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THE IMPORTANCE OF ATMOSPHERIC EXTINCTION MEASURES AND THE MEAN EXTINCTION CURVE FOR SAN PEDRO MÁRTIR

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RESUMEN

Se presenta, analiza y compara la curva de extinción para San Pedro Mártir. Se discuten los posibles errores sistemáticos que pueden resultar del uso indiscriminado de esta curva para corregir datos fotométricos, en lugar de una determinación cada noche de la extinción. Se describen las técnicas para determinar los coeficientes de extinción. Se compara la calidad fotométrica de San Pedro Mártir con la de otros observatorios.

ABSTRACT

The mean atmospheric extinction curve for San Pedro Mártir is given, analyzed, and compared. The possible systematic errors resulting from the indiscriminate use of this curve to correct photometric data rather than nightly determinations of the extinction are discussed. Techniques for determining the extinction coefficients are described. The photometric qualities of San Pedro Mártir are compared to other observatories.

Key Words: **ATMOSPHERIC EFFECTS — TECHNIQUE: PHOTOMETRIC**

1. INTRODUCTION

Stellar photometry has always played an important role in the development of the Mexican National Astronomical Observatory on the sierra of San Pedro Mártir, Baja California, México (hereafter SPM), first with the use of classical photoelectric photometers, such as the UBVRI photometer, the 13-Color (13C) photometers, and the 6-channel *uvby*-β photometer, and more recently with the use of CCD detectors. As an integral component of precise, accurate, and well-calibrated stellar photometry, a significant base of atmospheric extinction data has been acquired for SPM for the 13C and *uvby* photometric systems. These extinction data have been displayed and analyzed in some detail by Schuster (1982) and by Schuster & Guichard (1985), and more recently by Schuster & Parrao (2001) and by Schuster, Parrao, & Guichard (2002). It should be emphasized that precise atmospheric extinction determinations are needed not only for stellar photometry but also for any sort of photometry, spectroscopy, spectrophotometry, or imaging where accurate, absolute, well-calibrated photometric measures are needed for the derivation of physical parameters, such as in the study of galaxies, nebulae, planets, and so forth.

However, frequently with the pressure for telescope time and for publications, good atmospheric extinction coefficients are not determined during the nightly observations at the telescope due to the burdensome need to observe extinction stars three to five times during a night at varying air masses. Often the observer omits this process to save time and to observe more program objects, opting to reduce their images or photometric measures using the mean extinction coefficients given in the above references. In this note we discuss the mean atmospheric extinction coefficients of SPM for the 13C and *uvby* systems, the sizes of the extinction variations detected at SPM, and the sizes of the possible systematic errors should the observer choose to apply mean extinction corrections to his data rather than measuring his own nightly values.

2. THE FOUR-COLOR OBSERVING AND REDUCTION PROCEDURES

The *uvby* atmospheric extinction measures of this study have been made on SPM using the 6-channel, *uvby*–β "Danish" photometer at the 1.5m H.L. Johnson telescope. Our observing and reduction procedures follow closely the precepts detailed in Grønbech, Olsen and Strömgren (1976) and have been well documented in Schuster and Nissen (1988).

TABLE 1

EXTINCTION PAIRS USED AT SPM

Identifier	EPOCH (2000) R.A. (h, m, s)	DEC. (°, ′, ″)	V	(b-y)	m_1	c_1	$H\beta$	SP
			(mag)					
HD7895A	01 18 41.10	−00 52 03.2	8.002	0.482	0.329	0.303	2.557	K1V
HD9595	01 34 07.59	+02 26 46.7	8.902	0.403	0.183	0.408	2.609	G0
HD19983	03 13 03.21	+11 16 07.1	7.803	0.468	0.081	0.679	2.650	F5
HD22879	03 40 22.06	−03 13 01.1	6.684	0.369	0.120	0.273	2.580	F9V
HD76910	08 59 05.98	−00 37 25.9	8.489	0.302	0.114	0.393	2.628	F5
HD77354	09 01 56.82	−01 07 31.2	7.943	0.443	0.202	0.360	2.574	F8
HD108189	12 25 40.58	−00 16 55.8	7.724	0.491	0.257	0.335	2.571	G5
HD108678	12 29 03.86	+05 57 38.5	8.059	0.275	0.137	0.548	2.661	F2
HD125455A	14 19 34.86	−05 09 04.3	7.581	0.497	0.387	0.289	2.544	KIV
HD129755	14 44 30.59	−03 21 48.0	7.589	0.258	0.150	0.477	2.678	F2
HD161303	17 44 44.27	+02 26 50.3	8.462	0.294	0.147	0.550	2.697	F2
HD162503	17 51 22.09	+01 31 18.8	8.334	0.465	0.190	0.430	2.600	G0
HD186025	19 41 58.37	+01 10 55.4	8.862	0.382	0.126	0.504	2.661	F5
HD191264	20 09 01.22	+01 38 58.8	8.347	0.465	0.155	0.428	2.588	G0
HD198486	20 50 42.20	−04 47 27.2	8.043	0.355	0.169	0.458	2.624	F8
HD198585	20 51 12.45	+03 29 26.1	7.673	0.382	0.123	0.418	2.601	G0

