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A PHOTOMETRIC AND SPECTROSCOPIC EVALUATION OF THE SITE AT TONANTZINTLA OBSERVATORY[1]

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RESUMEN

Se presenta una evaluación sobre la calidad del cielo en el Observatorio Astronómico Nacional de Tonantzintla mediante la calibración fotométrica de un conjunto de estrellas estándar en M67 en las bandas B, V, R e I del sistema Johnson-Cousins y la observación del cielo a diferentes distancias cenitales con el espectrógrafo Boller & Chivens. El brillo del cielo se estimó (a) a partir de las observaciones CCD al cúmulo M67 y (b) utilizando un método visual en dirección de estrellas de magnitud conocida. Se obtuvo un valor de 18.5 ± 0.6 mag arcsec^{-2}. La curva de extinción atmosférica promedio presenta un comportamiento intermedio entre la observada para el OAN-San Pedro Mártir y la asociada a actividad volcánica. Los espectros del cielo en el OAN-Tonantzintla permiten identificar líneas asociadas a lámparas de HgI y NaI a baja y alta presión. Nuestros resultados permiten justificar la actualización y compra de nuevo equipamiento para convertir al OAN-Tonantzintla en el Laboratorio para la Enseñanza de la Astronomía Observacional.

ABSTRACT

Based on data obtained at the Observatorio Astronómico Nacional, Tonantzintla, an evaluation of the quality of the local sky is presented. The evaluation is carried out through an absolute CCD calibration to a set of standard stars in the field of M67 in the B, V, R and I Johnson-Cousins system and from Boller & Chivens long-slit spectroscopic observations of the local sky at various elevations. The sky brightness is estimated from our CCD frames yielding a mean value of 18.5 ± 0.6 mag arcsec^{-2}. The mean atmospheric extinction curve behaves midway between the normal extinction and that related to volcanic outbursts. From the long-slit spectra of the sky at OAN-Tonantzintla, HgI and NaI lines of high and low pressure lamps are identified. These results allow us to justify a major upgrading of the observatory, to convert the OAN-Tonantzintla into the Laboratory for Astronomy Education both for UNAM and for other educational institutions in the center-south part of the country.

Key Words: atmospheric effects — site testing — stars: fundamental parameters — stars: imaging — techniques: photometric — techniques: spectroscopic

1. INTRODUCTION

The Observatorio Astronómico Nacional at Tonantzintla (OAN-Tonantzintla), under supervision of the Instituto de Astronomía at the Universidad Nacional Autónoma de México (IA-UNAM), is located near the Cholula village in the state of Puebla, 150 km away from the Instituto de Astronomía headquarters in Mexico City. Due to the increasing amount of light pollution from the growing

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city of Puebla and nearby villages, the observatory became progressively inappropriate for deep astronomical observations. Observing priorities changed at Tonantzintla observatory and since the end of the 1970s the site has provided fundamental support for (i) instrumental development and testing (c.f. Voitsekhovich et al. 2005), (ii) observing programs of bright objects of various types (c.f. Pismis & Moreno 1984) and (iii) public outreach and physics/astronomy university programs.

A close collaboration between Facultad de Ciencias and the Instituto de Astronomía at UNAM brought the 1 m telescope of the OAN-Tonantzintla as one of the first professional telescopes in México available at college level providing physics and astronomy students with real access to modern scientific instruments. The acquisition of a scientific CCD at the end of the 1980s opened new possibilities for both photometric and spectroscopic observations at the site. In this paper an evaluation of the local sky conditions by using the current photometric and spectroscopic instrumentation is presented and the results are assessed in the context of promoting the OAN-Tonantzintla as a natural laboratory for astronomical and educational programs at UNAM.

The paper is organized as follows. In § 1.1 we present a brief synopsis of a historical investigation on the observatory's beginnings (Moreno-Corral et al. 2009, in preparation) that allows us to better understand the role of the OAN-Tonantzintla as the major astronomical facility in México during the 1960s. In § 2 we present the main characteristics of the current photometric and spectroscopic instrumentation available at the site. We also present the results of our *BVRI* photometric observations of a set of standard stars from the M67 star cluster, our estimate of the mean extinction coefficients and the sky surface brightness in the Johnson-Cousins bands. Additionally, the results of a campaign to estimate the sky brightness in an area of ~ 8 km^2 around the OAN-Tonantzintla are presented. In § 3 the results of the spectroscopic observations of the sky at various elevations are given and compared against the spectra of other astronomical sites. The most prominent emission lines in the spectra of the sky that contribute to the light pollution are identified. Sky spectra acquired at the OAN-Tonantzintla at different epochs are also presented and compared. In § 4 a general discussion of the photometric and spectroscopic results is presented, followed by some suggestions for more efficient observing runs at the site. Finally, based on an estimate about the actual capabilities of the 1 m + current instrumentation, the feasibility of in-situ/remote observing programs and their impact on the undergraduate/graduate physics and astronomy programs at UNAM is commented.

1.1. *Historical Overview*

The important number of astronomical discoveries carried out during the decade of 1947–1957 by Guillermo Haro and a group of collaborators using the 76-cm Schmidt camera of the Observatorio Astrofísico Nacional, subsidiary of the Secretaría de Educación Pública (Bok 1941; Mayall 1942), made him realize the necessity of complementing and diversifying their observational projects. Therefore, in 1958, as a director of the Observatorio Astronómico Nacional at the UNAM, Haro made an effort to provide this institution with a modern reflector telescope. As the plans drawn by J. Brinkan show (Haro 1958), it would be installed on the piece of land donated by the amateur astronomer Domingo Taboada (Moreno-Corral & López-Molina 1992), contiguous to that occupied since 1942 by the Observatorio Astrofísico Nacional in the town of Tonantzintla, Puebla.

In order to carry out this project, Guillermo Haro, in addition to the support provided by the UNAM authorities, sought external financing of several Mexican philanthropic foundations, and obtained from them, and principally from the Mary Street Jenkins Foundation of the city of Puebla (Trueblood 1988), considerable resources which permitted him to commission the fabrication of a modern reflector telescope with fork mount and Cassegrain focus. The office of the contractor engineer B.G. Hooghoudt of Leyden, Holland was designated by Guillermo Haro to design the mount and the rest of the mechanical parts of the new telescope which were then manufactured by the Holland firm Rademakers Aandrijvingen of Rotterdam. The mirrors for these instruments were polished in California, USA, under the supervision of the prominent optician Don O. Hendrix of the Hale Telescope Team (Osterbrock 2003). The diameter of the main mirror was 40 inches with a central aperture of 10 inches.

The members of the technical personnel of the Observatorio Astrofísico Nacional and the Observatorio Astronómico Nacional installed, wired and tested the telescope which was ready for its first light in 1961 (Poveda & Allen 1987). The first two instruments of the telescope were a nebular spectrograph and a photoelectric photometer. A few years later, the instrumental equipment of the telescope was increased, including a Boller & Chivens spectrograph built by Perkin-Elmer Corporation for the

Cassegrain focus, with the possibility of interchanging cameras and gratings. In addition, a photographic Fabry-Perot interferometer with fixed plate etalons, and narrow band nebular filters was provided. This instrument was essential for kinematic studies of galactic nebular regions as discussed in Pismis & Moreno (1984).

