E.A., Meyer, R.C., Hopkins, R.E. & Mock, W.H. 1939, J. Opt. Soc. Am., 29, 512-517.

Medusa, C. 1998, Thesis, University of Padova (advisor L. Fellin, co-advisor P. Cinzano).

Mikhailin, L.M. & Khvostikov, I.A. 1946, Compt. Rend. Acad. Sci. USSR (Moskow), 54, 223-226.

Pike, R. 1976, J. Royal Astron. Soc. Canada, 70, 116-126.

Roach, F.E. & Meinel, A.B. 1955, *Astrophys. J.* ,, 122,554.

Romanova, L.M. 1971 Fiz. Atmos. Okean, 7, 1153.

Romanova, L.M. 1973 Fiz. Atmos. Okean, 9, 198.

Romantzov, I.I. & Khvostikov, I.A. 1946, Compt. Rend. Acad. Sci. USSR (Moskow), 53, 703-705.

Rybicki, G. 1971, J. Quant. Spectrosc. Rad. Transfer, 11, 827.

Schneeberger, T.J., Worden, S.P. & Beckers, J.M. 1979, Publ. Astron. Soc. Pacific, 97, 530-532.

Smirnov, I.P. 1946, Compt. Rend. Acad. Sci. USSR (Moskow), 53, 707-710.

Smith, F.G. 1979, Report and Recomandations of IAU Commission 50, Reports on Astronomy, IAU Trans.XVIIA, 218-222.

Treanor, P.J.S.J. 1973, The Observatory, 93, 117-120.

Twomey S. 1977, Atmospheric aerosols (Amsterdam: Elsevier).

Yocke, M.A., Hogo, H. & Henderson, D. 1986, Publ. Astron. Soc. Pacific, 98, 889-893.

THE ARTIFICIAL SKY LUMINANCE AND THE EMISSION ANGLES OF THE UPWARD LIGHT FLUX

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ABSTRACT. The direction of the upward light emission has different polluting effects on the sky depending on the distance of the observation site. We studied with detailed models for light pollution propagation the ratio $\frac{b_H}{b_L}$, at given distances from a city, between the artificial sky luminance b_H produced by its upward light emission between a given threshold angle θ_0 and the vertical and the artificial sky luminance b_L produced by its upward light emission between the horizontal and the threshold angle θ_0. Our results show that as the distance from the city increases the effects of the emission at high angles above the horizontal decrease relative to the effects of emission at lower angles above the horizontal. Outside some kilometers from cities or towns the light emitted between the horizontal and 10° is as important as the light emitted at all the other angles in producing the artificial sky luminance. Therefore the protection of a site requires also a careful control of this emission which needs to be reduced to at most 1/10 of the remaining emission. The emission between the horizontal and 10° is mostly produced by spill light from luminaires, so fully shielded fixtures (e.g. flat glass luminaires or asymmetric spot-lights installed without any tilt) are needed for this purpose.

An adequate protection of the sky with the aim to save citizen's capability to see the heavens near or inside cities and towns requires the limitation of the upward emission at all emission angles. Nevertheless a specific limitation of light emitted at low angles over the horizontal is useful also in highly urbanized areas where an important fraction of the artificial sky luminance, even inside mean-size cities, is produced by the sum of the contributions of a big number of sources in the surrounding land. The use of fully shielded fixtures can greatly reduce this contribution from outside.

1. Introduction

The light pollution produced by the upward light emission from night-time lighting causes a sky glow which disturbs and, sometime prevents, both astronomical observations and the capability of citizens to see the night sky, a world heritage.

Even if all the upward light emission causes pollution, the direction of this emission has different effects depending on the distance of the observation site.

We studied with detailed models for light pollution propagation the ratio $\frac{b_H}{b_L}$, at given distances from a city, between the artificial sky luminance b_H produced by its upward light emission between a given threshold angle θ_0 and the vertical and the artificial sky luminance b_L produced by its upward light emission between the horizontal and the

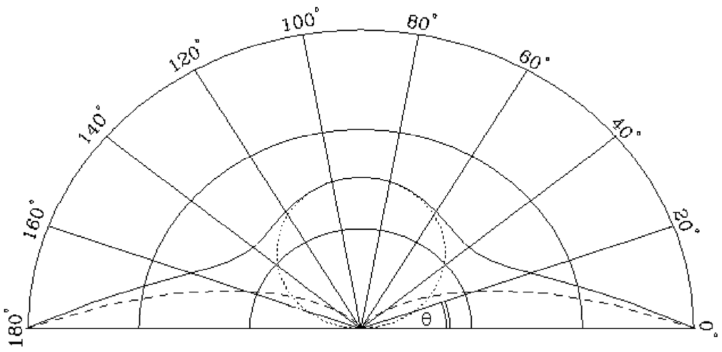

Fig. 1. Average city emission function from Garstang (1986).

threshold angle θ_0. In section 2 we summarize main steps in modelling the ratio. In section 3 we present our results. The conclusions are in section 4.

2. The modelling technique

The models are based on the modelling technique introduced and developed by Garstang (1986, 1987, 1988, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999) and applied in Italy by Cinzano (1999a, 1999b). Main steps are:

1. For each infinitesimal volume of atmosphere along the line-of-sight, the direct illuminance produced by the city and the illuminance due at light scattered once from molecules and aerosols are computed. The model assumes Rayleigh scattering by molecules and Mie scattering by aerosols.
2. The total flux that molecules and aerosols in the infinitesimal volume scatter toward the observer are computed from the illuminance
3. The artificial sky luminance of the sky in that direction is obtained with an integration.

Extinction along light paths is taken in account. The same atmospheric model as Garstang (1986, 1991) was assumed, with the density of molecules and aerosols decreasing exponentially with the height and the average scattering function of aerosols as measured by McClatchey et al. (1978). Computations has been done for standard clear atmosphere (Garstang 1996). We neglected the curvature of the Earth.

The average emission function of cities is the sum of the direct emissions from fixtures and the reflected emissions from lighted surfaces and is not well known. In a first set of models we used the average city emission function of Garstang (1986) (G=0.15, F=0.15). The function is shown in figure 1 together with the definition of the emission angle θ. We used the Garstang function considering it like a parametric expression which is a good approximation of the total city emission function, as stated by many successful comparisons of models to observational data (see cit.). We didn't give to its components any of the meanings gived by that author. We discarded the hypothesis that all surfaces emit only as a vertical Lambertian and that all fixtures emit only as θ^4 which was used by Garstang to introduce this expression. We considered parameters G and F only as shape parameters without any connection with reflected or directly emitted light. In a second set of models we used an isotropic city emission function for comparison purposes. When the line of sight approaches the city closer than 12 times its radius we use for it a seven points approximation (Abramowitz and Stegun 1964).

