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THE SPECTRUM OF THE KITT PEAK NIGHT SKY

PHILIP MASSEY, CARYL GRONWALL, AND CATHERINE A. PILACHOWSKI

Kitt Peak National Observatory, National Optical Astronomy Observatories*
P.O. Box 26732, Tucson, Arizona 85726-6732

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ABSTRACT

We have obtained absolute spectrophotometry of the Kitt Peak night sky at a variety of azimuths and zenith angles. Our zenith measurements confirm the finding of Pilachowski *et al.* that Kitt Peak is still a dark site, as we find $\langle B \rangle = 22.8$ mag/arc sec^2 and $\langle V \rangle = 21.9$ mag/arc sec^2 on 1988 February 18, a night of fairly low solar activity. (A year later the sky was appreciably brighter; this increase correlates well with solar activity as measured from the 10-cm flux.) The "pseudocontinuum" encountered by spectroscopists is about 0.02–0.05 mag/arc sec^2 darker in B and 0.2–0.3 mag/arc sec^2 darker in V than the broad-band measures. The major line contributor to the B band is Hg, while the dominant source of contamination to the V-band measures are atmospheric lines, most notably O I λ5577. Using fluxed observations of street lamps we find that the relative contribution to light pollution in the yellow-red (5000 Å–6500 Å) is 10% Hg, 30% LPS, and 60% HPS. The sky brightness increases a few tenths going from the zenith to a zenith distance of 60°, but the contribution of light pollution remains small. No significant azimuthal effects are seen: The sky is as dark toward Phoenix or Tucson as toward anywhere else, at least for zenith distances of 60° or less. Comparison with earlier measurements of the Kitt Peak sky brightness suggests that there has been no significant increase in light pollution at Kitt Peak from the mid-1960s to the late 1980s, a fact which we attribute to the stringent lighting ordinances adopted by the state.

Key words: observatory sites–light pollution

1. Introduction

Astronomical observations have been made from Kitt Peak National Observatory for over 30 years. In that time the population of nearby Pima County (which contains Tucson) has nearly tripled (De Gennaro 1989). To what extent have the dark-sky properties been compromised? This question is of timely importance given the plans for construction of new 4-m class telescopes on the mountain.

Pilachowski *et al.* (1989) have recently published the results of photoelectric photometry of the KPNO night sky. These observations were made near solar minimum (which occurred in 1986) and should therefore reflect the best the site can currently offer. Pilachowski *et al.* find sky-brightness values at the zenith of $\langle B \rangle = 22.9$ mag/arc sec^2 and $\langle V \rangle = 21.9$ mag/arc sec^2 during late 1986 and early 1987; a year later the mean values were $\langle B \rangle = 22.7$ and $\langle V \rangle = 21.6$. These numbers agree very well with those predicted by Garstang's (1986, 1989) night-sky brightness models. However, since the models indicate at best a very modest effect (<0.1 mag/arc sec^2) at the Kitt Peak zenith due to light pollution, the agreement is essentially due to Garstang's choice for the natural night-sky background brightness. The change in sky brightness from late 1986/early 1987 to late 1987/early 1988 is in accord with Walker's (1988) estimate of change in zenith sky brightness of San Benito Mountain with solar activity and shows a similar correlation with the solar 10-cm flux. By solar maximum, the zenith sky brightnesses may be a magnitude brighter than at solar minimum according to Walker. The Pilachowski *et al.* study indicates that Kitt Peak is still an exceptionally good site; the solar minimum zenith values are within 1/10 of a mag of those predicted by Garstang for Mauna Kea and Cerro Tololo.

While these numbers are of interest to those doing broad-band observations, they tell only a partial story to spectroscopists. Accordingly, we have undertaken a complementary program of spectrophotometry of the Kitt Peak night sky. These data can be used to assess the contribution of artificial lighting and atmospheric emission lines to broad-band measures and serve as a useful check on the previously reported broad-band photometry. Finally, this spectrophotometry allows us to measure the azimuthal dependence of artificial lighting: Is the sky significantly brighter toward Tucson and Phoenix?

