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The Spectrum of the Night Sky over Mount Hopkins and Kitt Peak: Changes after a Decade[1]

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ABSTRACT. Recent (1998–1999) absolute spectrophotometry of the night sky over two southern Arizona astronomical sites, Kitt Peak and Mount Hopkins, is compared to similar data obtained in 1988 at each site. The current zenith sky brightness in the range ∼3700–6700 Å is essentially identical at the two sites and is as dark now as Palomar Observatory was in the early 1970s, when it was generally considered a premier dark observing site. Converted to broadband measurements, our spectrophotometry is equivalent to $B = 22.63$, $V = 21.45$ mag arcsec^{-2}, for the zenith night sky. The contribution of high-pressure sodium street lights to broadband V is about 0.2 mag arcsec^{-2}, comparable to the strong airglow O I λ5577 line. During the period from 1988 to 1998–1999, the zenith sky brightness increased only modestly, with the largest changes being seen for Kitt Peak, where the zenith sky has brightened by ≈0.1–0.2 mag arcsec^{-2} in the blue-optical region. For Kitt Peak we also have both 1988 and 1999 observations at modestly large zenith distances (ZD ≈ 60°). In the directions away from Tucson, the sky has brightened by ≈0.35 mag arcsec^{-2} over the intervening decade. Toward Tucson the change has been larger, approximately 0.5 mag arcsec^{-2}. In most directions the increase in the sky brightness has lagged behind the fractional increase in population growth, which we attribute to good outdoor lighting ordinances, a fact which is further reflected in the decrease in Hg emission. However, our results emphasize the need for diligent attention as developments creep closer to our observing sites.

1. INTRODUCTION

The surface brightness of the moonless night sky is one of the fundamental qualities of an observing site. Furthermore, it is one that can degrade with time, as nearby population centers and their attendant light pollution grow. However, efforts to characterize the sky brightness via broadband photometry can be misleading, as such measures encompass both natural airglow and artificial sources. Significant night-to-night (and even hourly) variations of the intensity of OH emission and the O I λ5577 auroral line are well documented and depend in part on solar activity. (See Pilachowski et al. 1989; as well as Massey, Gronwall, & Pilachowski 1990, hereafter MGP.)

A more useful approach is to obtain absolute spectrophotometry of the night sky. With sufficient spectral resolution, natural airglow sources can be distinguished from those due to artificial sources, allowing a useful assessment of the effects of light pollution. Furthermore, such spectrophotometry allows a more meaningful evaluation of the background with which spectroscopists must contend.

The authors independently obtained such measurements on Mount Hopkins and Kitt Peak in 1988; second-epoch data were obtained in 1998 and 1999. Fortunately, we learned of each other's efforts in time for us to compare the behavior of the night sky over these two southern Arizona observatories.

2. OBSERVATIONS

Although the Kitt Peak and Mount Hopkins studies were begun independently, the data were obtained and reduced with nearly identical styles. Observations were

[1] The research described here is based on data obtained in part at the MMT Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

[2] Operated by AURA under cooperative agreement with the National Science Foundation.

made both at the zenith and at modestly large zenith distances (50°–60°). The observations were usually taken at least 15° away from the Galactic plane; in addition, the 1998/1999 CCD data were median filtered to remove any resolved stars. Details of our observations are given below.

2.1. Kitt Peak

The 1988 Kitt Peak data discussed here were obtained on 1988 February 18 (UT) and are described by MGP. The observations were obtained with the Intensified Reticon Scanner on the 0.9 m telescope with 10 Å FWHM resolution and covered the wavelength range 3800–6500 Å. Observations were obtained both at the zenith and at zenith distances of $\approx 60°$ toward selected azimuths.