Two milestones were fundamental for the future of the observatory after 1980: (1) the acquisition of a first generation Thomson CCD detector in the middle of the 1980s that, attached to the 1 m telescope, opened up new possibilities for observing, especially in photometric and spectroscopic modes, and (2) the opening of a graduate program in Astronomy & Astrophysics at UNAM at the end of the 1980s. The 1m telescope and its instrumentation were made available at college level providing fundamental support for physics and astronomy courses.

2. PHOTOMETRIC OBSERVATIONS OF THE SKY AT THE OAN-TONANTZINTLA

The main telescope at the Tonantzintla observatory is a 1 m f/15 Cassegrain with an equatorial mount yielding a plate scale of 13.53 arcsec/mm at the focal plane. The range of movements is ± 5.6 h in hour angle and from -60° to 80° in declination with a maximum pointing velocity of 1°/sec and a pointing error $\leq 1'$ for zenithal distance $z \leq 60^{\circ}$. The main optical detector is a thinned Metachrome II covered Thomson THX 31156 CCD of 1024×1024 pixels, each of 19 μm in size. Among its characteristics are a deep well $\sim 175,000\ e^{-}$, a dark current of $\sim 0.31\ e^{-}$/hour/pixel at gain mode 4, a readout noise of $\sim 3.5\ e^{-}$ RMS, a linear response of 0.58% and a reading rate of 50KHz. The telescope and detector combination attain a maximum field of view of $4.2' \times 4.2'$. A set of broad-band B (λ 4300 Å), V (λ 5400 Å), R (λ 6400 Å), I (λ 8900 Å) filters in the Johnson-Cousins systems is available in direct imaging mode.

2.1. *Broad-Band BVRI Photometry*

BVRI images in the Johnson-Cousins system were obtained with the Thomson CCD detector in 2×2 bin mode attached to the 1 m telescope, covering an area of $4.2' \times 4.2'$, with a scale of $0.49''$/pixel and a typical seeing of $3''$. Good weather conditions for observing standard stars are difficult to find at the OAN-Tonantzintla. For the sake of the present report we concentrate on the February 2005 observing runs. Our monitoring program consisted of a CCD photometric follow-up of a set of 25 equatorial standard stars from the "Dipper Asterism" M67 star cluster (Chevalier & Ilovaisky 1991; Landolt 1992) at different air masses in order to estimate local mean extinction coefficients, sky brightness and total apparent magnitudes of the stars. Due to the lack of a fine guiding system, exposure times did not exceed 5 minutes in the B band to avoid guiding problems in longer exposure times.

Images were debiased, trimmed, and flat-fielded using standard IRAF[5] procedures. First, the bias level of the CCD was subtracted from all exposures. A set of 10 bias images was obtained per night, and these were combined into a single bias frame which was then applied to the object frames. The images were flat-fielded using twilight sky flats taken in each filter at the beginning and/or end of each night. The most energetic cosmic-ray events were automatically masked using the COSMICRAYS routine. A final step in the basic reduction involved registration of all available frames in each filter to within ± 0.1 pixel. This step was carried out by measuring centroids for stars on the images and then performing geometric transformations using GEOMAP and GEOTRAN tasks in IRAF.

A total of 25 standard stars with a color range of $-0.1 \leq (B-V) \leq 1.4$ and a similar range in $(V-I)$ were observed at different air masses and were measured with a 28 pixel diameter aperture to determine, for a given frame, total apparent magnitudes in the B, V, R and I bands. Outside atmosphere values for magnitudes were obtained after estimating atmospheric extinction coefficients by means of linear least-square fitting procedures. Linear transformations to the Johnson-Cousins photometric system were also derived by least-square solutions. Figure 1 shows a B band image of the selected standard stars in the field of the M67 star cluster. Number designations were adopted following Chevalier & Ilovaisky (1991).

The reader should notice that the quantum efficiency of the Thomson CCD detector[6] is significantly lower in the B than in the I band. However, a 5 min integration time is enough to get a reasonable signal-to-noise ratio in the B band for stars as faint as $m_B \sim 15$ mag within the M67 field.

Once the principal extinction coefficients in B, V, R and I were estimated, a transformation of the instrumental magnitudes to a standard system was

[5]The IRAF package is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation (NSF).

[6]See `http://www.astrostnt.unam.mx`.

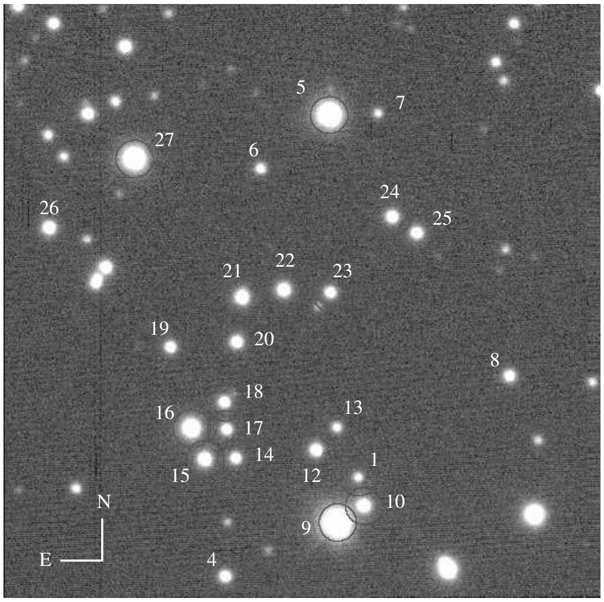

Fig. 1. B band image of stars in the field of the "Dipper Asterism" M67 star cluster acquired with the 1 m + Thomson CCD at the OAN-Tonantzintla covering an area of $4.2' \times 4.2'$, with a scale of $0.49''$/pixel. The numbers correspond to the stars used in the current study.

calculated (Hiltner 1960; Massey & Davies 1992) according to the following equations:

$$
\begin{aligned}
B - b &= \alpha_B + \beta_B (b - v)_0 \,, \\
V - v &= \alpha_V + \beta_V (b - v)_0 \,, \\
R - r &= \alpha_R + \beta_R (v - r)_0 \,, \\
I - i &= \alpha_I + \beta_I (v - r)_0 \,, \qquad (1)
\end{aligned}
$$

where B, V, R and I are the standard magnitudes, b, v, r and i are the instrumental (and airmass-corrected) magnitudes. α and β are the transformation coefficients for each filter. For more details on our reduction procedures, see Hernández-Toledo & Puerari (2001).

A comparison of our estimate of the apparent magnitudes in the B and I bands against those reported in Chevalier & Ilovaisky (1991) for the 25 stars in common is shown in Figure 2.