2. Observations and Reductions

The observations were made with the Intensified Reti-

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*Operated by the Association of Universities for Researh in Astronomy, Inc., under contract with the National Science Foundation.

con Scanner (IRS) on the No. 2 0.9-m telescope. The IRS is a dual-beam analog detector on the White spectrograph. Grating 26 was used in first order to provide wavelength coverage from λλ3800–6500. The spectral resolution (3.0 pixels) was ≈ 10 Å. The two entrance apertures were 22.6 arc sec in diameter (as discussed further below) and were separated by 1.0 arc min. The integration times were typically 20 minutes.

The observations reported here were primarily made on the moonless night 1988 February 18 (UT) at a variety of zenith distances and azimuthal angles throughout the night. One additional observation was made at the zenith roughly a year later (1989 March 29) at the beginning of the night while the Moon was well below the horizon. In the following we will refer to the azimuthal directions by the cities they are toward: Tucson has an azimuth of 64° and Phoenix has an azimuth of 346°. Observations were also made toward the mythical town of "Nowhere" (azimuth 205°), chosen to be away from the two large cities as well as Casa Grande (350°), Sells (265°), and Nogales (142°).

In making the observations, care was taken to make all observations at least 15° from the ecliptic or Galactic planes; the exception is the zenith measurement 1988 February 18.2, which was only 5° from the Galactic plane. Although the acquisition TV was used to ascertain that no stars brighter than 15th mag were being placed in either aperture, stars of even 18th mag would raise the counts within an aperture by 10%. Thus, the most useful check of whether the sky measurement was contaminated by an unfortunately placed star or not was the agreement between the two apertures. In a few cases the counts in one aperture would appear to be significantly higher than in the other, and the telescope would be moved slightly and the integration redone. Flux calibration was provided by observing spectrophotometric standard stars (Massey *et al.* 1988).

The data were reduced using the "onedspec" package in IRAF[1]. Exposures of a quartz lamp were divided into each observation. Exposures of a HeNeAr lamp were used to provide wavelength calibration. The observations were then flux calibrated (no atmospheric extinction correction was made on the sky data) and the flux-calibrated sky spectra of the two apertures were averaged.

Pilachowski *et al.* (1989) have emphasized that the greatest source of systematic error in such measurements is in the determination of the size of the entrance aperture(s) of the photometer, which requires an accurate knowledge of the plate scale as well as the physical size of the holes. In the course of this study we made an independent measurement of the plate scale of the No. 2 0.9-m telescope and found for one test a scale of 28.7 ± 0.2 arc sec/mm and for another 28.6 ± 0.1 arc sec/mm. These numbers differ somewhat from the value of 29.5 ± 0.5 arc sec/mm found by Pilachowski *et al.* who also used this telescope for their work. We adopt a value of 28.6 arc sec/mm for the present study in the spirit of keeping the current measurements independent of the Pilachowski *et al.* data; the resulting systematic difference of 0.07 mag/arc sec^2 will prove insignificant given the typical scatter within a night. Representative spectra are shown in Figure 1a and 1b.

In addition to the sky measurements, observations were made of some typical artificial lighting sources: a low-pressure sodium (LPS) lamp, a high-pressure sodium (HPS) lamp, and a mercury streetlamp. These spectra are shown in Figure 1c.

3. Analysis

We give in Table 1 the resolvable emission lines found in our sky data, along with their origin. These lines are also identified in Figure 1a–c where visible.

In order to produce synthetic broad-band photometry from our spectra we convolved each spectrum with the sensitivity functions of the *B* and *V* bandpasses as tabulated by Allen (1973). The contributions of the various night-sky emission lines were evaluated by constructing spectra free of the various contributions listed in Table 1 by linearly interpolating across the lines and then convolving these spectra with the sensitivity functions. (We assign all of the Na D emission to HPS+LPS in this exercise, although we expect that a small atmospheric contribution is also present.) The sky brightness determined from our spectra and the contributions made by the various sources are given in Table 2.