3. Results

Figure 2 shows the ratio $\frac{b_H}{b_L}$, at given distances from a city, between the artificial sky luminance b_H produced by its upward light emission between the threshold angle θ_0 and the vertical and the artificial sky luminance b_L produced by its upward light emission between the horizontal and the threshold angle θ_0. The ratios are computed for threshold angles θ_0 of 45°(top panel), 30°(middle panel) and 10°(bottom panel). Left panels show ratios for models with the Garstang city emission function (G=0.15, F=0.15), right panels show ratios for models with isotropic city emission function. Curve refers to zenith distances of 0°(solid curves), 30°(dotted curves), 45°(dashed curves), 60°(long dashed curves) toward the city.

The figure shows that only inside a city are the sky luminance produced by the emission over 45°and that produced by the emission between the horizontal and 45°of the same importance. Moving the observation site outward, their ratio decrease quickly. At a distance of ∼40 km the contribution near the zenith from light emitted over 45°by the city is about 1/100 of that from the light emitted between the horizontal and 45°. For higher zenith distances the ratio decreases slower but however it is small.

The sky luminance produced by the emission over 30° exceeds that produced by the emission between the horizontal and 30° inside the city boundaries but it is lower again outside. The ratios decrease with the distance from the city slower than in the previous case.

The sky luminance produced by the emission over 10° is much higher than that produced by the emission between the horizontal and 10° up to some km from the city. In models with Garstang emission function, the ratio $\frac{b_H}{b_L}$ near the zenith decreases at about 1 after ∼5 km and remains quite constant. In models with isotropic emission function, it decreases to about 2.5 after ∼10 km and also remains quite constant. For higher zenith distances the ratios can be slightly lower.

4. Conclusions

Our results show that:

1. An adequate protection of the sky with the aim to save citizen's capability to see the heavens near or inside cities and towns requires the limitation of the upward emission at all emission angles.
2. The protection of a site outside some kilometers from cities or towns requires not only a general control of upward flux (both coming from direct emission by fixtures and from reflexion by lightened surfaces) but also a careful control of the light emitted between the horizontal and 10°-20°. The light emitted in the range 0°-

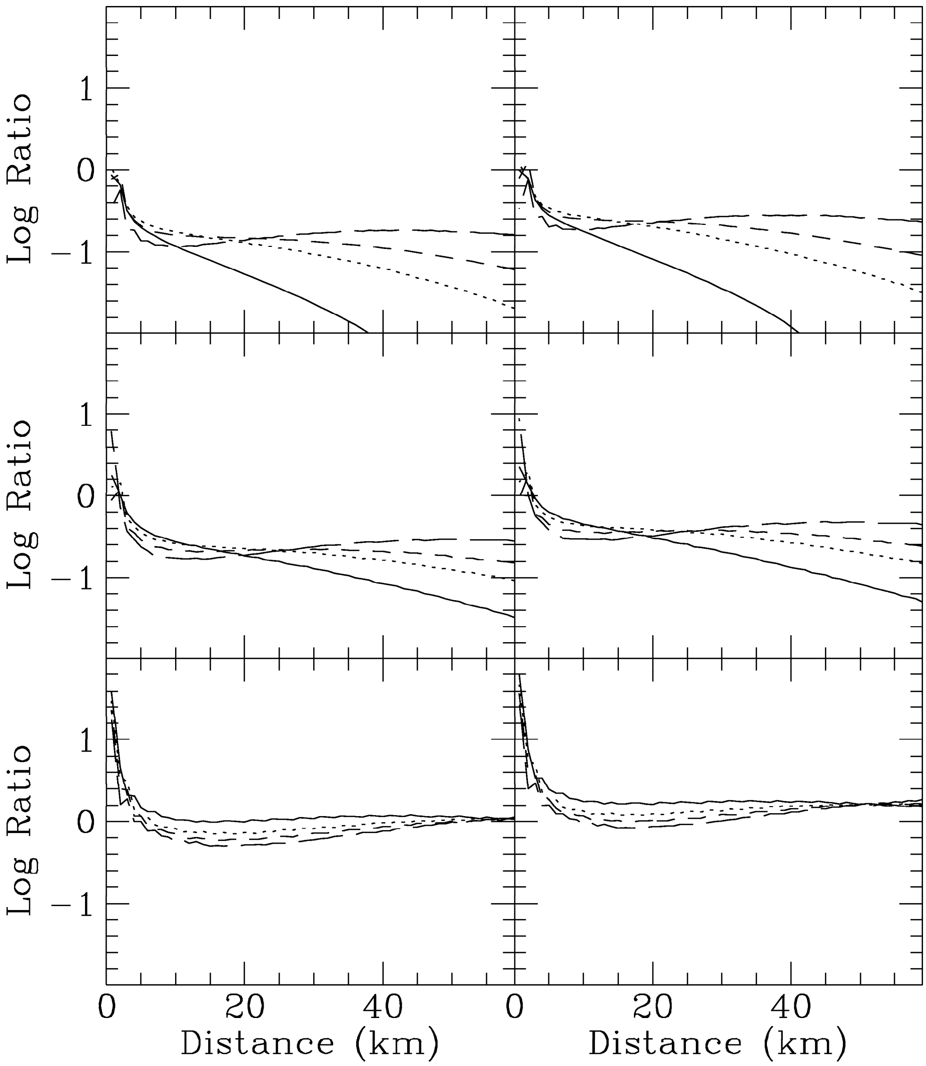

Fig. 2. Ratios $\frac{b_H}{b_L}$ between the artificial sky luminance b_H produced by upward light emission of a city between the threshold angle θ_0 and the vertical and the artificial sky luminance b_L produced by its upward light emission between the horizontal and the threshold angle θ_0. The ratios are computed for threshold angles θ_0 of 45°(top panel), 30°(middle panel) and 10°(bottom panel). Left panels show ratios for models with the Garstang city emission function (G=0.15, F=0.15), right panels show ratios for models with isotropic city emission function. Curves refer to zenith distances of 0°(solid curves), 30°(dotted curves), 45°(dashed curves), 60°(long dashed curves) towards the city.

10° is as important as the light emitted at all the other angles in producing the artificial sky luminance there.

3. Lightened horizontal surfaces have a mixed behaviour between a Lambertian diffusor (emitting very little light at small angles) and a reflector of the light emitted by luminaires (which maximum emission is at 60-70° from their axis giving a maximum reflection at 20-30°). So, the emission between the horizontal and 10° is mainly produced by direct emission from fixtures. This unnecessary contribution to sky luminance needs to be reduced to a negligible fraction (at most 1/10 of the remaining emission). So fully shielded fixtures (e.g. flat glass luminaires or asymmetric spotlights installed without any tilt) are required even at great distances from the site.
4. A specific limitation of light emitted at low angles is useful also in high urbanized areas where the artificial sky luminance is produced by the sum of the contribution of a big number of sources. From results of modelling sky luminance of the city of Padova (Cinzano 1999) can be inferred that the sky luminance inside a city of less than about 70000 inhabitants in Veneto Plain could be produced more by the sources in the surrounding land than by the city itself. The use of fully shielded fixtures can limit definitely this contribution from outside when the protection of citizen's sky vision capability is wanted.

