MEASUREMENTS OF LIGHT POLLUTION OF PADUA

GIANCARLO FAVERO[1], ALESSANDRO FEDERICI[2], ALEJANDRA RECIO BLANCO[3], RUGGERO STAGNI[2]

[1]*Private Observatory "Guido Ruggieri", 35134 Padova, Italy*

[2]*Dipartimento di Astronomia, Universita' degli Studi, 35100 Padova,Italy*

[3]*ERASMUS, Dipartimento di Astronomia, Universita' degli Studi, 35100 Padova, Italy*

ABSTRACT. We present the results of the Padua sky brightness measurement obtained in 1998 with CCD photometry. The average night-sky zenith brightness results $17.53 \pm 0.03\ m_V/arcsec^2$. 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

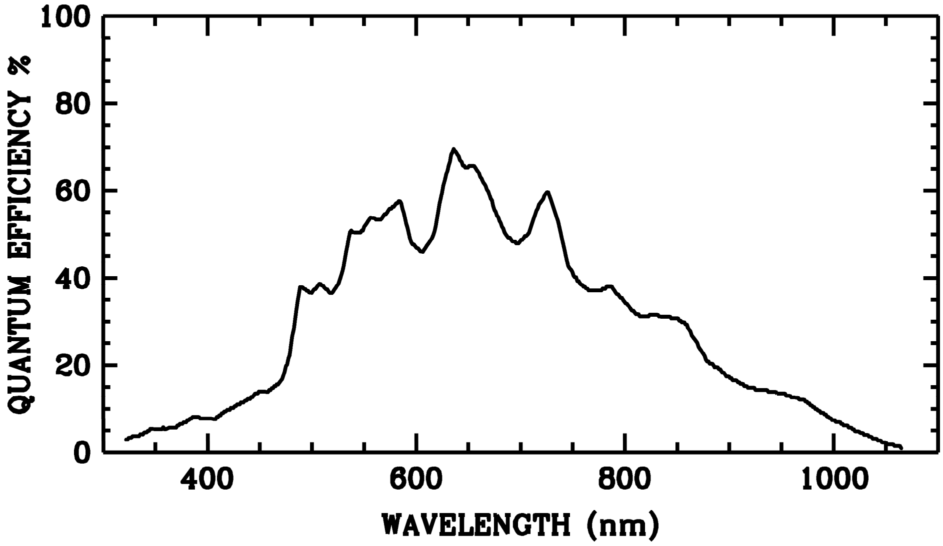

Fig. 1. The measured spectral sensitivity of the chip TC211.

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

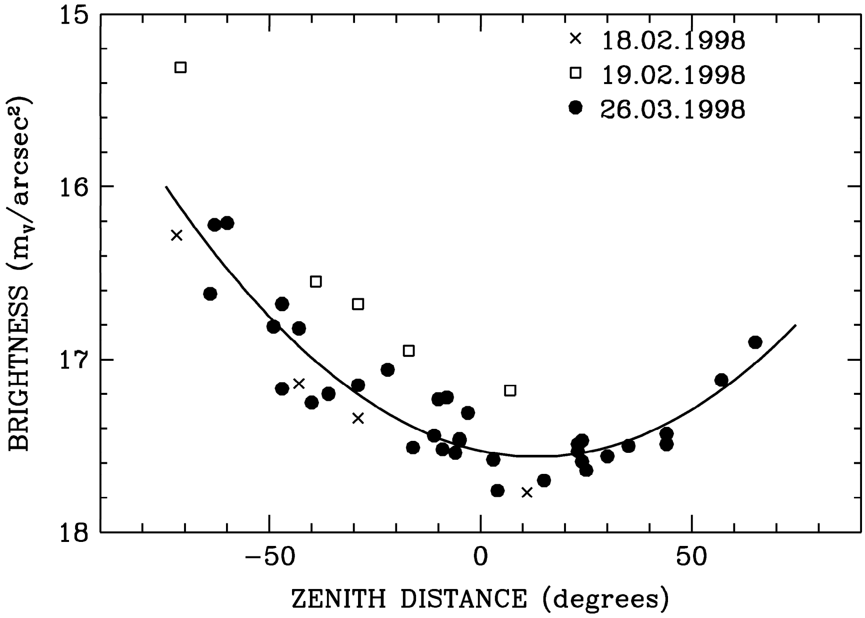

Fig. 2. Dots are sky brightness along six meridians trough downtown Padua for March the 26^{th}. Continous line is the fit of dots with a polynomial of the second degree. Crosses and squares are sky brightness for February the 18^{th} and 19^{th} respectively. Zenith distance is negative toward Padua 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)