Briefly, for the extinction coefficients the Bouguer method is used, and always we attempt to have an air-mass range greater than 0.8. If the extinction pair is well centered during the night, it is observed 5 times: > 4.0 and 2.5–2.0 hours both east and west of the meridian as well as crossing the meridian. If the pair is not so well centered, only four extinction observations of the pair are obtained with a single observation at ~ 3.0 hours substituted east or west, depending on the centering of the meridian-crossing with respect to midnight.

A small subset of our extinction determinations has been made through light cirrus clouds in the absence of moonlight. It has been our experience, which we have checked well several times, that observations in the indices $(b–y)$, m_1, and c_1 carried out with simultaneous multichannel photometers are not affected in any significant way by light (or even heavy) cirrus. Olsen (1983) reports similar results. Obviously the magnitude extinction of the Johnson V cannot be measured under such conditions, and no atmospheric extinction, neither for magnitudes nor indices, can be measured accurately with clouds *and* moonlight due to a probably variable background "sky" level.

Also, tests, ours and those of Grønbech et al. (1976), have shown that the second-order color extinction term in c_1 is small, less than 0.002, and so it has been ignored. So, the observation of extinction pairs has been retained not for this second-order color term but for the greater precision provided. Our extinction pairs usually contain F- and G-type secondary standard stars from Table XXVIII of Olsen (1983), similar to our high-velocity and metal-poor program stars. They are located near the celestial equator to optimize the observing efficiency and the photometric precision. Representative extinction pairs are shown in Table 1.

Extinction observations at small to intermediate air masses are usually of the form: three 10-second integrations of the star, one 10-second integration of the sky, and then three more 10-second integrations of the star. At large air masses the star is integrated for more time: 10-second integrations of the star for one to three minutes, then two 10-second integrations of the sky, and finally again 10-second inte-

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grations of the star symmetrically for one to three minutes, the total time depending on the air mass and the sky conditions. "Sky" measures are usually taken 1.0–1.5 arc minutes north or south of the star at regions clear of other stars; if the nearby sky seems to have a brightness gradient, for example due to the proximity of the moon, "sky" measures are taken symmetrically on two sides of the star.

All our *uvby* observations are reduced using Fortran programs provided by T. Andersen and P. E. Nissen, which follow closely the precepts of Grønbech et al. (1976) and are well documented by Parrao et al. (1988). All nights of an observing run, or observing season, are reduced together to derive the instrumental photometric system of our *uvby* photometer; a second program then transforms this instrumental system, using all standard-star observations, onto the Strömgren-Crawford standard photometric system. The output of the instrumental reduction provides nightly extinction coefficients with error estimates as well as the constant and temporal terms of the night corrections, as defined by Grønbech et al. (1976). For the instrumental system the following equations are solved:

$$m_{\rm obs}(s,n) \;=\; m(s,n) \;-\; k_{\rm m}(n)\,X(s,n) \qquad (1)$$

$$\begin{aligned} m_{\rm instr}(s) \;&=\; m_{\rm obs}(s,n) + L(n) \\ &+ M(n)t(s,n) - r(s,n) \end{aligned} \qquad (2)$$

Where $m(s,n)$ is the raw magnitude, color, or index taken at the telescope for star s on night n; $m_{\rm obs}(s,n)$ the "observed" value corrected for the atmospheric extinction; and $m_{\rm instr}(s)$ the instrumental value for that observing run, as defined by Grønbech et al. (1976, their equation 3). $k_{\rm m}(n)$ is the atmospheric extinction coefficient of a given night for the index m, and $X(s,n)$ and $t(s,n)$ the air mass and time of a given observation, respectively. $L(n)$ and $M(n)$ represent the constant and temporal terms of the night correction, respectively, and these plus the $k_{\rm m}(n)$ and the $m_{\rm instr}(s)$ are solved through a solution that requires that the sum of the squared residuals, $r^2(s,n)$, be minimized, and that the sum of the $L(n)$ be zero. The linear-time terms of the night corrections, the $M(n)$, depend upon "drift" stars observed symmetrically east and west of the meridian. These "drift" stars have more northerly declinations ($> +20°$) than the extinction stars and are observed only twice, symmetrically; this provides nearly independent solutions for the extinction coefficients and for the temporal terms of the night corrections.