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References

Abramowitz M., Stegun I.A. 1964, Handbook of Mathematical Functions, Washington, NBS.
Cinzano, P. 1999a, in this volume.
Cinzano, P. 1999b, in this volume.
Garstang, R.H. 1986, Publ. Astron. Soc. Pacific, 98, 364-375.
Garstang, R.H. 1987, in Identification, optimization and protection of optical observatory sites, eds. R.L. Millis, O.G. Franz, H.D. Ables & C.C. Dahn (Flagstaff: Lowell Observatory), p. 199-202.
Garstang, R.H. 1988, The Observatory, 108, 159-161.
Garstang, R.H. 1989a, Publ. Astron. Soc. Pacific, 101, 306-329.
Garstang, R.H. 1989b, Ann. Rev. Astron. Astrophys., 27, 19-40.
Garstang, R.H. 1989c, Bull. of American Astron. Soc., 21, 2, 759-760.
Garstang, R.H. 1991a, in Light Pollution, Radio Interference and Space Debris, IAU Coll. 112, ed. D.L. Crawford, Astron. Soc. of Pacific Conf. Series 17, p. 56-69.
Garstang, R.H. 1991b, Publ. Astron. Soc. Pacific, 103, 1109-1116.
Garstang, R.H. 1991c, The Observatory, 111, 239-243.
Garstang, R.H. 1992, Bull. of American Astron. Soc., 24, 740.
Garstang, R.H. 1993, Bull. of American Astron. Soc., 25, 1306.

Garstang, R.H. 1999, in this volume.
McClatchey, R.A., Fenn, R.W., Selby, J.E.A., Volz, F.E., Garing, J.S. 1978, Handbook of Optics, ed. W.G. Driscoll and W. Vaughan, McGraw-Hill, New York.
Treanor, P.J.S.J. 1973, The Observatory, 93, 117-120.

UPWARD FLUX OF PUBLIC LIGHTING: TWO TOWNS IN NORTHERN ITALY

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ABSTRACT. A survey was carried out on public lighting installations in two towns in northern Italy, i.e. Turin (population 1 million) and Treviso (80.000). The distribution of the different types of luminaire was evaluated and the percentage of luminous flux emitted upwards was calculated.

The results of this survey are reported and compared with the relevant publications and with the draft standard under discussion by the Italian standardising body (UNI). The expected results on threshold magnitude due to sky luminance and on the cost/benefit ratio for different types of installation and luminaire are also discussed.

1. Introduction

No one questions the need for public lighting to ensure a safe environment by night for drivers and pedestrians and to serve the townspeople's needs by illuminating monuments, gardens, sport facilities and other such sites in every town. These benefits, however, are unfortunately countered by the unavoidable effects of the luminous flux that lighting installations emit upwards (the so-called spill light) and road surfaces reflect upwards, thus increasing sky luminance with a negative fallout on the visibility of the heavenly bodies.

To respond to complaints from both professional and amateur astronomers about what they call "luminous pollution", the CIE has studied this problem at international level with a view to offering guidance to lighting experts and standardising bodies for a more careful design of lighting installations and luminaires [1][2]. Two years ago, the Italian UNI appointed a working group to draft a standard in this field, taking the following issues into account:

- safety for drivers and pedestrians;
- protection of astronomical sites;
- optimisation of the cost/benefit ratio;

- impact on the market.

In the context of said standardising project, the Istituto Elettrotecnico Nazionale G. Ferraris (IEN), the Azienda Energetica Metropolitana (AEM) of Turin and the University of Padua (UNP) carried out a survey on existing lighting installations in two towns in northern Italy, i.e. Turin (population 1 million) and Treviso (80.000), with a view to verifying the feasibility of a city lighting plan in compliance with the draft standard.

The results of this survey are presented here, together with a preliminary discussion of the technical and scientific issues involved in the evaluation of the results.

2. Lighting and astronomy

In Italy, lighting experts and astronomers are discussing the correlation between sky luminance, which reduces the visibility of heavenly bodies, and spill light from public lighting installations, their aim being to draw up a national standard for restricting sky luminance. A number of issues have been examined, the results of which are summarised below.

2.1. Measurement units

For the benefit of lighting experts, it may be useful to recall that astronomers classify star luminosity according to its magnitude, i.e. the illuminance on the observer's entrance pupil, be it naked eye or telescope, evaluated on a logarithmic scale. Though the relationship between the units of magnitude and lux has never been formally established, for the purpose of this paper it can be assumed as:

$$M = -k\ log(E/E_o) \tag{1}$$

where M is the magnitude, E the illuminance on the entrance pupil, E_o a reference illuminance and k a scale coefficient; though there is no consensus as yet on the values of E_o and k (the CIE is preparing to study this problem), k can be set at 2,5 magnitudes [1], while the value of E_o is irrelevant for the purposes of this paper. It is worth noting that M increases as E decreases, i.e. the fainter the star, the greater the magnitude.

2.2. Evaluating threshold magnitude

Several models have been proposed for evaluating sky luminance generated by public lighting and its effect on the absolute reduction in the visibility threshold for astronomical observations, but there is no international consensus on this evaluation at present. The CIE is proposing a campaign of measurements as a contribution to this problem, which depends not only on upward luminous flux, but also on local conditions such as orography and atmospheric pollution. Only comparative evaluations are made in this paper.

As mentioned before, the luminous flux coming to bear on the road surface is partially reflected upwards. The CIE reports a typical value of 10% for the ratio between the luminous flux reflected upwards and the total lumens emitted by the luminaire in space; measurements carried out in Turin by the IEN have confirmed this value.

The light emitted upwards by lighting installations is diffused by the atmosphere, leading to an increase in the luminance of the sky, with a consequent reduction both in the contrast of the heavenly bodies against the background of the sky and in the threshold magnitude, i.e. the greatest magnitude still visible by a naked or assisted eye. Lighting experts will certainly compare this effect with the veiling luminance created by car headlamps in foggy weather, but no mathematical evaluations are possible in this case because the bidirectional reflectance distribution function of the atmosphere and the luminous intensity distribution of spill light are generally not known.

It is nonetheless possible to assess the drop in threshold magnitude DM with reference to a known, or supposedly known, condition. The "sky glow formula", developed by the CIE [1] and illustrated here in eq. (2), enables an evaluation of the decrease in threshold magnitude which equates to the contrast between star and background in actual and reference conditions:

$$M = -2,5\ log(1 + a) \tag{2}$$

where a is the relative increase in the upwards luminous flux between the actual and the reference condition. In this paper, the reference condition is the unavoidable luminous flux reflected by the road (10% of the total luminous flux emitted), while a is the luminous flux emitted upwards directly by the luminaire in relation to the reflected luminous flux.

2.3. Characterisation of lighting installations

As far as the sky luminance generated by public lighting is concerned, lighting installations are classified according to the suggestions of the CIE [1] on the basis of their "upward waste light ratio" (UWLR), i.e. the proportion of the luminaire's luminous flux that is emitted above the horizontal when the luminaire is in its installed position.