Figure 2 shows that non significant systematics (zero point and first-order color terms) are influencing our magnitude estimates. The observed range in apparent magnitudes goes from (9–15) mag and from (8–14) mag in the B and I bands respectively. Vertical error bars in each panel indicate the average σ values per apparent magnitude bin. The B band σ values per bin increase from (0.17–0.25) mag from bright to faint star magnitudes. On the other hand, the I band σ values per bin vary from (0.25–0.35)

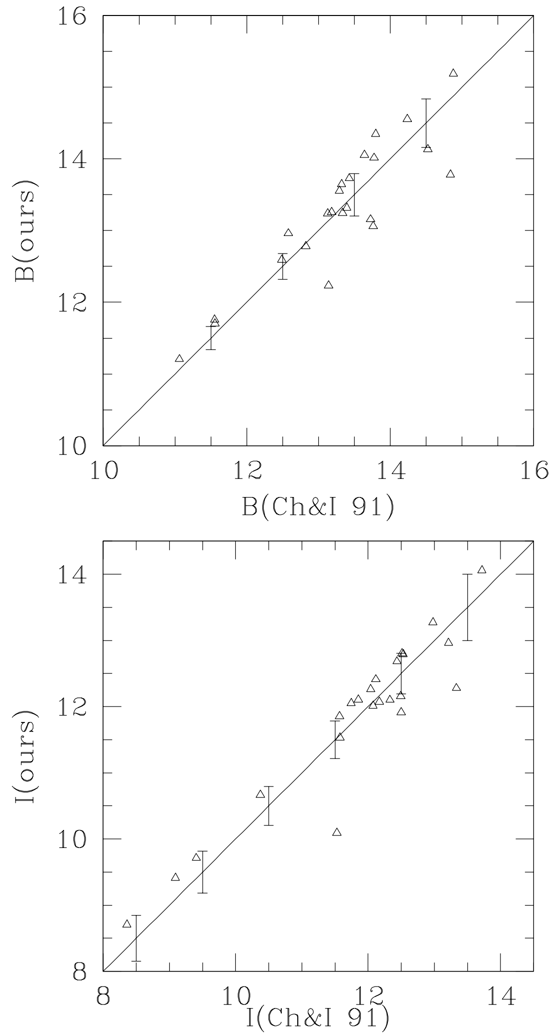

Fig. 2. Comparison between our estimated B and I band magnitudes and those from Chevalier & Ilovaisky (1991) for 25 standard stars in common.

mag indicating the intrinsically noisy nature of the red filters as well as an increasing contribution of the sky background at redder bands. From the observed variation of σ-values in Figure 2, typical values ~ 0.2 to 0.3 mag in the B and I bands are quoted as representative for the photometric calibration.

2.1.1. *Errors*

An estimation of the errors in our photometry involves (1) the procedures to obtain instrumental magnitudes and (2) the uncertainty when such instrumental magnitudes are transformed to a standard photometric system. For item (1), the extinction corrections to the instrumental magnitudes and airmass estimates were considered. After a least square fitting procedure, the associated errors to the slope for each principal extinction coefficient are; $\delta(k_B) \sim 0.05$, $\delta(k_V) \sim 0.05$, $\delta(k_R) \sim 0.06$ and $\delta(k_I) \sim 0.06$. An additional error δ(airmass) ~ 0.005 from the airmass routines in IRAF was also considered. For item (2), the zero point and first order color terms of the photometric transformation (equation 1) are the most important. The associated errors to the zero point and first order color terms were ~ 0.1 mag in the B, V, R and I bands. Total typical uncertainties are ~ 0.2 mag in B, V, R and I bands, close to the typical values quoted from the σ variations. We notice that the observing room has various sources of light coming mainly from the computer screen and various electronic LEDs. An appropriate shielding against that parasitic light at the observing room is suggested. We also suggest to evaluate in further observing runs the contribution of scattered light along the optical path of the 1 m telescope (c.f. Gutiérrez et al. 1996). This contribution could affect the data calibration, particularly when a frame is acquired by exposing to a bright light source (which was not the case in the present paper). Given the much fainter limiting magnitudes achievable with an autoguiding system, another recommendation *ad hoc* to the actual major upgrading of the observatory is the implementation of such a system.

2.2. *Sky Surface Brightness*

The surface brightness of the moonless night sky is a fundamental quantity of an observing site. The sky brightness at the OAN-Tonantzintla has been degraded with time, as the nearby population center of Puebla and its attendant light pollution has been growing. Sky brightness was measured in our CCD frames at different observing bands on moonless conditions by excluding areas apparently free of nebulosity, stars, cosmic-ray events or CCD defects. Since we have observations at different heights above the horizon (typically from 30° to 75°), the sky brightness at those heights could be estimated as well. Our results are presented in Table 1. Column (1) indicates the band of the observation, Column (2) is the airmass at the time of the observation, Column (3) the sky brightness values obtained at the Observatorio Astronómico Nacional San Pedro Mártir (OAN-SPM) under dark sky conditions. Similarly, Columns (4) and (5) represent the airmass and the corresponding sky brightness values obtained at OAN-SPM under bright (near full-moon) sky conditions. The airmasses at the time of our observations at 30° and 75° above the horizon are presented in Column (6). Finally, the corresponding sky brightness estimates at the OAN-Tonantzintla in dark sky conditions are presented in Column (7).

The results in Table 1 indicate a sky surface brightness value in the V band of $\sim 18.5 \pm 0.2$ mag arcsec^{-2} in the line of sight towards the city of Puebla and $\sim 19.0 \pm 0.2$ mag arcsec^{-2} at the local zenith area. Compared to the representative V band sky value for the OAN-SPM under moonless conditions, this difference of about 3 magnitudes is interpreted as the amount of light pollution contributed to the site from both the local villages around Tonantzintla and from the city of Puebla. The effect is equivalent to losing the ability to distinguish by the unaided eye stars of magnitudes fainter than ~ 4 in a clear dark night sky.

We warn the reader that although measuring the sky brightness via broad band photometry as shown here represents a first step forward, it has to be taken with caution since such measures encompass both natural air glow and artificial sources. Significant night-to-night (and even hourly) variations of the intensity of OH emission and the OI λ 5577 auroral line are well documented and depend in part on solar activity (see Pilachowski et al. 1989; Massey, Gronwall, & Pilachowski 1990).

To complement our sky brightness measures, in October 2008 we carried out a first campaign to estimate the sky surface brightness in an area of ~ 8 km^2 around the observatory. With the aid of 25 students from the Facultad de Ciencias and Instituto de Astronomía of the UNAM, simple, unaided-eye observations to look for the faintest stars toward the Orion constellation were carried out. The experiment was carried out on a moonless night, free of clouds, by matching the observed star configuration to one of six star maps of progressively fainter limiting magnitude that were prepared for that purpose. The method uses two facts, namely (1) that a widely accepted value for sky brightness at the zenith at a site completely free of man-made light sources and near solar activity minimum is $V \sim 21.4 - 21.8$ mag arcsec^{-2} and (2) that the unaided eye detects stars of apparent magnitudes as faint as 6 mag. Measures reading 6th magnitude stars would indicate a dark site with surface brightness near $V \sim 21.4 - 21.8$ mag arcsec^{-2} and free of light pollution, while a reading of 4th magnitude stars would indicate a site with a surface brightness worse than $V \sim 18$ mag arcsec^{-2} and thus a more degraded, light polluted sky. Different positions around the OAN-Tonantzintla were selected free of trees and tall buildings that could block the visibility where students found latitude and longi-