Typical (median) estimated errors for the atmospheric extinction coefficients of y, $(b$–$y)$, m_1, and c_1, observed as described above, are ±0.0030, 0.0016, 0.0025, and 0.0030, respectively, as estimated by the matrix inversions of the reduction program. This high precision has been obtained with only a little extra work and by using the observing and reduction techniques described above, in Schuster et al. (2002), and in Grønbech et al. (1976). The authors suggest that all photometric observers should describe briefly in their publications the observing and reduction techniques used and the corresponding errors of the extinction coefficients.

The 13C observing and reduction procedures are discussed in Schuster (1982) and in Schuster et al. (2002).

3. THE MAX, MIN, AND AVERAGE EXTINCTION CURVES AT SPM

In Figure 1 are shown the mean and extreme atmospheric extinctions observed at SPM over the years 1973–1999 with the 13C and 4–color photometers. The extinction values are plotted versus the equivalent wavelengths of the photometric band passes. For 13C these wavelengths have been taken from Mitchell & Johnson (1969). For the 4–color photometry the equivalent wavelengths have been taken from the manual of Nissen (1984) with a small correction to the u wavelength according to the atmospheric extinction model of Schuster & Parrao (2001). For 4-color photometry the equivalent wavelengths used here are: 3515, 4110, 4685, and 5488 Å.

Figure 1 shows the mean 13C extinction curve for 271 nights of 8C and 6RC photometry over the years 1973–1981, prior to the El Chichón volcano and its strong effects on the atmospheric extinction. 151 nights of 8C and 120 of 6RC photometry go into this average 13C curve. Also shown is the mean 4–color extinction curve for the period 1984–1999 with the observations from Oct'91 through Apr'94 omitted due to the effects of the Pinatubo volcano. For this "*uvby* average" curve 182 nights define the shape of the curve while only 158 nights the level. As mentioned above, a small subset of our observations have been made through light cirrus clouds without moonlight; observations made with the *uvby*–β photometer provide good color extinction coefficients through light clouds, but not good magnitude coefficients. Also plotted in Fig. 1 is a "*uvby* minimum" curve which represents the average of 12 nights with the lowest extinction determinations from six observing runs with the lowest average extinctions and most stable observing conditions: Jun'88, Nov'89, Oct'94, Oct'97, Nov'97, and Nov'98. The average of 12 nights is given here to present a value which is robust and representative. The "13–color minimum"

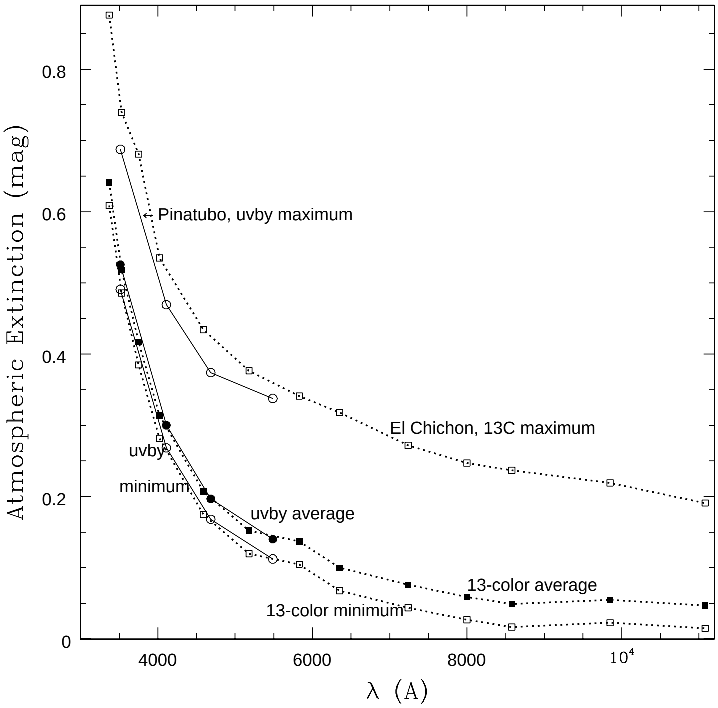

Fig. 1. Maximum, minimum and average atmospheric extinction curves for 13C (dotted curves) and *uvby* (solid curves) photometry taken at SPM.

curve has been normalized to the "*uvby* minimum" at the y band.