2.4. Energy saving

Though there is no unanimous consent on this issue, reducing sky luminance does not seem to coincide with any energy saving [3]. On the matter of the luminaires, good public lighting benefits from the reflecting characteristics of road surfaces and requires a high luminous intensity at angles 70-75° from the vertical. A reduction in UWLR could suggest a luminaire with a flat glass window, but the reflection factor of the air-glass interface is very high at such angles, as shown in fig. 1, with a consequent drop in efficiency and poor light control. A reduction in aperture angles, as in the so-called cut-off luminaires, calls for the installation of a greater number of luminaires with a consequent increase in the luminous flux reflected by the road, which outweighs the reduction in UWLR: the CIE reports an increase of about 1,5% for semi-cut-off luminaires [2]. The cost of both installation and energy would also increase.

Table I compares a number of conditions (though not complete, it is certainly sufficiently representative of what is available on the market) for luminaire windows and lamps for similar road lighting installations with an average road luminance of 1 cd/m^2 [3].

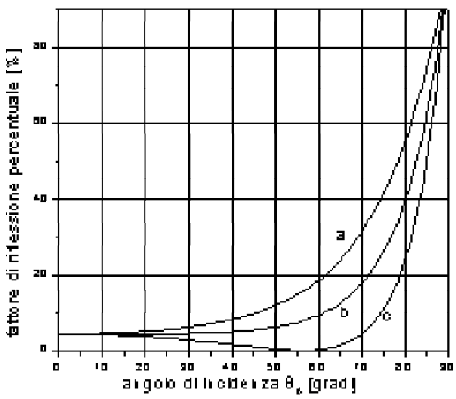

Fig. 1. Reflection factor for the air-glass interface. Curves a and c are for polarised light, b for unpolarised light.

The best energy-saving condition is achieved with luminaires using prismatic bowl windows and fitted with high-pressure sodium lamps (No. 3 in table I), with a UWLR of about 3%. Table I shows the increase in energy consumption for the other windows by comparison with this condition. The lower efficiency of luminaires with low-pressure sodium lamps (No. 6 in table I) is hardly surprising: in fact, the large size of these lamps prevents a valid control of the luminous intensity distribution.

Tab. I - Comparison between road lighting installations
Average road luminance 1 cd/m^2 Road reflection 10%

No.	Lamp	Window	Effic. %	UWLR %	Total upward flux	Power cons. $W/cd\ m^{-2}$	Energy %	Magnitude loss
1	Hp sodium	flat glass	73	0	10	141	+34	0 (*)
2	Hp sodium	curved glass	85	0,1	10,1	123	+17	0,01
3	Hp sodium	prism. bowl	80	2,8	13,5	105	0 (°)	0,3
4	Hp sodium	smooth bowl	82	1,8	12,2	118	+12	0,2
5	Mercury	smooth bowl	68	1,5	12,2	195	+86	0,2
6	Lp Sodium	prism. bowl	67	3,9	15,8	108	+3	0,5

(*) Best case for magnitude loss
(°) Best case for energy consumption

Table I also illustrates the reduction in the visibility threshold (in magnitudes) calculated using eq. (2): the flat window (No. 1 in table I) is naturally the best, but at the expense of a 34% greater energy consumption. The loss of star visibility in magnitudes for the other lamp/window combinations, referring to the high-pressure sodium/flat window, is shown in the last column of table I.

2.5. Structure of the UNI standard

The Italian standard on the reduction of sky luminance, which is still being developed, deserves some comment. This draft standard is based on a 3-zone system (the CIE recommended 4 [1]) for the Italian territory. The first zone is for international observatories, the second surrounds the first and protects national and amateur observatories and the third is for the rest of Italy. The draft does not consider single installations, but specifies the average UWLR value for each town, the general requirement being: to protect zones 1 and 2 and to improve the quality of luminaires and lighting installations in all zones; to avoid any increase in the cost of luminaires, installations and energy consumption except for zone 1, which will include only the three Italian international observatories; and to ensure a soft impact on the market. Even if the UWLR values are under debate, the drafting work group has prepared a proposal for an overall 1% in zone 1, 5% in zone 2 and 10% in zone 3 (including luminaires, installation geometry, tolerances, etc.). This means that flat window luminaires should be installed only in zone 1, whose radius should be at least 5 km, while the more economical prismatic bowl luminaires should be installed in the other zones.

3. Lighting installations in Turin

Turin is a heavily industrialised town with a population of about 1 million, which should be included in zone 3 of the draft UNI standard. The local electrical energy distributor AEM decided to prepare a public lighting plan that, for each type of road, specifies luminance and illuminance levels, the type of lamp and colour of the emitted light (for use as visual guidance and for illuminating monuments), the type of luminaire and also the maximum UWLR for each type of lighting (motorised roads, pedestrian streets, gardens, monuments, etc.).

In preparation for said plan, the AEM has carried out a survey with the co-operation of the IEN on the different types of luminaires and lamps currently installed in Turin. The results of the survey are summarised in Table II: to simplify matters, the luminaires are divided into 6 types and the typical appearance of each type of luminaire is shown in figs. 2 to 7. For a comparison with table I, it is to be noted that the UWLR values in table II include the spill light due not only to the luminaires, but also to their design inclinations and mounting tolerances.

The following comments relate to table II, which refers to the present situation of lighting installations.

- Turin comes very close to the UNI draft standard requirements for zone 3 because many road installations are recent. The average UWLR could even be further reduced, were it not for a considerable number of traditional luminaires that cannot be changed because they are an important feature of the historical city centre by night.

- The contribution of the freely-emitting spheres to the UWLR is very low because

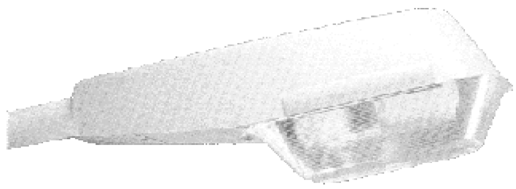

Fig. 2 Typical luminaire for street lighting on pole (n. 1 in table II)

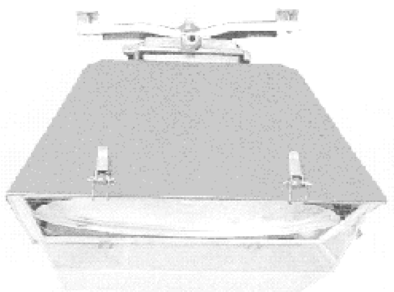

Fig. 3 Typical luminaire for street lighting on suspension (n. 2 in table II)

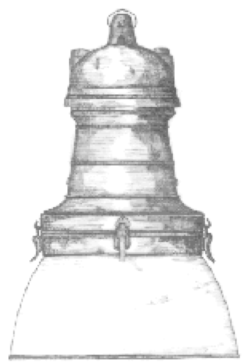

Fig. 4 Typical luminaire with diffusing photometric characteristics (n. 3 in table II)

Fig. 5 Typical lantern (n. 4 in table II)

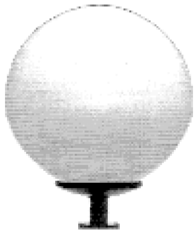

Fig. 6 Typical sphere (n. 5 in table II)

Fig. 7 Typical luminaire for garden lighting
(n. 6 in table II)

they account for only 1% of the total luminous flux generated in Turin. Nonetheless, each sphere will be equipped in the near future with a sort of internal reflector that will reduce their UWLR by half. The reduction in the town's average UWLR to be gained from this modification is only 0,2%, however, which corresponds - according to eq. (2) - to a very limited increase in sky visibility (about 0,02 magnitudes).