TABLE 1

AIRMASSES, AND SKY BRIGHTNESS VALUES OBTAINED AT THE OBSERVATORIO ASTRONÓMICO NACIONAL SAN PEDRO MÁRTIR (OAN-SPM) UNDER DARK AND NEAR FULL-MOON SKY CONDITIONS. SIMILAR QUANTITIES OBTAINED IN DARK SKY CONDITIONS AT THE OAN-TONANTZINTLA AT 75° ABOVE THE HORIZON AND AT 30° TOWARDS THE CITY OF PUEBLA ARE ALSO PRESENTED[a]

Sky Surface Brightness (mag arcsec^{-2})						
	OAN-SPM			OAN-Tonantzintla		
Band	X(air mass)	Sky	X(air mass)	Sky	X(air mass)	Sky
U	1.00	21.3	1.09	18.9	...	...
B	1.00	22.3	1.12	19.5	2.1/1.05	18.6/19.1
V	1.01	21.4	1.15	19.4	2.2/1.09	18.5/19.0
R	1.00	20.9	1.18	19.3	2.3/1.12	18.3/18.9
I	1.02	19.4	1.21	18.2	2.4/1.16	16.8/17.7

[a]OAN-SPM Sky Surface Brightness data from M. Richer `http://www.astrossp.unam.mx/sitio/brillo_cielo.htm`.

tude by means of a GPS. Once the students matched their unaided-eye observations to one of our magnitude charts they moved to a new pre-selected location at least 1 km away from their original location. For a more detailed description on the apparent magnitude-surface brightness transformation, see Schaefer (1990).

Figure 3 (left panel) shows a 2.7 km × 2.7 km area around the observatory and the specific positions (numbers) where the sky brightness was estimated. The position of the observatory (OAN-T) is also indicated. The right panel of Figure 3 shows a 2D representation of the data after fitting a spline surface function to the observed distribution of points in the 2.7 km × 2.7 km area. The final surface that passes through the original points is then converted into a color-scaled surface.

The data points were plotted over a map and a two-dimensional function was fitted to the data using a standard IDL routine. This routine uses thin plate splines to interpolate a set of values over a regular two dimensional grid, from irregularly sampled data values, in this case the measured visual magnitudes. The maximum at the surface (light yellow color) corresponds to dark sky conditions while the orange tones represent brighter sky conditions and its variations within the survey area[7]. Our results indicate a mean sky surface brightness value $V \sim 18.5 \pm 0.6$ mag arcsec^{-2} within the survey area and $V \sim 19.1 \pm 0.5$ mag arcsec^{-2} only at the local zenith area of the observatory, consistent with the results obtained from our CCD photometric estimates. This result confirms the feasibility of these visual procedures and their potential to cover wider areas under well-planned strategies and good weather conditions.

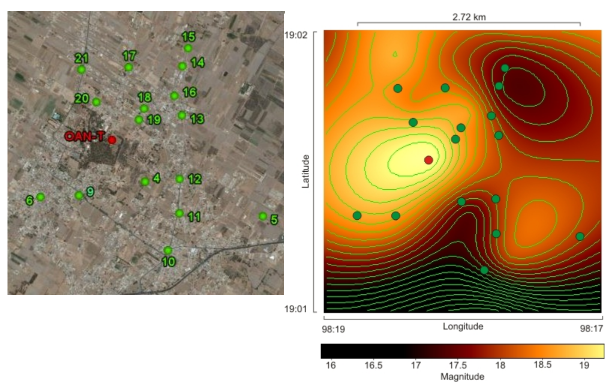

Fig. 3. Left panel: 2.7 km × 2.7 km area around the observatory and specific sites (numbers) where the sky brightness was estimated. The telescope site (OAN-T) is also indicated. Right panel: A color-scaled 2D representation of the data after fitting an spline surface function to the observed distribution of points. Light yellow colors represent dark sky values while the various orange tones represent brighter sky zones and their variations in the survey area. The darkest color corresponds to a zone where there is no available data thus producing an artificial falling down that must not be interpreted as a real variation. The contours (without levels) are used to identify maximum/minimum variations. x-y axes denote Longitude and Latitude while Surface Brightness (mag arcsec^{-2}) is indicated in the z-axis.

[7]The figure can be viewed in color in the electronic version of the paper.

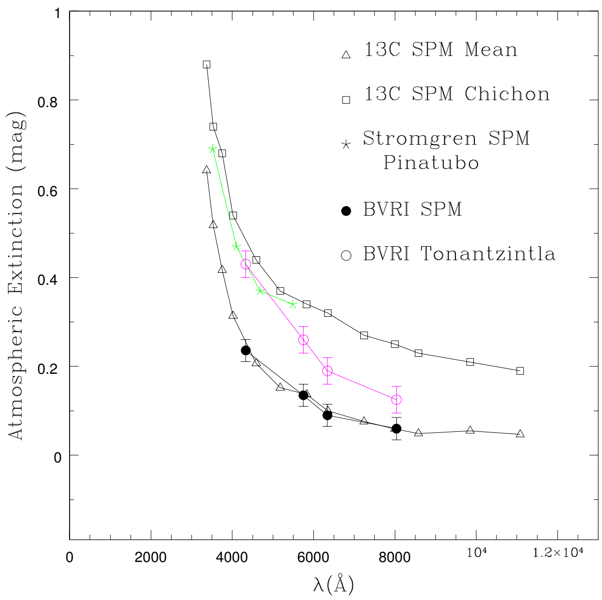

Fig. 4. The observed atmospheric extinction at the OAN-Tonantzintla (open circles) from our CCD frames in the Johnson-Cousins (BVRI) system. The mean extinction curve free of volcanic outbursts (empty triangles) and extreme extinction following the explosion of the volcanoes El Chichón and Pinatubo (empty squares and asterisk symbols) at the OAN-SPM with the 13C and 4-color Stromgren photometric systems (Schuster & Parrao 2001) are also presented. Filled circles denote the mean extinction (from 1998 to 2008 by Hernández-Toledo) at the OAN-SPM in the Johnson-Cousins (BVRI) system.

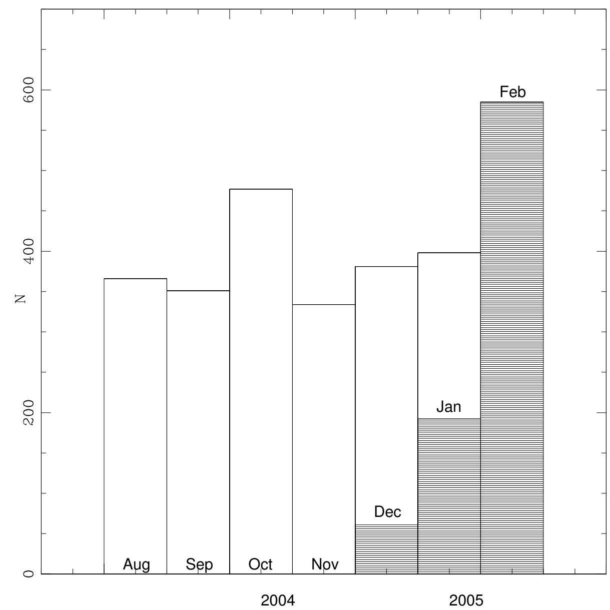

Fig. 5. A histogram of the monthly number of exhalations of water vapor and gases from the Popocatépetl volcano in the period august 2004-february 2005. The dashed histogram indicates the frequency of "moderate intensity" ash exhalations during that period.