Also plotted in Fig. 1 are the most extreme extinctions observed at SPM by us using the 13C and 4–color photometers. The 13C maximum occurred for the period following the El Chichón volcanic eruption. The level and blue part of this curve are defined by a single night, the 19/20th of Jun'82, while the red part of this curve includes 6RC data from several nights during 1982 following the eruption. The "*uvby* maximum" curve comes from the observations of a single night, 4/5 May'92, during the maximum effects at SPM due to the Pinatubo volcano. In Fig. 2 are shown the minimum, average, and maximum extinction curves for the *uvby* photometry alone. A tabular form for the mean and minimum atmospheric extinctions are given in Table 1 of Schuster & Parrao (2001); individual measures and monthly and yearly averages by Schuster et al. (2002).

Figure 3 shows the variation of the y-band extinction coefficient, $k_{\rm y}$, at SPM from Sep'87 through Apr'99 determined by us using the *uvby*–β photometer. The points are plotted as a function of the Julian dates of the observations, the mean value of $k_{\rm y}$ for SPM (0.140) has been subtracted, and the triangular points in the center indicate those nights affected by the aerosols from the Pinatubo volcano. The peak caused by Pinatubo and the peak at the right for Apr'98 are those discussed in more detail in Sections 5.2 and 5.3 of Schuster & Parrao (2001).

In Table 2 are shown the extreme atmospheric extinction variations in a different format: minimum and maximum $k_{\rm y}$ values from different observing runs. The data for Oct'84, Feb'85, and May'93 have been provided by other observers. The asterisks mark observing runs unaffected by volcanic aerosols but with high maxima. In this table the seasonal, or cyclical, behavior of the atmospheric extinction on SPM, to be discussed further below, can be noted: (a) there are eight observing runs for the months Oct-Nov over the years 1984–1998, and all of these have minima in $k_{\rm y}$ less than 0.115, and except for Nov'89 and Oct'96, maxima less than 0.131; (b) there are eleven runs over the months Feb–May from 1985 through 1999, these include all with the highest maxima, > 0.200, all have maxima greater than 0.146, and all but one, minima > 0.121. A clear dichotomy between spring and fall is easily discernible. The second part of this Table 2 shows the atypical

TABLE 2

THE MINIMUM AND MAXIMUM VISUAL EXTINCTION COEFFICIENTS BETWEEN 1984 AND 1999

	k_y	
season	minimum	maximum
Oct'84	0.1035	0.1307
Feb'85	0.1078	0.2151*
Sep'87	0.1209	0.1508
Mar'88	0.1214	0.1466
Jun'88	0.1132	0.1240
May'89	0.1612	0.2568*
Nov'89	0.1090	0.1800
Apr'90	0.1260	0.1630
Apr'91	0.1428	0.1694
Oct'94	0.1133	0.1224
Nov'94	0.1146	0.1217
Mar'95	0.1489	0.1644
Sep'95	0.1202	0.1264
Apr'96	0.1256	0.1734
Oct'96	0.1149	0.1576
Apr'97	0.1303	0.1553
Aug'97	0.1158	0.1524
Oct'97	0.1140	0.1196
Nov'97	0.1098	0.1151
Apr'98	0.1240	0.2930*
May'98	0.1312	0.2167*
Nov'98	0.1104	0.1300
Apr'99	0.1247	0.1562
mean	0.1239	0.1645
Pinatubo:		
Oct'91	0.1586	0.2311
Mar'92	0.2340	0.2780
Apr'92	0.2448	0.2777
May'92	0.2398	0.3377
Nov'92	0.1660	0.1941
Mar'93	0.1948	0.2057
May'93	0.1270	0.1840
Sep'93	0.1250	0.1721
Oct'93	0.1416	0.1452
Nov'93	0.1250	0.1480
Apr'94	0.1434	0.1910

The asterisks mark the high k_y values for non-volcanic situations.

minima and maxima for those runs probably affected by the Pinatubo aerosols. Pinatubo erupted in June 1991.

In Figs. 4 and 5 are shown the histograms for the

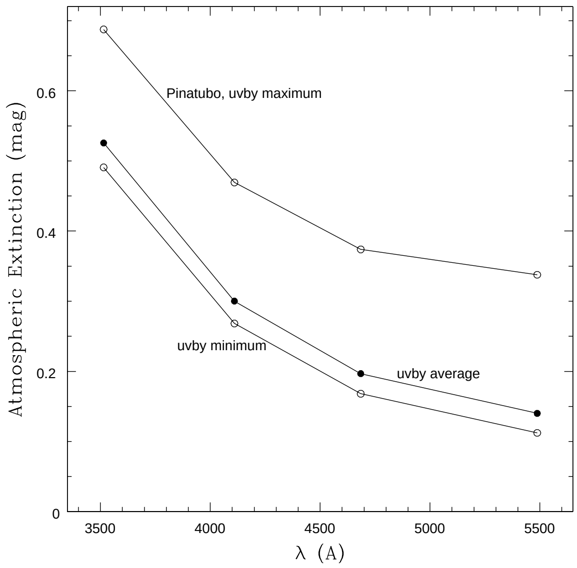

Fig. 2. Maximum, minimum and average atmospheric extinction curves for *uvby* photometry only.