- The contribution of road lighting installations (luminaires Nos. 1 and 2 in table II) to both total luminous flux and total power is about 72%: this means that a better potential energy saving can be obtained by improving the quality of their lighting design, using prismatic bowl luminaires (No. 3 in table I) wherever possible. Something can also be done for the type 3 diffusing luminaires (which contribute 11,4%). It is worth noting that in Turin the traditional luminaires (types 4, 5 and 6), that it would be difficult to modify, only contribute 9%.

- Monument lighting is switched off at night, at a time decided by the local authority, so - though its contribution to the total luminous flux is not very high - it has not been included in table II.

Tab. II Public lighting installations in Turin

No.	Luminaire	Quantity	Power MW	Flux Mlm	Rel. Flux %	UWLR %
1	Road (on post)	42593	8,3	635	68,8	6
2	Road (suspended)	2113	0,4	33,8	3,7	6
3	Diffuser	9761	1,6	105	11,4	20
4	Lantern	2952	0,6	33,5	3,6	33
5	Sphere	1101	0,1	10,1	1,1	50
6	Garden	5027	0,9	50,4	5,5	33
7	Others	3888	0,8	54,5	5,9	6
	Total	67435	12,7	922	100 (∘)	10,5

(∘) This value is the average UWLR weighted according to the relative luminous flux established for the whole town by the draft UNI standard.

As far as the improvement schemes of the Turin lighting plan are concerned, the objective for the town's average UWLR in the near future can be around 9,6%, thus complying with the zone 3 UWLR of the UNI draft standard. This value will be achieved when certain obsolete road lighting installations have been replaced with prismatic bowl luminaires over the next few years: this solution will assure the best use of energy. According to eq. (2), the threshold magnitude is thus expected to increase by about 0,1 magnitudes.

It should be noted, however, that an increase is also expected in the luminous flux installed because the towns people are constantly asking the local authority to install new luminaires and increase lighting levels for public safety reasons. Using eq. (2), it is easy to see that a 10% increase in the luminous flux installed, due only to the light reflected from the roads, which can easily be expected simply from the modernising of luminaires, will counterbalance the expected reduction of UWLR.

Unfortunately, no lighting design programme will enable a good view of the stars in Turin because the luminous flux reflected from the roads is already enormous, about 100 Mlm (assuming 10% of the emitted luminous flux) and, as mentioned above, it is constantly increasing. Even if there is no commonly-accepted model for calculating the reduction in the star visibility threshold due to the reflected light, this reduction is certainly quite high, partly because there is a virtually permanent inversion layer over Turin at about 300 m above the town which diffuses light on the sky. This is sadly a typical situation for many industrialised towns in Italy, especially in the north of the country. As for energy savings, in Turin this mainly depends on the replacement of the street lighting installations and has almost nothing to do with any reduction in the UWLR. The data in table I show that at lower UWLR (Nos. 1 and 2 in table I) a higher energy consumption is to be expected: for instance, adopting flat window luminaires for the street lighting installations in Turin (Nos. 1 and 2 in table II) instead of the foreseen prismatic bowl luminaires (No. 3 in table I) could eventually lead to an increase in energy consumption of about 22% for the whole town as opposed to an improvement in threshold visibility of only 0,1 magnitudes, making the cost/benefit ratio unacceptable. Again, experience in Turin demonstrates that there is no useful correlation between energy savings and a reduction in spill light.

4. Lighting installations in Treviso

Treviso is a town in the relatively well-developed north-east of Italy, characterised by the presence of numerous small manufacturing industries and businesses distributed over a territory that still retains the features of intensive agriculture. Unlike Turin, Treviso is a rather typical, medium-sized Italian town with a population of about 80.000. It is situated in the Veneto region, where a local law issued in July 1997 establishes certain restrictions on the use of public lighting with a view to containing upward luminous flux [4]. That is why the Department of Electrical Engineering at the University of Padua chose Treviso for a "sample" assessment of present-day luminous pollution levels. The first step in this direction was taken as part of a thesis [5], which enabled the amount of luminous flux dispersed upwards to be calculated for the different kinds of luminaire currently used in the town and in the surrounding territory. The results of this work are summarised in table III, which refers separately to the historical town centre, its suburbs, and the municipality as a whole.

The main types of lighting installation in Treviso are illustrated in Figs. 8 - 12. The mathematical methods involved are the same as were used for the city of Turin, as specified by the UNI draft standard. The data emerging on the two situations are therefore reported in the same way and are suitable for comparison.

The Treviso study actually included a great deal of other information for a more thorough assessment of the luminous pollution phenomenon. Some interesting results emerged from evaluating not only the flux emitted upwards by the luminaires, but also the flux reflected by road surfaces and vertical surfaces surrounding the lighting installation. In the case of Treviso, the proportion between direct and reflected fluxes is

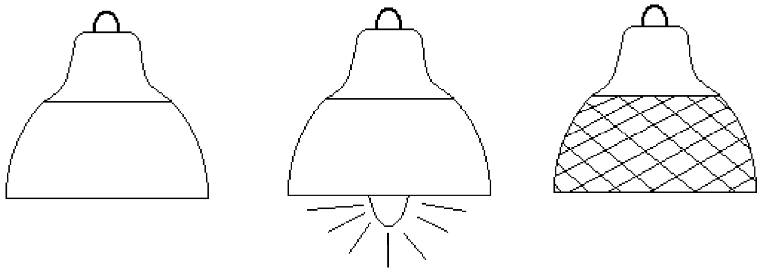

Fig. 8 - Typical luminaire for street lighting (open type) in Treviso

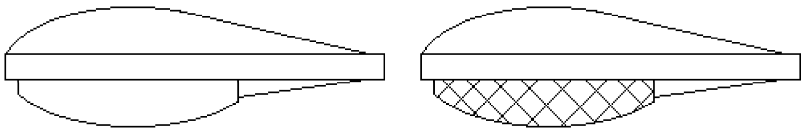

Fig. 9 - Typical luminaire for street lighting (diffuser type) in Treviso

around 1:2, so the reflected flux has the greatest weight in the total level.

Finally, several simulations were performed to assess how the reflecting features of the road surfaces affect the quantity of flux reflected upwards, always assuming that the requirements of the UNI standard 10439 for levels of horizontal illuminance and luminance are satisfied in all cases: preliminary results demonstrate that the type of road surface has relatively little bearing on the situation. Intuitively, this might be explained basically by the fact that a paler surface reduces the quantity of flux needed to obtain the required illuminance level (thus ensuring an undeniable advantage in energy terms), but simultaneously increases the reflection factor and thus the relative quantity of flux directed towards the sky - so these two factors tend to compensate for each other.