On 1988 February 18 the zenith sky varied by a few

TABLE 1

Line ID's

Line	Sources
HgI λ4047	Hg lighting
HgI λ4358	Hg lighting
NaI λ4669	HPS lighting
NaI λ4983	HPS lighting
NaI λ5149	HPS lighting
N I λ5199	Atmospheric
HgI λ5461	Hg lighting
OI λ5577	Atmospheric
NaI λ5688	HPS lighting
HgI λ5770	Hg lighting
HgI λ5791	Hg lighting
NaI λ5890(blend)	HPS,LPS,Atmospheric
NaI λ6161	HPS lighting
OI λ6300 – 64	Atmospheric

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[1] IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

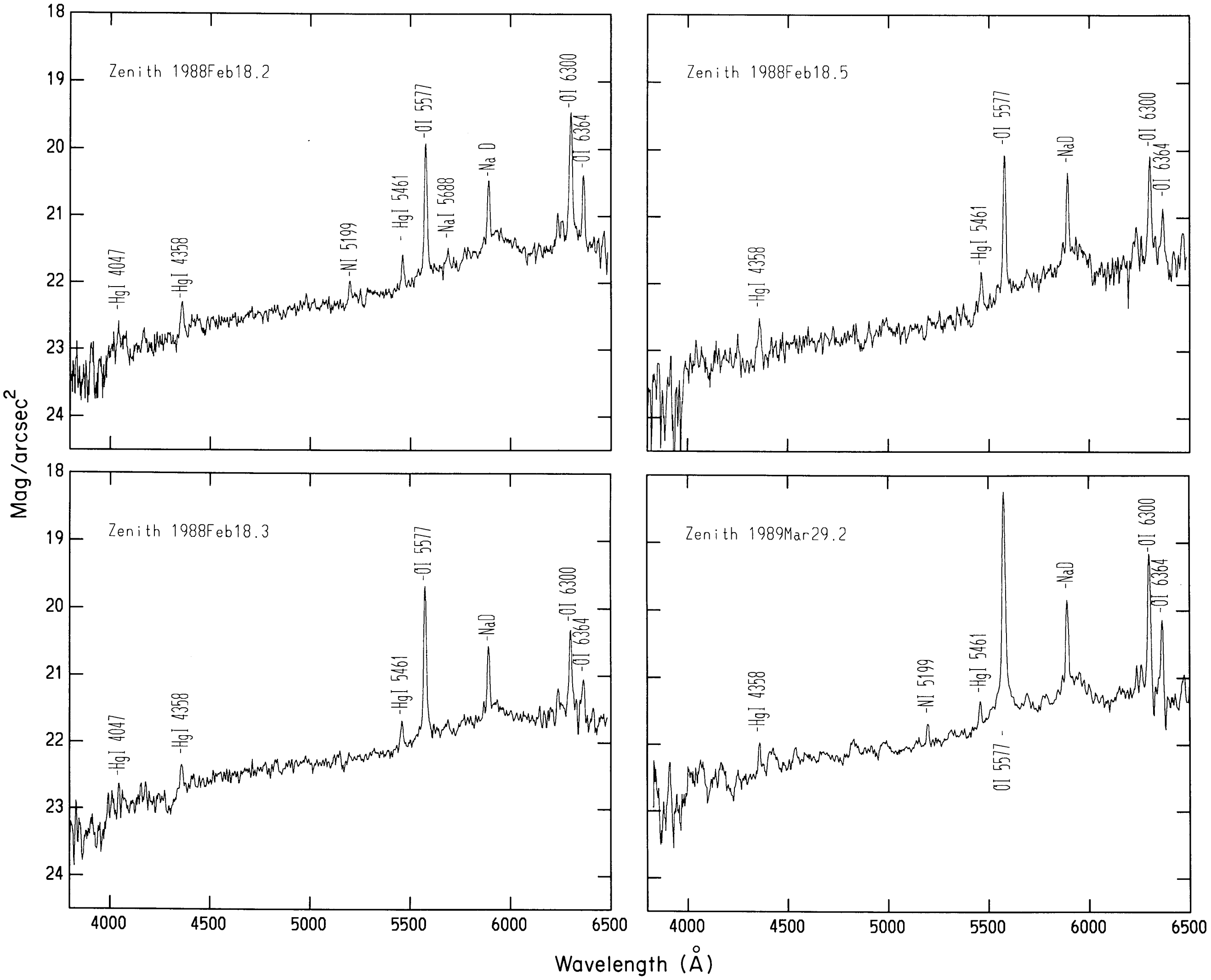

FIG. 1a–Representative spectra of the zenith sky.