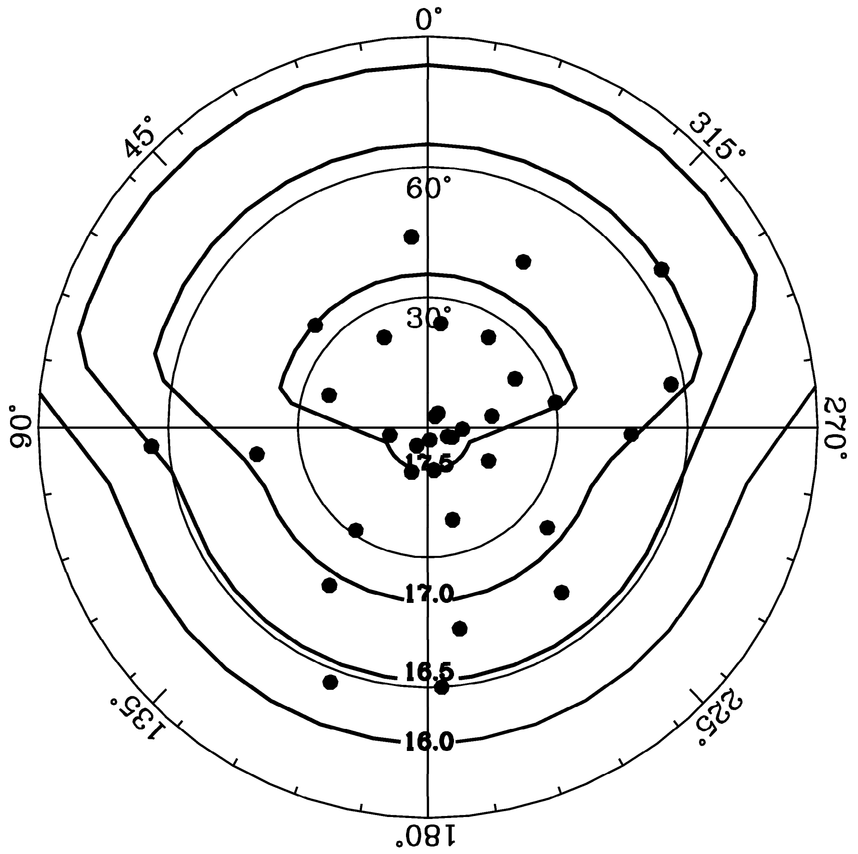

Fig. 3. Isophots of Padua's sky from "Guido Ruggieri" Observatory. South (180°) is toward Padua city-center. Dots are observed data of March 26, 1998.

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-

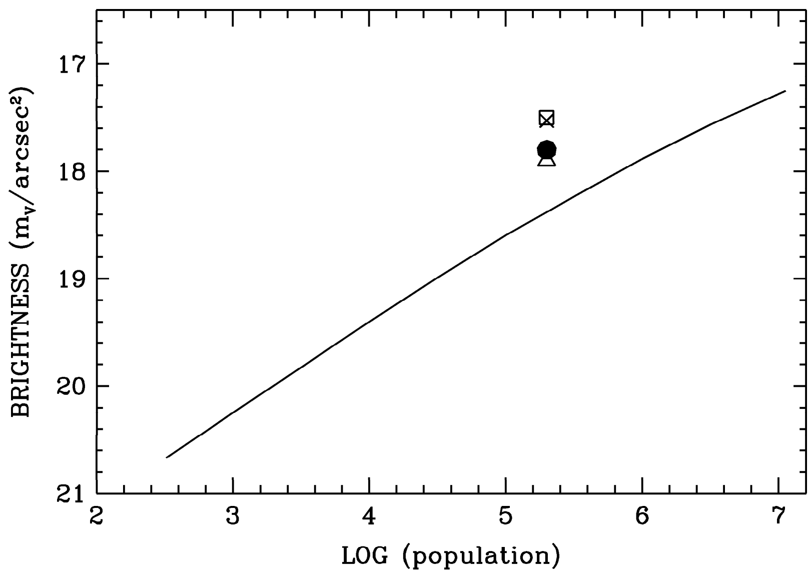

Fig. 4. City-center zenith brightness as function of population. Solid line is a model for very clean atmosphere (Garstang 1986). Theoretical dot is the prediction for Padua alone in 1998 and for standard clean atmosphere (Cinzano 1999). Square is the datum by the same Cinzano's model of Padua plus hinterland 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.

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