**Light Pollution At High Zenith Angles, As Measured at Cerro Tololo Inter-American Observatory**

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ABSTRACT. On the basis of measurements of the $V$-band sky brightness obtained at Cerro Tololo Inter-American Observatory in 2006 December and 2008 December we confirm the functional form of the basic model of Garstang. At high zenith angles we measure an enhancement of a factor of 2 over Garstang’s later model when there is no marine cloud layer over La Serena/Coquimbo. No corresponding enhancement is found in the $B$ band.

Online material: color figures

1. INTRODUCTION

In a previous article (Krisciunas et al. 2007 hereafter K07) we presented measurements of the $BVRI$ sky brightness at Cerro Tololo Inter-American Observatory (CTIO), obtained with the CTIO 0.9 m, 1.3 m, and 1.5 m telescopes and CCD detectors. As a sanity check we also obtained $B$ and $V$-band data with a 15 cm reflector and single channel photometer previously used by Krisciunas (1997) for an 11 yr series of sky-brightness measurements obtained at the 2800 m level of Mauna Kea. We found that at a zenith angle of $\sim 80°$ we could measure the effect of artificial lights in La Serena some 55 km away. The excess $V$-band light amounted to an enhancement of 44% to 72% above the model of Garstang (1989). The 2006 December single-channel $B$ and $V$-band measurements are included in the analysis in this article.

In 2008 December we obtained more data with the single-channel system of Krisciunas (1996). Our purpose was twofold: (1) to confirm the functional form of the basic model of Garstang by taking data at the full range of zenith angles; and (2) to determine a baseline level of the light pollution measurable from Cerro Tololo. As La Serena’s and Coquimbo’s populations continue to grow, we can use these measurements to determine the effectiveness of the lighting-control measures in place.

2. THE DATA

Our more and more antiquated, but still functional, photometric system consists of a 15 cm f/5.9 Newtonian reflector and a very light photometer whose light sensitive element is an uncooled RCA 931A photomultiplier (pm) tube—effectively the same as a 1P21 tube. The $V$-band filter is a 2 mm thick piece of Schott GG495 glass, which has a short wavelength cut-on at about 4800 Å. At 5500 Å it reaches a maximum transmission of 91%, which it retains to the red end of the visible portion of the electromagnetic spectrum. The effective $V$-band filter transmission results from the combination of this transmission curve and the quantum efficiency (QE) of the pm tube, which falls to near zero at 7000 Å (Lallemand 1962, Fig. 1). The $B$-band filter is composed of a 2 mm thick piece of Schott GG385 glass and a 1 mm thick piece of Schott BG-12 glass. Together they give a filter transmission that cuts on at 3600 Å, has peak transmission