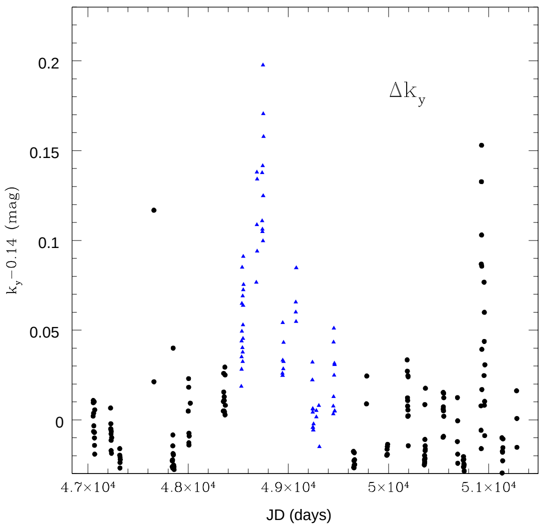

Fig. 3. Variations of k_y at SPM from 1987 through 1999 from *uvby* photometry only, as a function of the Julian dates of the observations. The triangular points show those observations affected by the Pinatubo volcano.

k_y atmospheric extinction values measured at SPM by us during 158 photometric nights from Sept'87 through Apr'99, minus those nights affected by the volcano Pinatubo. These are the same 158 nights used to set the level of the "*uvby* average" curve of Fig. 1, and have been taken from Table 3 of Schuster et al. (2002), minus the nights measured by other observers and minus those affected by Pinatubo. (Due to the nature of our observing projects, high-velocity and metal-poor stars, many of our observing runs have been centered near the optimum visibility of the Galactic Poles; for this reason we have few or no nights observed during the months of December-January and June-August; vacations and weather also contribute to this bias). In Fig. 4 the hatched area shows the nights from the months of October-November, and Fig. 5, the values from the months of February-May; a significant difference between these two groups can be easily noted. The nights from June-September are intermediate with k_{y} values in the range 0.115–0.150. It should be noted that nearly three fourths of the k_{y} values fall at or below the mean value of 0.140, that the median value is 0.132, and the minimum and maximum k_{y} values of Figs. 1 and 2 are 0.112 and 0.338, respectively.

4. SYSTEMATIC ERRORS

In Fig. 6 a comparison is presented between systematic extinction errors and random photometric errors. The former are obtained by applying extinction corrections from the mean extinction curve only, and the latter from normal V magnitude observations when the nightly extinction coefficients are well determined. For the Johnson V magnitudes measured with the *uvby*–β photometer at SPM, this latter random error has been estimated at 0.009 magnitude from Table II of Schuster & Nissen (1988) and from Table 2 of Schuster et al. (1993). To estimate the systematic errors, the previous extinction correction equation is taken,

$$m_{obs}(s,n) \;=\; m(s,n) \;-\; k_{\mathrm{m}}(n)\,X(s,n). \tag{3}$$

For the use of a mean extinction coefficient,

$$m'_{obs}(s,n) \;=\; m(s,n) \;-\; k_{\mathrm{m},mean}\,X(s,n), \tag{4}$$

and so the introduced systematic error is

$$\Delta m_{obs}(s,n) \;=\; [k_{\mathrm{m}}(n) - k_{\mathrm{m},mean}]\,X(s,n). \tag{5}$$

Three cases are considered: that the real atmospheric extinction k_{y} is at the minimum shown in Figs. 1 and 2, that the real extinction is at the maximum Pinatubo value of Figs. 1 and 2, and that the real extinction is at the maximum non-volcanic value for the night of 26/27 Apr'98 discussed in Section 5.3 of Schuster & Parrao (2001); this latter maximum was probably produced by the passage over SPM of a desert aerosol cloud from the north. Figure 6 shows that for a very good photometric night with the minimum atmospheric extinction, the systematic extinction error from applying the mean extinction curve