tenths of a magnitude/arc sec^2; such fluctuations are also found in the data of Pilachowski *et al.* (1989) and Walker (1988). On this night it was indeed "darkest before the dawn", at least at the zenith. Walker's data show a systematic decrease in sky brightness throughout most nights, while the data of Pilachowski *et al.* are more random. Our measurements are too scant to discuss a trend throughout the night, but the data do show that the sky-brightness fluctuations are not due to the O I λ5577 line varying in intensity during the night—the contribution made by this atmospheric line has little effect given its dilution throughout the *V* bandpass. (The actual flux in O I λ5577 varied by a factor of two as is apparent from Fig. 1a, but this variation had little effect on the broad-band measures.) The average zenith values for this night are $\langle B \rangle$ = 22.79 mag arc sec^2 ± 0.15 (s.d.) and $\langle V \rangle$ = 21.87 mag arc sec^2 ± 0.13(s.d.); these are in excellent agreement with those found by Pilachowski *et al.* (1989) and serve as an independent confirmation that the zenith sky is still quite dark at Kitt Peak.

The zenith values on 1989 March 29 show a significantly brighter value. While some of the increased brightness at *V* is indeed due to the increased flux in the O I λ5577 line (see Fig. 1a in addition to Table 2), this is not the only source of the increase—the "pseudocontinuum" itself is considerably brighter. This is well reflected in increased sky brightness in the *B* bandpass, which is little affected by atmospheric lines as can be seen from Table 2.

Is this increase in sky brightness due to increased solar activity? Walker (1988) found a good correlation of zenith sky brightness with solar activity where the latter was measured by the "decorrected" Ottawa 10-cm flux (e.g., *not* referred to 1 AU but to the Earth's actual distance from the Sun) as determined on the *previous* UT day. Pilachowski *et al.* (1989) found a similarly excellent correlation for their measurements. We show in Figure 2 the data from Figure 1 of Pilachowski *et al.* where we have added our new measurements. The 10-cm values come

