LIGHT POLLUTION, AN ENVIRONMENTAL PROBLEM FOR ASTRONOMY AND FOR MANKIND

DAVID L. CRAWFORD
International Dark-Sky Association
3225 N. 1st Avenue, Tucson AZ 85719 USA
Email: crawford@darksky.org

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!*

The International Dark-Sky Association
IDA, Inc.
3225 N 1st Avenue, Tucson AZ 85719 USA

Web: www.darksy.org
Email: ida@darksky.org
Telephone: 520-293-3198
Fax: 520-293-3192

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: $E = (I cos\theta)/d^2$.

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