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FIG. 1.—15 minute exposure over La Serena and Coquimbo, 2008 Dec 28 UT, taken just south of the 40 cm No. 1 dome at CTIO. See the electronic edition of the PASP for a color version of this figure.
| UT Date       | Azimuth (deg) | Zenith Angle (deg) | Filter | Sky Brightness (mag arcsec$^{-2}$) | Flux (nL) |
|--------------|--------------|--------------------|--------|------------------------------------|-----------|
| Dec 28       | 1:41         | 94.75              | 17.81  | V                                  | 22.014    |
|              | 2:22         | 268.80             | 4.01   | V                                  | 21.949    |
|              | 2:30         | 309.34             | 83.35  | V                                  | 20.626    |
|              | 3:11         | 265.72             | 14.61  | V                                  | 21.922    |
|              | 3:21         | 271.50             | 69.67  | V                                  | 21.331    |
|              | 3:42         | 263.72             | 21.30  | V                                  | 21.926    |
|              | 4:03         | 266.87             | 12.95  | V                                  | 21.929    |
| Dec 28       | 4:11         | 309.20             | 83.09  | V                                  | 20.665    |
|              | 4:34         | 264.66             | 19.65  | V                                  | 21.917    |
| Dec 28       | 4:41         | 304.36             | 82.36  | V                                  | 20.631    |
| Dec 28       | 4:57         | 263.07             | 24.61  | V                                  | 21.912    |
| Dec 28       | 1:44         | 94.54              | 17.17  | B                                  | 22.781    |
| Dec 28       | 2:18         | 269.04             | 3.14   | B                                  | 22.878    |
| Dec 28       | 3:25         | 308.92             | 83.85  | B                                  | 22.217    |
| Dec 28       | 3:40         | 263.85             | 20.87  | B                                  | 22.919    |
| Dec 28       | 4:01         | 267.02             | 12.52  | B                                  | 22.829    |
| Dec 28       | 4:09         | 309.49             | 82.76  | B                                  | 22.258    |
| Dec 28       | 4:33         | 264.73             | 19.44  | B                                  | 22.713    |
| Dec 28       | 4:43         | 304.36             | 82.36  | B                                  | 22.205    |
| Dec 28       | 4:55         | 263.21             | 24.18  | B                                  | 22.788    |
| Dec 29       | 3:05         | 265.85             | 14.17  | V                                  | 21.828    |
| Dec 29       | 3:13         | 263.92             | 59.38  | V                                  | 21.616    |
| Dec 29       | 3:24         | 306.93             | 79.19  | V                                  | 21.083    |
| Dec 29       | 3:46         | 263.13             | 23.23  | V                                  | 21.962    |
| Dec 29       | 3:52         | 270.59             | 55.86  | V                                  | 21.712    |
| Dec 29       | 4:01         | 310.08             | 82.10  | V                                  | 21.140    |
| Dec 29       | 4:25         | 265.00             | 18.56  | V                                  | 21.877    |
| Dec 29       | 4:35         | 265.47             | 64.96  | V                                  | 21.667    |
| Dec 29       | 4:40         | 302.73             | 82.53  | V                                  | 21.124    |
| Dec 29       | 4:54         | 263.00             | 24.81  | V                                  | 21.829    |
| Dec 29       | 3:06         | 265.62             | 14.38  | B                                  | 22.740    |
| Dec 29       | 3:15         | 263.69             | 59.82  | B                                  | 22.626    |
| Dec 29       | 3:26         | 306.63             | 79.54  | B                                  | 22.429    |
| Dec 29       | 3:45         | 263.26             | 22.80  | B                                  | 22.849    |
| Dec 29       | 3:55         | 270.34             | 56.30  | B                                  | 22.688    |
| Dec 29       | 4:03         | 309.79             | 82.42  | B                                  | 22.641    |
| Dec 29       | 4:27         | 264.87             | 18.99  | B                                  | 22.809    |
| Dec 29       | 4:33         | 265.70             | 64.53  | B                                  | 22.697    |
| Dec 29       | 4:43         | 302.31             | 83.08  | B                                  | 22.523    |
| Dec 29       | 4:52         | 263.14             | 24.38  | B                                  | 22.826    |
| Dec 30       | 2:04         | 92.50              | 11.14  | V                                  | 21.825    |
| Dec 30       | 2:12         | 309.81             | 81.66  | V                                  | 20.920    |
| Dec 30       | 2:25         | 271.33             | 49.84  | V                                  | 21.670    |
| Dec 30       | 2:51         | 266.49             | 11.99  | V                                  | 21.875    |
| Dec 30       | 2:57         | 267.35             | 56.77  | V                                  | 21.552    |
| Dec 30       | 3:06         | 309.10             | 76.79  | V                                  | 21.203    |
| Dec 30       | 3:34         | 263.73             | 21.27  | V                                  | 21.942    |
| Dec 30       | 3:40         | 271.76             | 53.90  | V                                  | 21.653    |
| Dec 30       | 3:47         | 312.57             | 80.47  | V                                  | 21.289    |
| Dec 30       | 4:02         | 266.43             | 14.22  | V                                  | 21.952    |
| Dec 30       | 4:07         | 268.36             | 59.75  | V                                  | 21.608    |
| Dec 30       | 4:16         | 305.66             | 78.93  | V                                  | 21.160    |
| Dec 30       | 4:34         | 264.11             | 21.35  | V                                  | 21.843    |
| Dec 30       | 4:41         | 262.08             | 82.46  | V                                  | 21.283    |
| Dec 30       | 4:48         | 272.95             | 56.59  | V                                  | 21.711    |
| Dec 30       | 5:00         | 262.32             | 26.94  | V                                  | 21.828    |
at 4000 Å, diminishes to zero shortly after 5000 Å, but then has a
∼15% red leak starting at 7000 Å. Given the near-zero QE of the tube at the red end, the red leak would have no significant
effect on the \( B \)-band measurements.