2.3. *Mean Extinction Coefficients*

Figure 4 shows the observed atmospheric extinction at the OAN-Tonantzintla (open circles) from our CCD frames in the Johnson-Cousins (BVRI) system. To compare our results, the mean extinction curve free of volcanic outbursts (empty triangles) and extreme extinction following the explosion of the volcanoes El Chichón in March 1982 and Pinatubo in June 1991 (empty squares and asterisk symbols) are presented. The OAN-SPM data were obtained over the years 1973 through 1999 with the 13C and 4-color Stromgren photometric systems (Schuster & Parrao 2001). The extinction values are plotted versus the equivalent wavelengths of the photometric band passes. For the 13C system these wavelengths have been taken from Mitchell & Johnson (1970). We also present data obtained at OAN-SPM in the last 10 years by Hernández-Toledo from CCD *BVRI* photometric data to validate the methodology used at Tonantzintla.

The mean extinction *BVRI* curve and its variations at the OAN-Tonantzintla at the time of our observations lies between the normal extinction (as referenced by OAN-SPM data) and that related to volcanic outbursts. Notice that our extinction measurements at the OAN-SPM confirm that the mean extinction (free of volcanic outbursts) has not changed significantly in the last 10 years. While the mean extinction curve at the OAN-SPM was modeled assuming that the extinction over 3200 Å $< \lambda <$ 6500 Å can be represented by three independent contributions due to Rayleigh-Cabannes, aerosol scatterings and ozone absorption, the extreme extinction was interpreted in terms of wavelength dependences for the volcanic aerosols. The 13C extinction observations from Schuster & Parrao (2001) showed clear evidence for an evolution and growth of the aerosol particles from El Chichón. These results suggest that the extinction at Tonantzintla could be related to the activity of the nearby Popocatépetl volcano. To investigate that possibility, we have used the on-line data from the government monitoring program of the Popocatépetl volcano, where daily/monthly reports on the number of exhalations of water vapor, gases and ashes and an archive of daily images can be found[8]. Figure 5 shows a histogram of the monthly number of exhalations of water vapor and

[8] `http://www.cenapred.mx.`

Fig. 6. Archive image of the government monitoring program of the Popocatépetl volcano showing a moderate intensity ash exhalation in a date close to our observations.

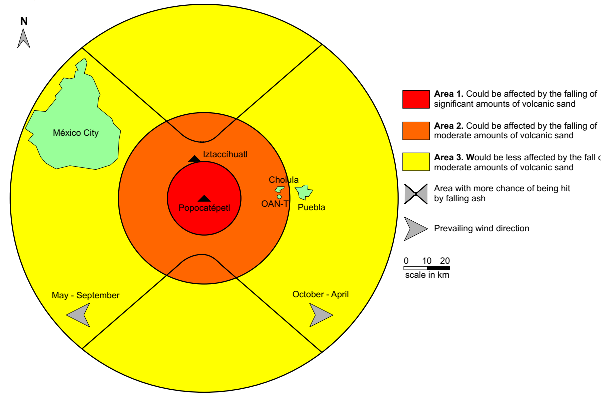

Fig. 7. Zones of probable fall of ashes and sand and the dominant wind direction along the year around the Popocatépetl volcano.

gases from the Popocatépetl volcano during a period of six months previous to our observations at the OAN-Tonantzintla. The dashed histogram indicates in addition, the frequency of "moderate intensity" ash exhalations reported during that period.

Although the number of monthly exhalations of water vapor and gases did not change significantly from August to December 2004, a flag associated to the intensity of exhalations of ashes turned on to "moderate" since the beginning of 2005 (dashed histogram), reaching a maximum frequency at the time of our observations in February 2005. Figure 6 is an archive image from the government monitoring program showing an exhalation of the Popocatépetl volcano at a time close to our observing dates.

Figure 7 shows a diagram of the site around the Popocatépetl volcano indicating the zone of probable fall of ashes and sand as well as the dominant wind direction along the year. The Tonantzintla observatory is located within a zone (mid gray) that could be affected by the fall of moderate amounts of ashes and sand.

A probable scenario explaining the observed anomalous extinction is that a "sea" of volcanic aerosols was coexisting in the local environment during our observations. With the aid of the government monitoring program, it is strongly suggested to check the statistics and tendencies about the fall of ashes previous to any further observation at the OAN-Tonantzintla.

3. SPECTROSCOPIC OBSERVATION OF THE SKY AT THE OAN-TONANTZINTLA

A classic Cassegrain (Boller & Chivens) spectrograph is also available at the OAN-Tonantzintla. Among its principal components are a set of diffraction gratings of 150, 400, 600 and 830 groove/mm, and a He-Ar comparison lamp (for more details see `http://www.astrostnt.unam.mx`). Long slit spectroscopy of the night sky at the OAN-Tonantzintla is also presented. The data were obtained with the Boller & Chivens spectrograph attached to the 1 m telescope during various campaigns in 2005 and 2006. From these observations we present only those for moonless clear skies (October 2005). Sky spectra at different heights above the horizon were also obtained.

With the Thomson CCD installed and a 150 groove/mm grating the useful wavelength coverage is from 3900 Å to 6200 Å with a dispersion resolution of 5.6 Å/pixel. A slit width of 300 μm was used to expose the sky. The measured resolution at half maximum in some individual emission lines is $\sim$ 50 Å. Standard IRAF procedures were used following bias subtraction and wavelength calibration with He-Ar arc lamps observed before and after each sky target. Neither atmospheric extinction correction, flat fielding nor flux calibration were applied. After wavelength calibration, the identification of the emission lines was verified within the IRAF *splot* routine. Exposure times were set to 1800s in all the acquired spectra.

The wavelength-calibrated night-sky spectrum at the OAN-Tonantzintla is shown in Figure 8. No attempt has been made to correct it for the airmass. The upper panel shows two spectra: The one in red was acquired from the east direction 30° above the

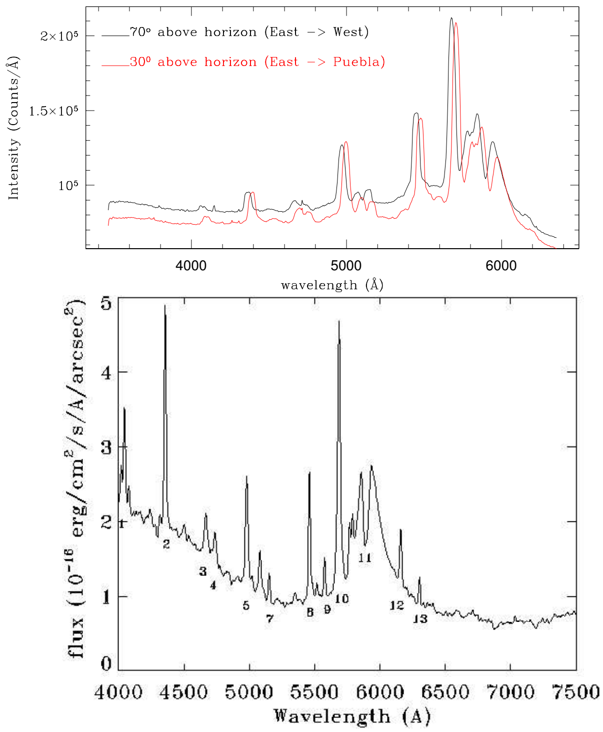

Fig. 8. Upper panel: λ-calibrated spectrum acquired at an elevation of 30° above the horizon (in red) towards the city of Puebla and the spectrum at 70° above the horizon (in black). Lower panel: Flux and λ-calibrated sky spectrum at the DDO observatory in Canada. Identifying numbers below the emission lines are described in De Robertis et al. (2002).

horizon towards the city of Puebla. The one in black was acquired at about the local zenithal sky area, 70° above the horizon. The x-axis shows wavelengths in Angstroms and the y-axis shows relative intensity units per Angstrom. For a comparison, the lower panel shows a sky spectrum acquired at the David Dunlap Observatory (DDO) by De Robertis, Fingerhut, & Blake (2002).