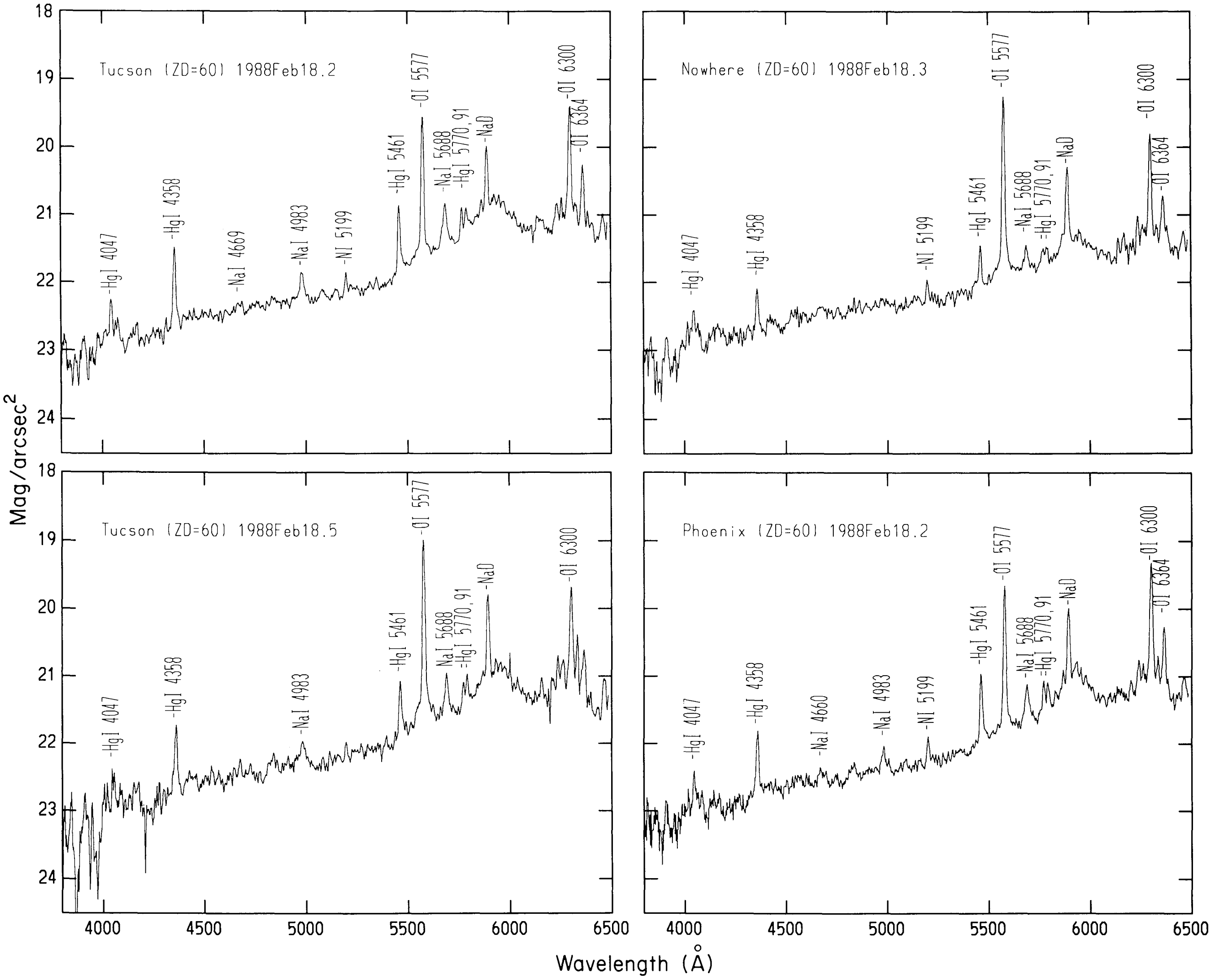

FIG. 1b–Representative spectra of the sky at a zenith distance of 60°.

from the Solar-Geophysical Data prompt reports (1988). We can see that the March 1989 data fit in well with that expected from the increased solar activity.

We see in Table 2 that the "spectroscopist's sky brightness" is about 0.02 to 0.05 mag/arc sec^2 fainter in *B* and 0.2 to 0.3 mag/arc sec^2 fainter in *V* than the broad-band measures. The dominant sources of line emission to the broad-band *V* values are atmospheric, with HPS+LPS making a contribution of less than 0.1 mag/arc sec^2 to the *V* measures. Hg is the dominant line contributor to the *B* measure, but even so it is fairly insignificant, amounting to less than 0.5 mag/arc sec^2.

The relative contributions of HPS, LPS, and Hg lamps to light pollution at Kitt Peak can be assessed from these observations as well. Although the lamp spectra had been fluxed in the sense that the relative line intensities for a given lamp are free of instrumental effects, these were by no means on any kind of absolute scale and so we needed to normalize these lamps relative to each other. For each of the sky spectra we subtracted a smooth continuum (in units of flux F_ν), leaving only the line emission from the airglow and artificial light. The lamp spectra were then each normalized to the continuum-subtracted sky spectrum by finding the multiplicative factor that resulted in the best match between the lamp spectrum and the strength of the emission lines attributed to each lamp in the night sky. The integral of each normalized lamp spectrum then represents the approximate relative contribution from that source. As discussed above, Hg lamps dominate the light pollution seen in the blue spectral region. In the red (from 5000 Å to 6500 Å) Hg lamps contribute only about 10% of the pollution, while LPS lamps contribute about 30% and HPS lamps about 60%. During the next decade the distribution of light among these three sources may well change as Tucson and Pima County convert to LPS lighting and