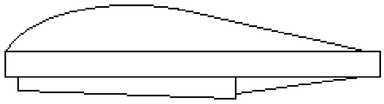

Fig. 10 - Typical luminaire for street lighting (flat diffuser type) in Treviso

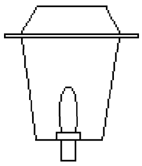

Fig. 11 - Tipycal luminaire for historical centre in Treviso (lantern)

5. Conclusions

The surveys carried out in Turin and Treviso show that a good-quality lighting is essential for compliance with the draft UNI standard on the reduction of sky luminance in zone 3. In both towns, the upward luminous flux limit for zone 3 can be satisfied by modernising the road lighting installations, which account for the vast majority of all public lighting installations. The use of luminaires with a prismatic bowl window and, wherever possible, with high-pressure sodium lamps ensures the most efficient use of energy.

The results reported in this paper demonstrate that, in order to ensure both good sky visibility and low energy consumption, the astronomical observatories should be surrounded by dark zones (the so-called "star parks"), where lighting installations should not be allowed. The very high luminous flux reflected from the road surfaces in towns

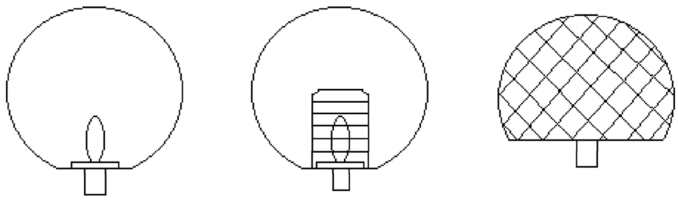

Fig. 12 - Typical luminaire for garden and pedestrian areas
in Treviso (sphere)

prevents a good view of the celestial bodies and simply reducing spill light does not pay off. Considering the distribution of the different types of lighting installation in towns, even the use of flat-window luminaires instead of the prismatic bowl luminaires for street lighting installations, leaving as they are now the other types of lighting installations (monuments, pedestrian streets, garden, etc.), would improve the visibility threshold in the UNI standard's zone 3 by less than 0,15 magnitudes. It is easy to verify that, extending the results on the distribution of lighting installations given in table II to a town in zone 2 (for which the UWLR should be 5% according to the draft UNI standard), the use of flat window luminaires in the conditions reported above would lead to about the same improvement in the visibility threshold. In both zones, the increase in energy consumption would between 20% and 30%, so the cost/benefit ratio is distinctly unfavourable.

References

1. Guidelines for minimizing sky glow, CIE TC 4.21, 1997
2. Guide on the limitation of the effects of obtrusive light from outdoor lighting installations, CIE TC 5.12, 1995
3. P. Iacomussi, G. Rossi, P. Soardo - La limitazione del flusso luminoso emesso verso l'alto, Atti del Convegno Inquinamento luminoso e risparmio energetico, Nove, p. 49-55, 1997
4. Legge Regionale 27 giugno 1997, n.22. Bollettino ufficiale della Regione del Veneto 1/7/97, n.53
5. C. Medusa - Valutazione dell'inquinamento luminoso prodotto dalla pubblica illuminazione esterna del Comune di Treviso. Tesi di laurea. Università di Padova. Anno acc. 1997/98. Relatori: L.Fellin., P.Cinzano.

Tab. III - Public lighting installations in Treviso

Luminaire	number	Power kW	Flux Mlm	Relative flux %	UWLR %
historical town centre					
Road (open type)	456	59,8	2,6	53,2	15,7
Road (with diffuser)	137	19,8	1,0	20,5	3,5
Road (flat diffuser)	10	1,8	0,08	1,7	5,4
Lantern	117	12,6	0,60	12,3	39,7
Sphere	160	16,2	0,60	12,3	38,8
TOTAL	880	110,2	4,88	100	19,13
suburbs					
Road (open type)	3497	264,0	7,8	28,6	8,5
Road (with diffuser)	1376	158,1	7,6	27,8	2,9
Road (flat diffuser)	1399	178,4	10,5	38,5	1,2
Lantern	0	0	0	0	-
Sphere	326	35,9	1,4	5,1	43,3
TOTAL	6598	636,4	27,3	100	5,94
global values					
Road (open type)	3953	323,7	10,4	32,4	10,3
Road (with diffuser)	1513	177,9	8,5	26,5	2,9
Road (flat diffuser)	1409	180,2	10,6	32,9	1,2
Lantern	117	12,6	0,6	1,9	39,7
Sphere	486	52,1	2,0	6,3	42,0
TOTAL	7478	746,5	32,1	100	7,94
Unclassified	35(*)	?	0,4 (*)	-	-

(*) Not considered in computations

THE FIGHT AGAINST LIGHT POLLUTION IN ITALY

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ABSTRACT. The author outlines the steps of the fight against light pollution in Italy in the last years.

1. Introduction

The problem of light pollution is unfortunately, as diffused in Italy as it is in all industrialized and populated countries. In fact, until some time ago, nothing had really been done, neither to limit the phenomenon nor even to understand it.

In 1990, in the meeting of SAIt in Abano, I proposed to found a committee of study; its purpose was to determine which, technically, are the most polluting light sources, both as form and as spectral emission. Furthermore, after having studied the diffusion of the phenomenon throughout the national territory - especially near the most important Observatories - our goal is to find the best solution. This Organism, composed of three members Prof. Massimo Capaccioli from Padova, Prof. Salvatore Cristaldi from Catania and myself, began its work inviting all the national Observatories to fill in a questionnaire. Ten out of twelve answered: from the results of the questionnaire the following information emerged, and was presented at the meeting of S.A.lt in Torino in 1991.

2. The situation in Italian Astronomical Observatories in 1990

The following is a brief statistical and objective analysis of the received data (Di Sora 1993).

- Forty per cent (40%) of the Observatories operate under skies that possibly do reach a magnitude 6 with a pollution index judged to be tolerable; thirty per cent (30%) are capable of reaching values of approximately magnitude 5; the remaining twenty per cent (20%) do not exceed magnitude 3. In each case the source of pollution is both private and public.
- Forty per cent (40%) of the sites are disturbed by mercury lamps and in the remaining cases it was seen that sodium lamps, mostly the high pressure ones, can

also be disruptive.However, the use of sodium lamps is less dangerous than that of mercury ones.

- As far as possible recovery of the quality of the skies is concerned, 20% of the interviewees gave a positive response, 30% responded negatively, while the remaining 50% declared that there exists the possibility.

Regarding the work done by the Observatories, an interesting and significant remark emerges concerning the matter of contacting organisation that are responsible for existing equipment.

- Forty per cent (40%) of the Institutions never contacted the competent authorities, obviously deducing as a result: ". . . Wild street lamp!" The remaining sixty per cent (60%) of the Observatories, when contacting the companies mentioned above, realised that some concern exists regarding the advanced state of the matter.