Notice a relative displacement of $\sim$ 3 pixels in the sky spectra at the two extreme elevations (30° and 70°). Possible causes could be movements of the long slit on the focal plane or flexures at large zenith distances. The line identification was made from our λ-calibration and by combining the information given in Massey & Foltz (2000), Osterbrock & Martel (1992), De Robertis et al. (2002) and Sheen & Byun (2004). The strongest lines in our night sky come from high pressure sodium (HPS), i.e. NaI emissions. Besides the very broad feature centered at 5893 Å, strong lines are also seen at around 4980, 5685, and 6157 Å. Another kind of city lights, mercury-vapor

TABLE 2

LINE IDENTIFICATION OF THE SKY SPECTRA AT THE OAN-TONANTZINTLA. THE WAVELENGTHS ARE IN ANGSTROMS[a]

Element
HgI 4358
NaI 4665,4669, NaI 4748,4752, NaI 4978,4983 (HPS)
NaI 5149,5153 (HPS)
HgI 5461
OI 5577 airglow (marginal)
NaI 5683,5688 (HPS,LPS)
NaI 5890,5896 (HPS), wings extend with self-absorption
NaI 6154,6161 (HPS,LPS)

[a]Carried out from our λ-calibration.

lamps and their Hg emission lines are also present in the OAN-Tonantzintla sky but appear to be not as strong as the HPs ones. We identified mainly HgI mercury lamp lines and NaI sodium lines of high and low pressure (HPS and LPS) lamps. Our identification of the emission lines in the sky spectrum at the OAN-Tonantzintla is presented in Table 2.

Among the strong lines of the natural sky emission, we suspect a marginal detection of the [O I]5577 line. There is one emission line at around 5080 Å for which a solid identification could not be made. The spectrum of Osterbrock & Martel (1992) does contain this line but without any identification. The DDO sky spectrum also shows this line clearly, but again without identification. An old study of Toronto sky by Lane & Garrison (1978) has a remark that multivapor lamps produce an emission at 5073.08 Å. Typical street-lamp spectra were presented by Osterbrock, Walker, & Koski (1976).

The upper panel of Figure 9 shows the sky spectra at the OAN-Tonantzintla acquired from the east direction 30° above the horizon towards the nearby city of Puebla, while the lower panel shows a plot of the sky spectrum at the OAN-Tonantzintla as reported by Torres-Peimbert & Robledo-Rella (1990). The 1990 spectrum was obtained with the 1.0 m telescope, the Thomson CCD + an intensified tube attached to the Boller & Chivens spectrograph using a 600 grooves/mm with a blaze of 10°. It is assumed here that this spectrum was acquired towards the city of Puebla.

Although there is no detailed information about the 1990 spectroscopic observations, particularly the height above the horizon and azimuthal direction, a comparison of these two spectra suggests that the observed relative intensity of the sodium and mercury lines and their contribution to the light-polluted lo-

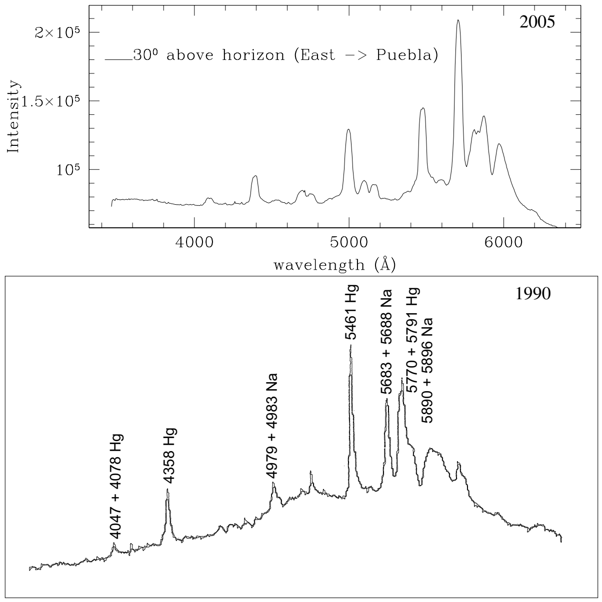

Fig. 9. Upper panel: The night-sky spectrum at the OAN-Tonantzintla. Lower panel: Night-sky spectrum at the OAN-Tonantzintla obtained in 1990 by Torres-Peimbert & Robledo-Rella.

cal sky at the OAN-Tonantzintla could have changed in the last 15 years. This is consistent with the fact that public lighting in the surroundings of the observatory and in the nearby city of Puebla has been gradually changed from mercury to sodium lamps in the last 20 years.

4. DISCUSSION AND CONCLUSIONS

Under reasonable weather conditions (cloudless and moonless nights), an absolute photometric calibration of standard stars of apparent magnitudes from (9–15) and (8–14) in the B and I bands, respectively, yielded no significant systematic shift of the zero points and color terms of the Johnson-Cousins photometric system. A total propagated error ~ 0.2 mag that slightly increases up to 0.3 mag at fainter magnitudes in the I band has been obtained. These errors reflect the convolved behavior of various components of the photometric system, namely: the current transmittance of the filters, the status of the optics of the telescope at the time of the observations, the current efficiency of the CCD and also the amount of light pollution in the sky, among other possible factors. In spite of this, reasonable photometric work can still be done for bright stars. We also suggest to evaluate in further observing runs the contribution of scattered light along the optical path of the 1 m telescope (c.f. Gutiérrez et al. 1996). This contribution could affect the data calibration, particularly when a frame is acquired by exposing to a bright light source (which was not the case in the present paper). Given the much fainter limiting magnitudes achievable with an autoguiding system, we also recommend the implementation of such a system as part of a major upgrading of the observatory.