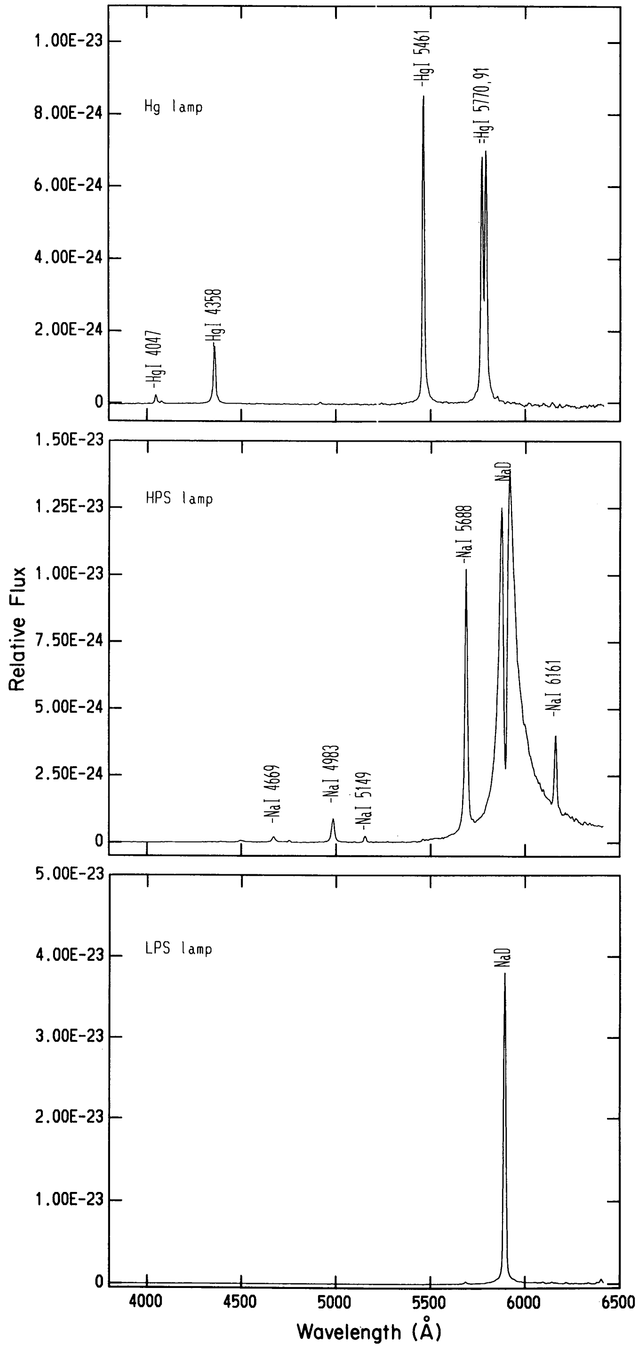

FIG. 1c–Representative spectra of three different types of street lights.

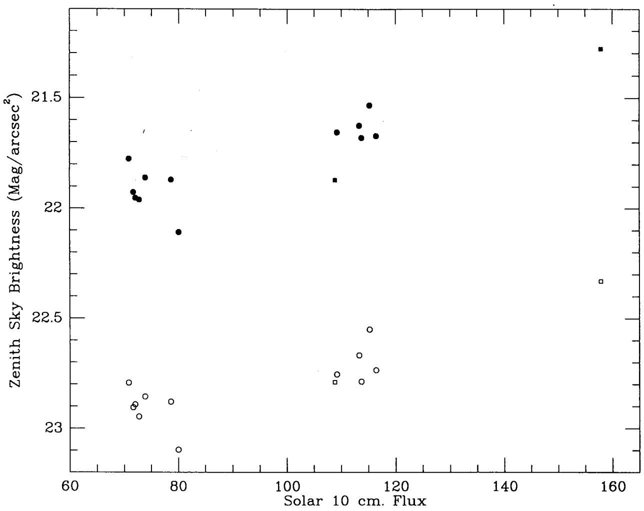

FIG. 2–Correlation of the zenith sky brightness with "decorrected" Ottawa 10-cm flux from the previous UT day. The filled symbols are *V*-band measurements, and the open symbols are *B*-band measurements. The circles are the Pilachowski *et al.* (1989) photoelectric values, and the squares are the average zenith values measured here. This figure is adapted from Figure 1 of Pilachowski *et al.*

Hg lamps are phased out.

The sky brightness increases by a few tenths going from the zenith to a zenith distance of 60°. On some of the 12 nights of data used by Pilachowski *et al.* (1989) the change in sky brightness with respect to zenith distance was steeper than that; on other nights it was flatter. It is interesting to note from our data in Table 2 that the flux in each set of emission lines tracks well with the increase in continuum level (e.g., the relative contribution to the sky brightness remains nearly constant with respect to zenith distance). By comparing Figure 1b to Figure 1a we can see that the Hg lines *are* somewhat stronger relative to the continuum at a zenith distance of 60° than at the zenith, but the effect is quite small. We believe that this finding can be credited to the community support for astronomy exhibited in Arizona by the adoption of strict lighting ordinances that have forbidden the installation of new mercury streetlights and which encourage the use of LPS and, in limited cases, HPS. Although the sodium lamps make spectroscopic observations at the sodium lines more difficult, the contamination to the *V* band is still quite modest and is, in fact, significantly less than that contributed by atmospheric night-sky lines.