From 2008 December 28 to December 30 UT, our typical observing strategy was as follows: (1) start and end the night with measurements of standard stars chosen from the Bright Star Catalogue (Hoffleit & Jaschek 1982) so that the photometric zero points are interpolated and never extrapolated; (2) measure the background sky near the zenith, then very low in the sky, then at an intermediate zenith angle; (3) measure a standard star approximately every 40 minutes. Our principal standard stars were BS 1179 and \( \zeta \) Cae, with \( \rho \) For observed less often. The first two stars could be observed on the same gain

| UT Date | UT | Azimuth (deg) | Zenith Angle (deg) | Filter | Sky Brightness (mag arcsec\(^{-2}\)) | Flux (nL) |
|---------|----|---------------|-------------------|--------|-----------------------------------|----------|
| Dec 30  | 2:02 | 92.65 | 11.57 | \( B \) | 22.557 | ... |
| Dec 30  | 2:16 | 309.22 | 82.32 | \( B \) | 22.167 | ... |
| Dec 30  | 2:22 | 271.72 | 49.19 | \( B \) | 22.511 | ... |
| Dec 30  | 2:52 | 266.43 | 12.21 | \( B \) | 22.677 | ... |
| Dec 30  | 3:00 | 266.99 | 57.42 | \( B \) | 22.477 | ... |
| Dec 30  | 3:10 | 308.47 | 77.47 | \( B \) | 22.373 | ... |
| Dec 30  | 3:29 | 264.05 | 20.20 | \( B \) | 22.773 | ... |
| Dec 30  | 3:41 | 271.63 | 54.11 | \( B \) | 22.605 | ... |
| Dec 30  | 3:45 | 312.87 | 80.15 | \( B \) | 22.327 | ... |
| Dec 30  | 3:59 | 266.58 | 13.79 | \( B \) | 22.842 | ... |
| Dec 30  | 4:09 | 268.11 | 60.18 | \( B \) | 22.619 | ... |
| Dec 30  | 4:14 | 305.96 | 78.58 | \( B \) | 22.289 | ... |
| Dec 30  | 4:32 | 264.25 | 20.92 | \( B \) | 22.713 | ... |
| Dec 30  | 4:43 | 261.83 | 82.89 | \( B \) | 22.457 | ... |
| Dec 30  | 4:51 | 272.56 | 57.24 | \( B \) | 22.500 | ... |
| Dec 30  | 4:59 | 262.46 | 26.52 | \( B \) | 22.609 | ... |

*Year is 2008. UT is in hours and minutes. Azimuth and zenith angle are probably accurate to \( \pm 0.2^{\circ} \). For \( V \)-band values, the sky brightness is also converted to flux in nL.*

Fig. 2.—Observed \( V \)-band sky brightness at Cerro Tololo during solar minimum and at a variety of zenith angles. The upper (dashed) locus is based on the model of Garstang (1989) for Mt. Graham. The lower (solid) locus is based on the model of Garstang (1991) for Junipero Serra, California. See the electronic edition of the PASP for a color version of this figure.

Fig. 3.—Ratio of observed \( V \)-band sky brightness and Garstang (1991) model shown in Fig. (2). Essentially, only at high zenith angles do we find observed sky brightness in excess of Garstang’s model. See the electronic edition of the PASP for a color version of this figure.
setting used for the sky-brightness measures; this eliminates one source of potential systematic error. The output of the pm tube is amplified by a factor up to $10^6$ with an analog amplifier. The output is displayed real-time on a milliammeter and recorded with a Hewlett Packard strip chart recorder.

To determine the photometric zero points each night, we assumed mean extinction coefficients of $k_v = 0.154$ mag airmass$^{-1}$ and $k_b = 0.274$ mag airmass$^{-1}$, based on several years of CCD photometry at CTIO. Since our standards were observed between 1.0 and 1.1 airmasses, the adopted extinction values hardly mattered, but on any given night the derived sky-brightness values are systematically in error by the difference of the true extinctions and the assumed values. Of greater consequence is the drift of the zero points with time. We found that the drift was linear and amounted to a maximum of 0.03 mag hr$^{-1}$. The sky-brightness measures presented here take into account these linear drifts. It should be noted that extinction corrections are not made to sky-brightness measures, only to measures of standard stars.