The 1999 Kitt Peak observations were made in as similar a manner as possible given the change in instrumentation over the past decade. These new data were obtained on 1999 November 5, 8, and 10 (UT), using the same 0.9 m telescope with the GoldCam CCD spectrometer. A first-order, 600 line mm^{-1} grating (No. 26) was used with a GG375 blocking filter for wavelength coverage from 3700 to 6700 Å. A 10.″2 slit was used (assuming the same 28.″63 mm^{-1} plate scale as measured for the earlier study) in order to obtain a 10 Å (FWHM) resolution. Independent measurements were made of the spatial scale along the slit as the demagnification of the spectrograph was not known with sufficient accuracy, and we adopt a scale of 1.″725 per 15 μm pixel. The uncertainty in this value is $\sim 1.5\%$, which would lead to a systematic uncertainty of 0.02 mag arcsec^{-2}, if the slit plate scale is taken as precise. The data were taken with a 2406 × 512 section of the Loral CCD binned by 5 in the spatial direction in order to reduce the digitization noise. The final extraction swath was 50 binned pixels wide, and thus corresponded to an area of 4401 arcsec^2, about 5 times greater than that used in the 1988 study. Bright twilight exposures were used to match the dome flat fields to the slit illumination function of the night sky. Unilluminated portions of the CCD were used to correct for any residual bias or dark-current contributions. Exposure times were typically 900 s, during which the telescope was tracking. One or more observations were obtained at zenith on all three nights. Two observations were made, each on a separate night, toward Tucson (azimuth 64°), Phoenix (azimuth 346°), and Nogales (azimuth 142°), all obtained at a zenith distance of approximately 60°. One or more spectrophotometric standards BD +28°4211, Hiltner 600, Feige 34, and Feige 110 were observed each night to determine the instrumental sensitivity and were reduced adopting a mean extinction law appropriate for Kitt Peak. Wavelength calibration was by means of nebular observations.

We found that the individual zenith observations matched well (<0.1 mag), other than for the usual variations in the O I λ5577 night-sky lines, and we averaged the multiple observations. Similarly the dual observations made at various azimuths at large zenith distances were found to be in excellent accord and were averaged for the following analysis.

2.2. Mount Hopkins

The 1988 Mount Hopkins data were taken on the night of 1988 June 6 (UT) with the 4.5 m Multiple Mirror Telescope (MMT) using the Blue Channel of the MMT Spectrograph and an intensified Reticon detector. A 300 line mm^{-1} grating was used in first order with no blocking filter. This will lead to some order overlap longward of about 6500 Å. The spectral resolution is about 10 Å (FWHM). A 300 s exposure was taken through two 5″ diameter circular apertures while tracking near the zenith. Wavelength calibration was carried out using observations of a HeNeAr lamp. As is the case for the KPNO data, no extinction correction was applied to the observations of the night sky. A small dark count correction of 0.004 photons s^{-1} pixel^{-1} was subtracted from the data. No pulse-pair corrections were made. The instrumental sensitivity function was calculated using observations of the standard star G138-31 assuming a mean extinction law appropriate for Mount Hopkins. The data from the two apertures were reduced independently and averaged to produce the final spectrum.

The second-epoch Mount Hopkins data were obtained by P. Berlind on 1998 November 25 using the 1.5 m Tillinghast telescope at the Fred Lawrence Whipple Observatory and the FAST spectrograph (Fabricant et al. 1998) and a 2688 × 512 Loral CCD detector. A 300 line mm^{-1} grating was used in first order with no blocking filter, yielding spectral resolution of about 10 Å. Exposures of 1800 s were taken through a 5″ slit at the zenith and at the four cardinal points at zenith distances of roughly 50° (except for the eastern exposure, which was taken at a zenith distance of about 35°; see Table 1). Wavelength calibration was carried out using observations of a HeNeAr lamp. No dark correction was made, and the data were not corrected for atmospheric extinction. The instrumental sensitivity function was calculated using observations of the standard stars Feige 110 and G191-B2B, again assuming a mean extinction law. The final spectrum was extracted using a median filter applied over the unvignetted part of the slit.

Errors in telescope plate scale and the size of the entrance apertures are systematic but are expected to contribute an uncertainty less than about 5% (0.05 mag arcsec^{-2}) for either data set. It was difficult to calibrate the MMT's Intensified Reticon detector because of uncertain pulse-pair coincidence at the high count rates incurred while observing relatively bright standard stars. This is of particular concern when using a very blue or very red standard star since the pulse-pair coincidence would be a function of wavelength. Since G138-31 is blue (DC white dwarf), the result would be

TABLE 1

Sky Brightness Measures (mag arcsec^{-2})