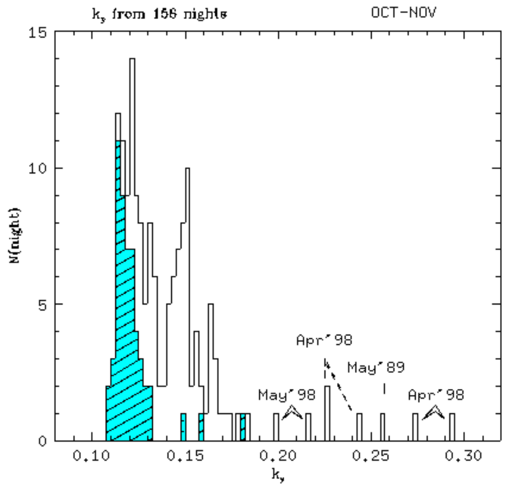

Fig. 4. Histogram for the k_{y} extinction values measured at SPM by us during 158 photometric nights from Sept'87 through Apr'99 minus those nights affected by the volcano Pinatubo. The histogram box size is 0.0025. The hatched area shows the extinction determinations for the months of October-November, which include some of the best photometric nights on SPM.

is at least three times the random photometric error of 0.009; the more extreme maximum cases have systematic errors many times (> 15) the random error.

If in addition to program stars one observes standard stars to calibrate the transformation coefficients (but not the extinction), then part of this systematic extinction error will be absorbed into the constant of the transformation equation, for the V magnitude the "A" of the following transformation equation,

$$V \;=\; A \,+\, y \,+\, B(b-y). \tag{6}$$

However, systematic errors still remain which are proportional to the difference between the air mass of the program star and the mean air mass of the standard stars. Also, the scatter of the transformation equations will be larger unless all standard stars are observed at more or less the same air mass.

Also, observers often assume that the overall atmospheric extinction can be characterized well by measuring the extinction stars in only one filter band, that the changes in the mean atmospheric extinction curves of Figs. 1 and 2 are more or less neutral. In Schuster & Parrao (2001) the following simple model was derived to represent well the mean atmospheric extinction over the range 3700–6500 Å, where λ is measured in microns,

$$k(\lambda) = 0.0254\lambda^{-0.87} + 0.0067\lambda^{-4.05} + 0.2581k_{\mathrm{oz}}(\lambda).$$

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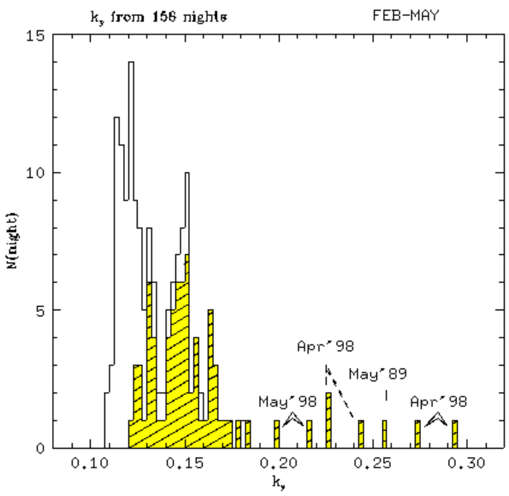

Fig. 5. Same histogram as in Fig. 3, extinction values measured at SPM during 158 photometric nights from Sept'87 through Apr'99. The hatched area shows the extinction determinations for the months of February-May, which include most of the higher extinction nights on SPM.

The three terms of this model represent the aerosol and Rayleigh-Cabannes scatterings and ozone absorption, respectively. However, it can be easily seen that in general the physical changes in this model are *not* neutral. In Fig. 6 of Schuster & Parrao (2001) and in the above equation it is clear that the changes in the ozone absorption and the Rayleigh scattering are always non-neutral with wavelength; and the Rayleigh scattering varies with the atmospheric pressure, and the ozone absorption can change significantly over rather short time scales (Hayes & Latham 1975). On the other hand, the aerosol component might change neutrally for very

large particles having an exponent "α_p" near zero, but the typical "α_p" for SPM is +0.87 as shown in the above equation. For the extreme examples shown in Fig. 6, color extinction-coefficient errors of ~ 0.025 can easily be obtained from the aerosol component, changing *only* the α_p exponent, not the turbidity factor (the 0.0254). Even larger errors will be induced if this turbidity also varies, such as an overall (u through y) color-extinction change of 0.036 for the maximum Pinatubo night. And at the other extreme, much smaller particles, as for the Aug'97 observing run with an α_p of +1.67 shown in Fig. 5 of Schuster & Parrao (2001), an overall color-extinction error as great as $\sim$ 0.06 might result from using the mean extinction curve (assuming constant turbidity). Conversely, the color-extinction error of the extreme non-volcanic night, 26/27 April'98, would