The sky brightness at the OAN-Tonantzintla was estimated from two complementary methods: (1) from our CCD frames at the different observing bands and at different elevations and (2) from visual estimates through a campaign covering an area ~ 8 km^2 around the observatory. Both methods consistently yield a similar result of ~ 18.5 mag arcsec^{-2} in the V band towards the city of Puebla and $\sim$ 19.0 mag arcsec^{-2} at the more local zenithal area of the observatory. Compared to the representative V band sky value for the OAN-SPM of ~ 21.4 mag arcsec^{-2} under moonless conditions, the difference of about 3 magnitudes is interpreted as the amount of the light pollution that is being contributed to the site from both the very local and nearby lighting of the villages around Tonantzintla and from the city of Puebla. The effect is equivalent to loosing the ability to distinguish by eye stars of magnitudes ~ 4 and fainter in a clear night sky. The results from method (2) above also confirm the feasibility of visual procedures to estimate the sky surface brightness and show their potential to cover wider areas under good weather conditions. Walker (1977, 1991) and Garstang (1986, 1989) have estimated the increase in brightness at zenith distance 45°, in the direction of a conurbation of population P at distance D km to be $\sim PD^{\alpha}/C$, where C is a coefficient that does not depend on P and D but on factors such as the light emission per head of the population and the reflectivity of the ground. Garstang (1986, 1989) estimated the α index as the slope of the log (brightness) – log (D) relation for a value of the brightness of 0.01 mag arcsec^{-2} times the natural background, reporting in addition, a linear interpolation of α and log (C) as a function of log (P) which allow us to estimate more appropriate values of α and log (C) for a given population P. Although Garstang's results are valid for intermediate/large distances, we use them as a first approximation to estimate the expected increase in brightness caused by the city of Puebla as seen from the OAN-Tonantzintla.

A population census for the city of Puebla in 2005 yielded a population P of $\sim$ 1,400,000 inhabitants. Given the extension of the city, a mean distance D of 20 km to the observatory is considered as appropriate. Since log (P) = 6.15, by using the interpolated data in Garstang (1986, 1989) we estimate log (C) ~ 1.8 and $\alpha \sim -3.6$ yielding an increment in brightness Δ mag ~ 0.46. This variation is in agreement with the observed variation of ~ 0.5 mag arcsec^{-2} in sky brightness from our measurements from the local zenith to the east direction 30° above the horizon towards the city of Puebla.

Being close to the cities of Puebla to the east and Cholula to the north, both having potential for large growth, the OAN-Tonantzintla faces the danger of increasing deterioration of its sky conditions. In order to maintain competitiveness for educational and other scientific programs, it is important to preserve the sky brightness conditions through (1) our awareness of the night sky characteristics in future monitoring campaigns (more measurements over the next years will allow us to monitor changes) and (2) encouraging local authorities about the need to regulate public lighting and at the same time, showing the benefits (economic impact) of such initiatives when well planned and correctly implemented.

The mean extinction coefficients at $BVRI$ bands and their variations are needed to correct observations for the local effects of the atmospheric extinction. It is found that the extinction curve at the OAN-Tonantzintla lies between the normal extinction values and those related to volcanic outbursts, suggesting a possible connexion to the activity of the nearby Popocatépetl volcano. Compelling evidence in favor of this hypothesis came from data on monthly exhalations of gas, ashes and sand available from the government monitoring program of the Popocatépetl volcano. Since the OAN-Tonantzintla is located within a zone of probable fall of ashes and given the information on the dominant wind direction along the year, a "sea" of volcanic aerosols was probably coexisting in the local environment during our observations. It is therefore still necessary: (1) estimate far from outbursts extinction values and (2) study if aerosols other than volcanic ashes are contributing to the observed extinction, finding out if they show any seasonal pattern as it is the case of springtime winds stirring up dust to the local environment. It is known that the chemical composition of the ashes can vary from volcano to volcano and even from exhalation to exhalation. It would be also interesting to investigate the chemical composition of the ashes at the Popocatépetl volcano in order to properly model the optical properties of the corresponding aerosols and their contribution to the extinction curve. This is the type of monitoring work that could be done via our remote observing system or in-situ with the new instrumentation that is being installed at the observatory.

Light pollution at observatory sites (McNally 1994; Holmes 1997) arises principally from tropospheric scattering of light emitted by sodium- and mercury-vapor and incandescent street lamps. The wavelength-calibrated night-sky spectrum at the OAN-Tonantzintla shows mainly HgI mercury lamp lines and NaI sodium lines either of high and low pressure (HPS and LPS) lamps. The relative contribution of the mercury and sodium lamps to the local light pollution at the OAN-Tonantzintla might have changed in the last 15 years as a comparison of the spectra acquired in 1990 with those obtained in this work suggests. This is consistent with the gradual change from mercury to sodium lamps in the public lighting in the last 20 years. The observed pattern of sky lines has allowed us to detect a ~ 3 pixel shift at two extreme positions 30° and 70° above the horizon probably caused by the instrument flexures when the telescope is set at large zenithal distances.

The light pollution contribution to broad-band optical $BVRI$ bands is affecting the range of wavelengths between 4500 and 6000 Å. The 4358 Å Hg line can be a hazard for observers wanting to compare the intensities of the 4363 and 5007 Å OIII lines (for measuring the temperature of astrophysical plasmas). The 5460 Å Hg line lies in the center of the y band of the Stromgren $ubvy$ system. The Na D 5890/6 Å line typically contaminates both the broad V and R bands.

Before discussing the feasibility of various astronomical projects, it is still necessary to mention a series of practical problems, detected at the time of our observations, that must be solved in order to have more efficient local (and remote; see below) observing runs. For example, it is difficult to judge how photometric the conditions at the OAN-Tonantzintla are, especially during moonless nights. It is important to have access (locally and remotely) to the meteorological data and to obtain information on windspeed, temperature, humidity and pressure. Weather information complemented with a 1 μm fish-eye transparency camera can be very useful to monitor cloud cover. Such cameras are experiencing large technical improvements and lowering in cost, and should be considered for acquisition within the current upgrading program of the observatory. Twilight flats are among the most demanding parts both for local and remote observations, because there is little time available and the observer needs to know

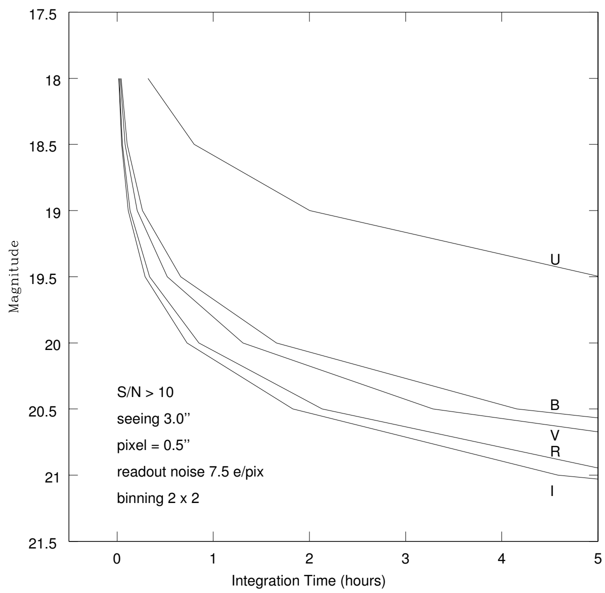

Fig. 10. An estimate of the integration time required to observe a point-like object of apparent magnitude 18.0 mag in the $UBVRI$ bands, given some CCD characteristics, with a S/N > 10 in a 0.84 m telescope and a typical sky brightness of 18 mag arcsec^{-2} as observed in the OAN-Tonantzintla.

what the count level was in previous flats. The possibility of including fast statistics estimators within the acquisition programs should be considered. The acquisition of twilight flats in "service mode" by the telescope operator at the OAN-Tonantzintla will benefit from such improvements. Another problematic process is that of focusing. This process is carried out by using one or more exposures of preselected fields of bright stars (preferably close to the target). Since for this purpose it is not necessary to read out the full CCD, the possibility of reading smaller sections of the CCD when estimating focus should also be considered and implemented. It is also recommended that the image acquisition programs let any basic information be included in the image headers for further image reduction purposes.