A curious and unexpected finding in Table 2 is that the contribution of artificial lighting to the spectrum of the night sky does *not* show an obvious azimuthal effect: At a zenith distance of 60° the sky is not appreciably worse toward Tucson or Phoenix than it is in any other direction. This can be seen by intercomparing the spectra shown in Fig. 1b: The Hg and Na lines are only slightly weaker toward "Nowhere" than they are toward Tucson or Phoenix. Pilachowski *et al.* (1989) did not study their data as a function of azimuth, only of zenith distance, but the small scatter in their elevation plots within a single night suggests that any azimuthal variations were not large. At greater zenith distances some azimuthal effects *must* be present, given that one can readily distinguish Tucson and Phoenix by eye at night near the horizon, but at least within "sensible" observing limits such efforts are so far small.

There has been one previously published study of absolute spectrophotometry of the Kitt Peak night sky:

TABLE 2

Sky Brightness Contributions (mag/arcsec^2)

ZD	Azimuth	UT	Sky Bright.		HPS+LPS		Hg		Atmosph.		Everything	
			B	*V*	*B*	*V*	*B*	*V*	*B*	*V*	*B*	*V*
0°	Zenith	1988Feb18.2	22.71	21.78	0.00	0.05	0.02	0.01	0.00	0.10	0.02	0.17
		1988Feb18.3	22.68	21.83	0.00	0.04	0.02	0.01	0.00	0.11	0.02	0.17
		1988Feb18.4	22.76	21.81	0.00	0.05	0.01	0.01	0.00	0.15	0.02	0.21
		1988Feb18.5	23.01	22.06	0.00	0.07	0.02	0.02	0.00	0.12	0.03	0.21
		Average:	22.79	21.87	0.00	0.05	0.02	0.01	0.00	0.12	0.02	0.19
0°	Zenith	1989Mar29.2	22.33	21.28	0.01	0.05	0.02	0.01	0.01	0.29	0.03	0.39
45°	Tucson	1988Feb18.4	22.79	21.76	0.01	0.05	0.02	0.02	0.00	0.21	0.04	0.33
	Nowhere	1988Feb18.4	22.59	21.55	0.01	0.06	0.02	0.01	0.01	0.26	0.04	0.33
		Average:	22.69	21.66	0.01	0.05	0.02	0.02	0.00	0.24	0.04	0.33
60°	Tucson	1988Feb18.2	22.54	21.48	0.01	0.08	0.04	0.03	0.00	0.11	0.05	0.23
	Tucson	1988Feb18.5	22.63	21.48	0.01	0.09	0.03	0.02	0.00	0.18	0.05	0.32
	Phoenix	1988Feb18.2	22.67	21.61	0.01	0.08	0.03	0.03	0.01	0.11	0.05	0.24
	Nowhere	1988Feb18.3	22.61	21.73	0.01	0.06	0.03	0.02	0.00	0.15	0.04	0.24
	Nowhere	1988Feb18.5	22.34	21.44	0.01	0.07	0.01	0.02	0.00	0.15	0.02	0.28
		Average:	22.56	21.55	0.01	0.08	0.03	0.02	0.00	0.14	0.04	0.26

that of Broadfoot and Kendall (1968). Their observations were obtained over several years prior to 1968 (Broadfoot, private communication). The study extends from 3100 Å–10000 Å at comparable resolution to ours. Their data show a surface brightness of ≈0.5 Rayleigh/Å near the *B* band and ≈1.0 Rayleigh/Å near the *V* band; these translate[2] to 22.9 mag/arc sec^2 and 21.9 mag/arc sec^2 which, coincidentally, are identical with the most recent solar minimum values. These data confirm that light pollution at Kitt Peak did not increase significantly from the mid-1960s to the late 1980s.

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[2] A perusal of Allen (1973) leads to the conversion (mag/arc sec^2) = $31.18 - 2.5\log(\text{Å}) - 2.5\log(R/\text{Å})$.