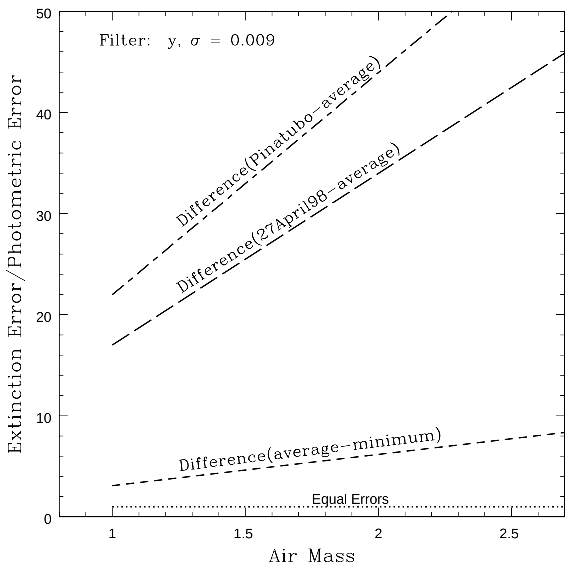

Fig. 6. Ratio of systematic extinction errors divided by a typical photometric error of 0.009 magnitude, for the y band, as a function of air mass, when applying only the average extinction correction to photometric data for different real atmospheric conditions: a minimal atmospheric extinction, a maximum extinction due to a volcano (Pinatubo), and a maximum non-volcanic extinction (the night of 26/27 April 1998; probably desert aerosols).

be small, only 0.005, due to large particles and a small α_p, $\sim$ 0.15, but with high turbidity. In contrast even the small change from the "average" to the "minimum" curve in Fig. 2 is not neutral at the 0.007 level over the filter bands *uvby*. Again, the proper use of standard stars will help to reduce the systematic color-extinction errors.

5. THE COMPARISON OF SPM WITH OTHER OBSERVATORIES

Comparisons of the atmospheric extinction of SPM with that of other important astronomical observatories has been made in Schuster (1982) and in Schuster & Parrao (2001). In Fig. 7 several of these comparisons are summarized.

The "SPM average" and "SPM minimum" curves are from Figs. 1 and 2. The "La Silla, Geneva 7-color minimum" curve has been taken from Burki et al. (1995); it shows their minimum values for the two years just prior to the El Chichón volcano. The "La Silla uvby minimum" plot is has been taken from Sterken & Manfroid (1992), their pre-Pinatubo atmospheric extinction values with seasonal variations removed. At the y band other comparisons are shown taken from the compilation of Galloway

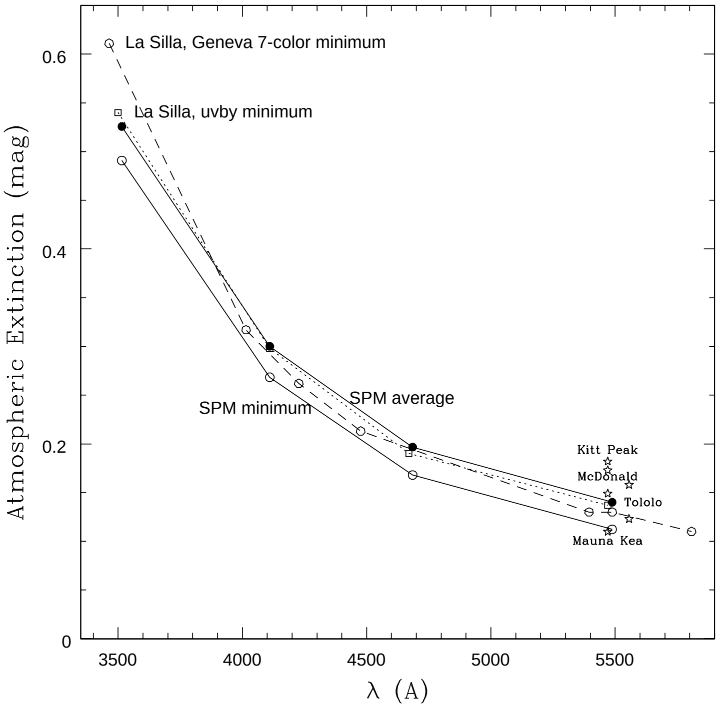

Fig. 7. Comparison of atmospheric extinction for various observatories. The "SPM minimum" and "SPM average" are our determinations (solid lines); the "La Silla uvby minimum" comes from Sterken & Manfroid (1992; their pre-Pinatubo values with seasonal variations removed; dotted lines); the "La Silla, Geneva 7-color minimum" from Burki et al. (1995; their minimum pre-El Chichón values; dashed lines); and the visual atmospheric extinctions for Kitt Peak, McDonald, Cerro Tololo (three points), and Mauna Kea from Galloway (1975; starred points at 5500 Å) and from Gutiérrez-Moreno et al. (1982; starred points "Tololo" at 5556 Å).