Therefore, this clearly demonstrates that it is possible to obtain favourable results with a minimum of effort and firmness. However, it has been fully recognised that bringing this problem to the attention of the Public Authorities and of the big companies that produce lighting materials could mean taking one big step forward in resolving the problem.

Concerning the features that should be prevent in a c.d. lamp and in order to conform to an anti-light pollution norm, 60% of the Observatories opted for the use of low-pressure sodium lamps. The remaining half shared the ideas of the Committee, already partially at work, to reduce by fifty per cent (50%) the lighting in normally illuminated areas after a certain hour.

3. The Bill N.751

Nevertheless the situation was such to impose a law making solution. In fact, precise and organic laws do not exist in Italy regarding external lights. Even the manufacturers of illuminating equipment operate in total freedom. Technical offices and engineers do not know the minimum problem regarding the diffusion of light up-wards. For this reason the Committee elaborated, in collaboration with other Observatories, a bill presented at the meeting of S.A.It. in Teramo in 1992 and signed by Honourable Lino Diana and others. The merit of it, compared to similar measures approved in other countries, derives from the fact that:

1. It is not a strictly territorial law but one that operates in all the country.
2. Besides, the protection of the sky in general, and of some Observatories in particular, it established a serious and vigorous term of politics of the lighting engineering apparates and of power saving consumption.

A possible adoption of this bill could bring the following results:

a appreciable reduction of light pollution in the unprotected areas to within ten to fifteen years;

b nearly the total redaction of light pollution in the protected areas (20) within three to five years;

c saving of energy for about three hundred to five hundred billion lira only for the use of external lighting, private and public;

d rationalization on the designing and the use of the light sources;

e limitation of the dazzle phenomenon.

The studies done by the Committee determined, therefore as main responsible factors of light pollution, the following facts

1. street lamps with open optics (spheres, lanterns and similar);
2. traditional street-lamps with protective curve glass, even worse if refractor according to the principle of Fresnel. In fact this type of street-lamp, contrary to assertions of some engineers and manufacturers (really few only in Italy), not only send and waste a large quantity of light and energy above 90 degree - to the thirty times more in comparison with the cut-off one (30-35 cd/klm vs. 0-1 cd/klm) - but even provokes irksome phenomena of dazzling (typical value of G is 4.5). So much so that the UNI rule n. 10439 (passed in 1995) implicitly advises against its use (see the prospect 1 of this). Besides all this is eminently demonstrated by the occurrence that, in the U.S.A. - aside from the presence of astronomical observatories - the new street-lamps are all cut-off type and the old ones with refractor and curved bowl had been modified with simple metallic screens. In fact, just last year, the General Electric (the most important producer of street lamps in the U.S.A.) communicated that by now, the manufacture of cut-off lamps have surpassed that of prismatic bowl one. Besides, in Italy, there is the bad habit (out of ignorance or for evident commercial interests) to mount also the street-lamps with prismatic bowl at the same distance (25-30 metres) of that cut-off one (according to measures collected statistically by the Astronomical Observatory of Campo Catino and other organizations).
3. lights oriented with angles more than 30 degrees if symmetric and 0 degrees if asymmetric and not equipped with eventual shelters;
4. systems that work at full power without the possibility of being reduced after certain hours and with optics not parallel to the road surface;
5. from a spectrographic point of view light sources which are different from sodium ones.

We think that, if we want to reduce dramatically light pollution, it is opportune to do it over all the national territory, specially around the most important Observatories and around ones. For this reason the bill, not therefore a simple local ordinance, has as a final aim the reduction power consumption causing the compulsory use of sheltered street lamps and low consumption everywhere only with regard to installations carried out after the approval of the bill. As for protected areas, a modification of the installations is expected within four or five years. Criteria is also put forward for the realization of installation to be able to reduce considerably the amount of the light sent up-wards. Clearly the bill foresees also that after its approval, light sources not corresponding to such criteria, will neither be sold in Italy.

The main type of street lamp recommended is the "cut-off" one, with light emission, above 90 degree, of 0 candles for 1.000 lumen. With a flat and encased plain of glass and a 0 degree inclination compared to the ground, it totally cuts off the emission of light out-wards and up-wards giving the minimal contribution to light pollution only through the reflection of the road, furthermore not visible beyond certain distances.

Curved, refractor, white and dull protective glass, with diffused effects, are prohibited. Open optics (spheres, lanterns and others) but with transparent glass must be equipped of proper metallic screens to regulate the light flux. Traditional spot-light must be used from up-towards down and not vice versa In any case when this is not possible, the use of upper screens capable of limiting the light flux within the perimeter of illuminated surfaces, is compulsory (for example, the front of a building). Lamps with high efficiency, like the sodium ones, are nearly all foreseen. Flux reductors or line shutters are foreseen too. Sanctions for transgressors, only in protected areas, with variable radius (5-25 km) around the Observatories are applied only after an intimation by local police. Those that are not up-to-date can modify their installations avoiding in this way the sanctions.

The bill finances those town-halls interested in favouring rapidly the conversion of installations in those areas. Among the protected Observatories, there are also amateur observatories. In any case, even the town-halls that are not part of the protected areas, can apply the principles of this bill, through the approval of a special contract prepared by the Astronomical Observatory of Campo Catino (OACC).

Other events and activities in Italy until 1994 are reported in Di Sora (1994) and Cinzano & Di Sora (1994).

4. The last three years

After 1995 the fight against light-pollution has shown a remarkable acceleration. At the side of the SAIt, that has renewed the cited Commission (Salvatore Cristaldi - Catania, Pierantonio Cinzano - Padova, Mario Di Sora - Frosinone and Valentina Zitelli - Bologna), has been the UAI (The Union of Italian Amateur Astronomers) with the same strong resolution it had when its Light Pollution Commission was founded in 1990 by Pierantonio Cinzano, at that time a student. The Commission was directed by Luigi Baldinelli of the AAB (Amateurs Astronomers of Bologna) and, at the moment, by Carlo Rossi of the AAMT (Amateur-Astronomer Association of La Tolfa Mountains). Other institutions have been involved such as AIDI (Italian Lighting Association), ASSIL (The Association of Lighting Manifacturers), ENEL (Italian National Institution for Electrical Energy) and LEGAMBIENTE (ecologists). This has allowed to increase considerably the debate front rending the problem of public dominion.