The solution of these problems along with the implementation of a fine guiding system for the 1 m telescope will result in more efficient observations and enable other observing possibilities at the OAN-Tonantzintla. Even more, our remote observing system will also benefit from those solutions since the judging and transfer of images could be very quick and image quality could be analyzed either locally or remotely as well. This opens new observing possibilities for scientific and educational programs as discussed below.

Figure 10 shows an estimate of the integration time required to observe a point-like object of apparent magnitude 18.0 (typical in optical follow-up of gamma ray bursts) in the $BVRI$ bands with a 0.84 m telescope + CCD detector array of given characteristics. This approximation is intended to figure out the capabilities/limitations of the 1m telescope + the current CCD at the OAN-Tonantzintla. A signal-to-noise ratio greater than 10, a seeing of 3 arcsec, a typical sky surface brightness value in the range of 18 mag arcsec^{-2} in the $BVRI$ bands as observed in Tonantzintla, a CCD pixel size of $\sim$ 0.5 arcsec and readout noise of $\sim$ 7.5 e/pix were considered. The OAN photometric simulator[9] has been used for this purpose.

The above integration times were estimated by assuming CCD quantum efficiencies (QE) in the $BVRI$ bands higher than it is actually the case for the current CCD at the OAN-Tonantzintla. Thus the curves in Figure 10 represent zero-order estimates to the real integration times required to reach a point-like object of a given magnitude at a given signal-to-noise ratio. The feasibility of various in-situ and/or remote observing programs for objects as faint as 20 mag is nevertheless apparent without requiring prohibitive integration times to obtain well sampled data over reasonably long time intervals.

4.1. *OAN-Tonantzintla: a Laboratory for the Teaching of Astronomy at College Level and Graduate Programs at UNAM*

In spite of the limitations imposed by light-pollution and given the current status of the instrumentation at the OAN-Tonantzintla, the feasibility of various educational and astronomical projects at college and graduate levels is nevertheless apparent. These possibilities could be increased if the current photometric and spectroscopic instrumentation (as well as the new instrumentation that is being acquired for the actual major upgrading of the observatory) is combined with the implementation of a fine guiding system for the 1 m telescope. Other observing possibilities at the OAN-Tonantzintla like the active Remote Observing System (hereafter ROS) for the 1 m telescope and other observing strategies like CCD differential photometry must also be considered.

The ROS is operated in real time via Internet allowing us to control telescope pointing, guiding, focusing and CCD image acquisition at the main and

[9]A. Watson (`http://www.astrossp.unam.mx/indexspm.html`).

auxiliary finder telescopes from the Instituto de Astronomía headquarters in Mexico City. The whole system was modeled within the Unified Modeling Language (UML) and the design has proved to be versatile enough for a variety of astronomical instruments and to offer a common framework for integrating different operating system platforms (Linux, MS Windows, uIP). The remotized telescope is mainly devoted to CCD photometry and spectroscopy with the aim of optimizing the data-acquisition process, increasing the number of users that will have access to the available instrumentation and giving support to research and to our graduate astronomy program.

The ROS at the OAN-Tonantzintla can be used from simple observation up to integrating the system into a carefully planned theme of a physics/astronomy course. In fact, it opens up a research facility for our graduate program. Students could learn how to acquire and reduce data from upgraded instruments, thus providing excellent preparation for graduate work. One specific project that could be immediately planned is the determination of the optical atmospheric extinction coefficients through systematic remote observations in appropriate weather conditions. The access to these facilities provides a sense of participation and accomplishment at a time when many students feel overwhelmed by formal physics/astronomy courses where only textbooks and lectures are invoked.

The study of supernovae in-situ or via the ROS could yield important data to understand the death of stars if high enough quality, frequently sampled data are obtained over reasonably long time intervals. For example, the sharp rise in brightness and the initially rapid color evolution allow the identification of the type of progenitor star involved. Another important parameter is the estimate of the bolometric light curve, which in the case of the OAN-Tonantzintla would consist primarily of observations of the optical continuum during one or two years. This is feasible since supernovae in the Virgo cluster have an apparent visual magnitude m $\sim 11-13$ mag at maximum (depending on their type) and can in principle be monitored at Tonantzintla for at least a year up to the limiting magnitude of the 1 m instrumental set.

Optical multi-band observations of novae can also be used to built approximate bolometric light curves, as in the case of supernovae. For good results, the observations must be done over a wide time scale. Well sampled bolometric and color curves can be observed following them up to the late stages which have been less studied. The characterization of novae in nearby galaxies is also possible, for example, bright novae in M31 can reach ~ 15 visual magnitude at maximum allowing us at OAN-Tonantzintla to follow their light curve up to the limiting magnitude of the 1m telescope.

An important characteristic of quasi-stellar objects (QSOs) and active galactic nuclei (AGNs) is their rapid variability. Significant variations are observed in such objects over time scales as short as years, months or days. The utility of multi-wavelength continuum data will be enhanced when analyzed in conjunction with other ground-based and space-based observations. One such recent example is the radio quasar 3C 454.3 (Villata et al. 2006) that underwent an exceptional optical outburst lasting more than 1 year. The maximum brightness detected in the R band was $R = 12.0$, which represents the most luminous quasar state thus far observed. This type of multiwavelength campaigns are a clear example of a program where the 1 m telescope can be inserted. In the case of 3C 454.3 continuous optical, near-IR and radio monitoring was performed in several bands, followed by pointings by the Chandra and INTEGRAL satellites providing additional information at high energies.

The above are just a few examples of potential astronomical applications where reasonably long time intervals of observations are required. Considering that the best window for observations in terms of weather at Tonantzintla includes the period of October-April, and that some other smaller windows are available along the year, decisions to observe either in-situ or remotely from Mexico City can be easily assessed. A long-term program would produce an extra benefit in the sense that we will be able to notify other observers about the current status (c.f. brightness) of such objects.

The results presented here are relevant to providing support for the actual major upgrading of the observatory in terms of new photometric, spectroscopic and other instrumentation that is being acquired for scientific and educational purposes. The instrumentation will be capable of supporting the needs of the next generation of faculty and students of college/graduate programs at the Universidad Nacional Autónoma de México. This will convert the OAN-Tonantzintla to the natural Laboratory for Teaching of Astronomy at the college level and graduate programs at the Universidad Nacional Autónoma de México.

Astronomers and Facultad de Ciencias staff and other science-related schools inside and outside the Universidad Nacional Autónoma de México are invited to make use of these facilities for their observing/eduacational programs. It is only on the basis of experience in using them and through their collaboration that we will be offering an efficient and responsive means of carrying out astronomical observations for scientific/educative purposes. There are certainly other important benefits to be gained from the proper use of these observing facilities. Public outreach goals through collaborative outreach efforts with the Universidad Nacional Autónoma de México and other public and private universities and schools are just another example. The OAN-Tonantzintla could be eventually considered as a National Facility for Astronomy Education for the center-south part of the country.

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