(1975) for the Kitt Peak, McDonald, Cerro Tololo, and Mauna Kea observatories, and also from the Cerro Tololo observations of Gutiérrez-Moreno et al. (1982). In these graphs of Fig. 7 it can be seen that SPM compares quite favorably. The "minimum" curve of SPM surpasses those of La Silla, and at the y band SPM has the lowest atmospheric extinction except perhaps for Mauna Kea.

6. CONCLUSIONS

1) San Pedro Mártir is a very good site for photometric astronomy with a mean visual atmospheric extinction coefficient, $k_{\rm y}$, of 0.14 mag/air mass. Nearly two-thirds of the photometric nights have $k_{\rm y}$ values equal or below this mean, with a median of about 0.13 and a minimum of about 0.11.

2) The atmospheric extinction of SPM compares very favorably with all other important astronomical observatories, being equal to or surpassing most, such as La Silla, Kitt Peak, Cerro Tololo, and McDonald. One site which is probably superior to SPM in this respect is Mauna Kea.

3) The best months on SPM for photometric observations are October-November when the atmospheric extinction is low ($\langle k_{\rm y} \rangle \sim 0.12$) and the observing runs mostly stable. The months of February-May are less consistent with higher average $k_{\rm y}$ values ($\langle k_{\rm y} \rangle \sim 0.15$), and some spikes to very high extinction probably caused by aerosols from the deserts to the northeast or urban centers to the northwest. The summer months of June-September are intermediate with a $k_{\rm y}$ average of about 0.13 and no spikes.

4) Even though SPM is a good photometric site, it has been shown that the use of mean extinction coefficients is generally a risky business with possible systematic errors in the reduction of magnitudes several times the random photometric errors which one can obtain by measuring well the nightly extinction values. The observation of standard stars under conditions similar to the program stars can mitigate such problems.

5) At any observatory the atmospheric extinction over the wavelengths 3700–6500 $\mathring{A}$ is due generally

to three physical processes: aerosol and Rayleigh-Cabannes scatterings plus ozone absorption. These, especially the latter two, are not neutral with wavelength; usually the aerosol scatterings are also not neutral but they might be, if the particles are large enough. So, if the observer needs good colors with an accuracy of 0.01 mag. or better, for example to determine accurate and precise stellar temperatures and surface gravities as a prelude to high resolution spectroscopic studies, it behooves him to determine the color extinctions accurately and *nightly*, and not to rely on an assumption of neutral displacements of the atmospheric extinction curve. Otherwise color errors might result which are as large as 0.06 times the air mass!

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REFERENCES

Burki, G., Rufener, F., Burnet, M., Richard, C., Blecha, A., & Bratschi, P. 1995, A&AS, 112, 383
Galloway, T. R. 1975, Lawrence Livermore Lab. Preprint, UCRL-51898
Grønbech, B., Olsen, E. H., & Strömgren, B. 1976, A&AS, 26, 155
Gutiérrez-Moreno, A., Moreno, H., & Cortés, G. 1982, PASP, 94, 722
Hayes, D. S., & Latham, D. W. 1975, ApJ, 197, 593
Mitchell, R. I., & Johnson, H. L. 1969, Comm. Lunar and Planet. Lab., 8, 1
Nissen, P. E. 1984, Technical Manual, Description and Data for the Danish 6-channel $uvby$–β Photometer
Olsen, E. H. 1983, A&AS, 54, 55
Parrao, L., Schuster, W., & Arellano-Ferro, A. 1988, Reporte Técnico No. 52, Instituto de Astronomía, UNAM, Mexico City
Schuster, W. J. 1982, RevMexAA, 5, 149
Schuster, W. J., & Guichard, J. 1985, RevMexAA, 11, 7
Schuster, W. J., & Nissen, P.E. 1988, A&AS 73, 225
Schuster, W. J., Parrao, L., & Contreras-Martínez, M.E. 1993, A&AS, 97, 951
Schuster, W. J., & Parrao, L. 2001, RevMexAA, 37, 187
Schuster, W. J., Parrao, L., & Guichard, J. 2002, The Journal of Astronomical Data, 8, No. 2, 1
Sterken, C., & Manfroid, J. 1992, A&A, 266, 619

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