Once we determine the equivalent $B$- and $V$-band magnitudes of the sky in our $6.522$ arcmin$^2$ beam, we obtain the number of magnitudes per arcsec$^2$ by adding $10.927$ to the single-beam magnitudes. This additive factor is just $2.5 \log_{10} A$, where $A$ is the beam size in arcsec$^2$.

Almost all of our high zenith angle measurements made in 2006 December and 2008 December were taken over La Serena. On nights when there is no marine cloud layer, the city is clearly visible from the observatory. In Figure 1 we show a photo of this situation, obtained by one of us (M. G. S.).

The sky-brightness data are found in Table 1. For the $V$ band we also give the flux in nanolamberts, using equation (3) of K07 or its equivalent (Garstang 1989, eq. [27]).

Flux measured in nanolamberts (nL) is technically only relevant for the $V$ band, as it approximates the response of the human eye. We can convert the $B$-band sky brightness in mag arcsec$^{-2}$ to the flux $b_{||}$ in photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ by using the inverse of equation (39) of Garstang (1989), namely:

$$b_{||} = \exp \left[ \frac{41.965 - B}{1.0857} \right].$$

The observed flux of the sky near the zenith can effectively be corrected to the zenith by dividing it by the secant of the zenith angle. This is basically the same as equation (19) of Schaefer (1990)

$$B_{\text{zen}} = B_{\text{obs}} / (1 + Z_{\text{rad}}^2 / 2),$$

where $Z_{\text{rad}}$ is the zenith angle in radians.

### 3. DISCUSSION

The mean sky brightness at the zenith in 2008 December was $V = 21.958$ mag arcsec$^{-2}$. An individual $V$-band measurement at that flux level was accurate to $\pm 0.060$ mag arcsec$^{-2}$. This is based on 17 observations within $27^\circ$ of the zenith and corrected to the zenith using the formula of Schaefer (1990) given at the end of § 2. The mean zenith $V$-band flux was $56.24$ nL, with a $1\sigma$ scatter of $\pm 3.11$ nL (5.5%). The mean $B$-band zenith sky brightness was $22.826$ mag arcsec$^{-2}$. An individual $B$-band measurement at that flux level was accurate to $\pm 0.10$ mag arcsec$^{-2}$. These mean values are among the faintest levels we have ever measured, indicating that the solar minimum was still in effect in 2008 December.

The individual $V$-band data points from 2006 December and 2008 December are shown in Figure 2. We have included the locus of Garstang (1989) derived for Mt. Graham, offset by +3.0 nL, and the locus of Garstang (1991) for Junipero Serra (California), similarly offset. Since we did not correct our measurements for the presence of faint stars in the beam, some offset is understandable. Garstang’s improved 1991 model includes the addition of an ozone layer, a more accurate representation of the atmospheric molecular density variation as a function of height, a better mathematical representation of the scattering angular function of aerosols, and a thin layer of dust of arbitrary optical thickness and height above sea level. These modifications lead to a reduction of the predicted brightness of the night sky.

The ratio of our $V$-band data to the slightly offset locus of Garstang (1991) is shown in Figure 3. This shows that except at high zenith angle, we do not measure any significant enhancement of the $V$-band sky brightness at CTIO, even when from the mountain we can clearly see La Serena below. For comparison,
the reader is directed to the interesting article by Luginbuhl et al. (2009), which includes pictorial and graphical data along with modeling based on the Garstang (1991) model and an approximate correction for double scattering.

Our $B$-band data, converted to photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, are shown in Figure 4. Unlike our $V$-band data, there is no strong enhancement of the $B$-band light at high zenith angle when the lights of La Serena/Coquimbo are visible to the naked eye. This may be because the artificial lights presently in operation do not put out much light in the $B$ band. Spectra of the scattered light should be obtained to check this.

There is one curious “anomaly” in Figure 2. Our final high zenith angle measurements on 2008 December 30 were obtained over the town of Andacollo—a much more southerly azimuth than La Serena. Though Andacollo was clearly visible (i.e., not covered by cloud), we measured no enhancement of the $V$-band flux in this direction compared to the model of Garstang (1991). We surmise that this is due to the smaller population in Andacollo and a smaller amount of airborne dust there. A combination of dust and light emitted above the horizontal gives us enhanced light levels over La Serena and Coquimbo when they are visible at Cerro Tololo.

As the populations of La Serena and Coquimbo continue to grow, the observations presented here may serve as a reference. If the lighting ordinances in place are effective, we may see only minimally increased light pollution at CTIO.

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