In the last years the following positive results have been achieved. At central legislative level the presentation of the cited bill (n. 751) and another one by Honourable Daniele Apolloni (presented with the n. 4515 at the House of Deputies). Some districts have moved approving laws as regards. At the moment the Venetian and the Valle D'Aosta region have provided in this way. While it results that there are other bills in Lombardia, Tuscany and Piemonte. The most important experiments, at local level, is that of some towns that have approved real rules such as those that have been in force in Arizona since 1958. This regulation has been elaborated by the Director of OACC Mario Di Sora (also Co-ordinator of SAlt Light–Pollution Commission) and it is at the disposal of all cities that would like to approve it. The right application of the same, guarantees a reduction of the light-pollution of 50% and of power consumption of 30% - 40%. The first town that approved it (1984) was Florence, even if the major concentration of dark cities are situated in the province of Frosinone and just near

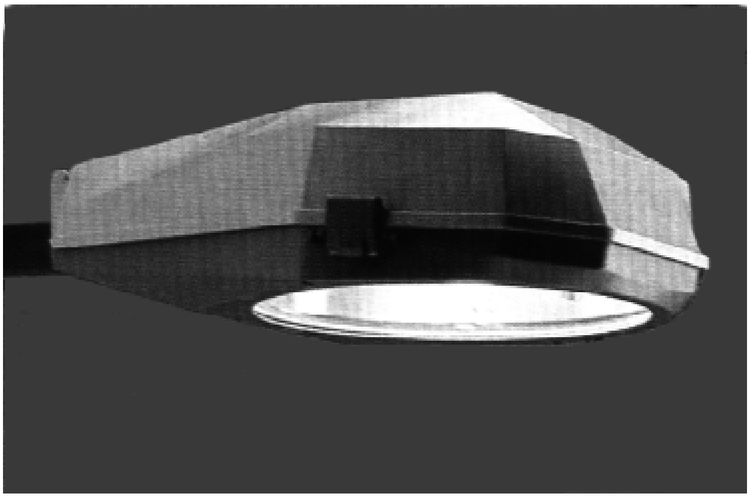

Fig. 1. A fully shielded fixture (courtesy FIVEP).

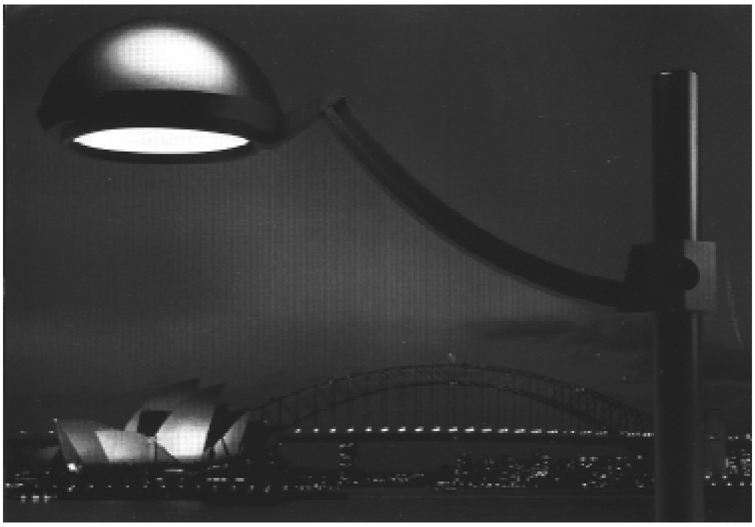

Fig. 2. A fully shielded fixture for urban design (Courtesy AEC Illuminazione).

Fig. 3. A fully shielded lantern for hystorical settings (Courtesy Domenico Neri Illuminazione).

the Astronomical Observatory of Campo Catino, Frosinone, Alatri, Ferentino, Ceccano, Giuliano di Roma, Guarcino, Fumone, Collepardo, Cassino. Very positive the result that was achieved in Civitavecchia by the amateur astronomers of the AAMT. Thanks to the approval of this rule and to an agreement between the town-hall and the ENEL with this last corporation (an intervention of five billion lira) will provide to the remaking of all installations in accordance with the new standards. In the mean time, in 1997, a Working Group was established at U.N.I. (Italian National Institution for Standardisation) with the contribution of astronomers, amateur astronomers, manufacturers, engineers and managers of lighting installations.

During the early stages there were some misunderstandings, but today also the producers have understood the importance and the gravity of this problem. And so FIVEP, Neri. Mareco, Philips, AEC, Schrèder, Guzzini (only to cite the most important as an example) have modified their products preferring the construction of optics with

Fig. 4. A beautiful example of axymmetric reflector with a shield expressely studied to avoid upward light emission even when installed with non zero inclination.(Courtesy Costruzioni Elettriche Schreder).

Fig. 5. An aximmetric fixture for urban lighting (Courtesy I Guzzini Illuminazione).

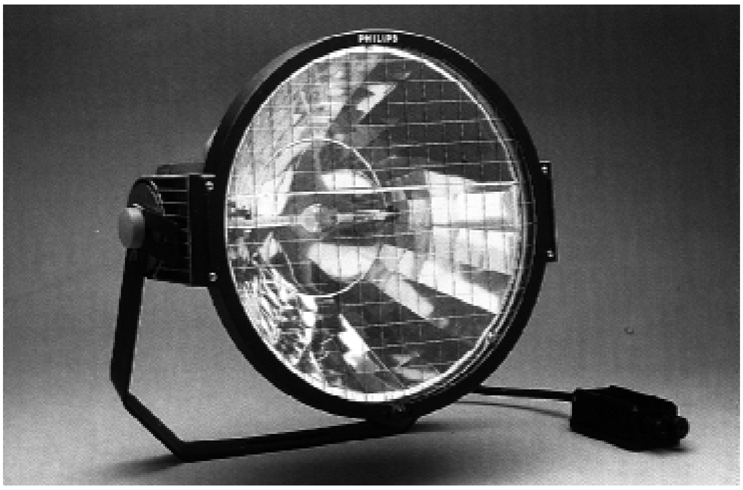

Fig. 6. The optic of this ArenaVision spot-light contains a shield with the purpose of limiting upward flux (Courtesy Philips).

Fig. 7. A less polluting alternative to the globes (Courtesy Mareco).

an emission of light upwards reduced or near 0. Some examples are shown in figures 1-6. An important Italian company, I Guzzini Illuminazione, has set up an original publicity campaign against light pollution on the most important Italian newspapers.

By now it is impossible to count the various meetings that took place in Italy regarding light-pollution. One of the most relevant was organized the 13th October 1998 in Frosinone with the participation of David Crawford, Executive Director of the International Dark-Sky Association. Furthermore every year a national day of light-pollution is organised by many institutions with the sponsorship of the International Dark-Sky Association. In this occasion the amateur-astronomers obtain the turning-off of the street-lamps to show everybody the wonders of the dark-sky. I would also like to stress that in 1997 the first Italian book specially devoted to this problem (225 pages) entitled "Light-pollution and protection of nocturnal sky" (Cinzano 1997) was published, certainly one of the best ever written.

5. Conclusions

In conclusion, I would like to say that, in spite of the fact that this problem was dealt with, with a considerable delay, we have however come a long way in the last five years. We have tried better what has been done by other countries previously. We hope that our experiment goes through with success serving for the best, not only the astronomical community but everyone.

References

Cinzano, P. 1997, Inquinamento luminoso e protezione del cielo notturno, Istituto Veneto di Scienze Lettere ed Arti, Venezia, p. 225.

Cinzano, P. and Di Sora, M. 1993, Mem. Soc. Astron. It., 64, 489-494.

Di Sora, M. 1993, Mem. Soc. Astron. It., 64, 173-177.

Di Sora, M. 1998, Inquinamento luminoso e risparmio energetico, Oss. Astron. Campo Catino, p. 16.