	Broadband[a]			Narrowband[b]		
Location	B	V	HPS[c]	λ4250	λ4550	λ5150
1998 Mount Hopkins:						
Zenith (ZD = 5°)	22.63	21.46	0.17	22.69	22.40	22.17
North (ZD = 48°)	22.39	21.19	0.32	22.48	22.18	21.92
East (ZD = 34°)	22.34	21.30	0.18	22.42	22.10	21.87
South (ZD = 50°)	22.48	21.29	0.26	22.58	22.27	22.02
West (ZD = 53°)	22.47	21.27	0.23	22.57	22.26	22.00
1988 Mount Hopkins:						
Zenith (ZD = 2°)	22.52	21.55	0.04	22.58	22.29	22.11
1999 Kitt Peak:						
Zenith (average of 4; ZD = 1°–3°)	22.63	21.44	0.17	22.67	22.39	22.14
Tucson (average of 2; ZD = 58°–60°)	22.17	20.90	0.21	22.25	21.95	21.68
Phoenix (average of 2; ZD = 59°–60°)	22.38	21.08	0.22	22.44	22.15	21.88
Nogales (average of 2; ZD = 59°–60°)	22.36	21.08	0.16	22.44	22.14	21.84
1988 Kitt Peak:						
Zenith (average of 2; ZD = 4°–10°)	22.80	21.66	0.04	22.89	22.49	22.25
Tucson (average of 2; ZD = 53°–54°)	22.67	21.37	0.21	22.81	22.45	22.12
Phoenix (ZD = 61°)	22.75	21.45	0.19	22.85	22.50	22.22
Nowhere (average of 2; ZD = 56°–61°)	22.68	21.55	0.04	22.77	22.41	22.17

[a] Broadband synthetic "B" and "V" were computed using the response curves from Allen 1973 and applying a 0.14 mag arcsec^{-2} in order to match the standard system. The convolutions were performed after replacing the variable O I λ5577 line by an averaged value.

[b] Narrowband magnitudes were computed using a constant response over a 100 Å interval centered at the specified wavelengths.

[c] "HPS" denotes the contribution to the V magnitude made by high-pressure sodium.

an underestimate of the instrument's efficiency at shorter wavelengths which would result in an overestimate of sky brightness at blue colors. We *estimate* that this effect could be as large as 0.10 mag in $B-V$.

3. RESULTS

In comparing our spectrophotometry of the night sky of Kitt Peak with that of Mount Hopkins, or describing changes with time or zenith distance, it is useful to have not only the spectra but also a few characteristic numbers. We are interested in broadband B and V, as these are representative of the brightness encountered by imaging. Similarly, we will use a few line-free regions to compute monochromatic magnitudes, as these are then characteristic of what spectroscopists will experience at best. The values are given in Table 1 and were computed by convolving the sensitivity curves of the B and V bandpasses (Allen 1973) with our F_λ data, which we then converted to mag arcsec^{-2}. In computing the broadband V we eliminated the effects of variable O I λ 5577 on our data by replacing the line with the average line flux measured from our data. On average, the O I line contributes 0.16 mag arcsec^{-2} at V at zenith, but with variations of ≈0.1 mag arcsec^{-2} just within our limited data set. For B we also had to apply a 0.14 mag correction to bring the values in accord with the standard system. This value was determined using the published photometry of the spectrophotometric stars used in this study and is consistent (within 0.03 mag) with what we find by convolving the Kurucz (1992) model of Vega with our filter responses. Uncertainties in the zero points are irrelevant for the intercomparisons we make here but do matter for comparison with the B sky brightnesses determined by actual broadband observations or by night-sky models (e.g., Garstang 1989).

In Figure 1 we compare the current (1998/1999) zenith sky brightness of Mount Hopkins and Kitt Peak. The agreement speaks for itself. Despite differences in instrumentation (and corresponding uncertainties in the plate scales) and the fact that we have limited data on how much variations are seen at either site, the data are indistinguishable in absolute level. The corresponding broadband values of the zenith sky at the two sites are $B = 22.63$ mag arcsec^{-2} and $V = 21.45$ mag arcsec^{-2}.

The excellent agreement between the two sites is slightly fortuitous given nightly variations (0.05–0.10 mag) seen in our multiple observations. We estimate that the absolute error in each observation is ~0.03–0.06 mag arcsec^{-2}. This estimate comes from the quadrature sum of errors arising from (1) the uncertainties in the absolute plate scale (0.02–

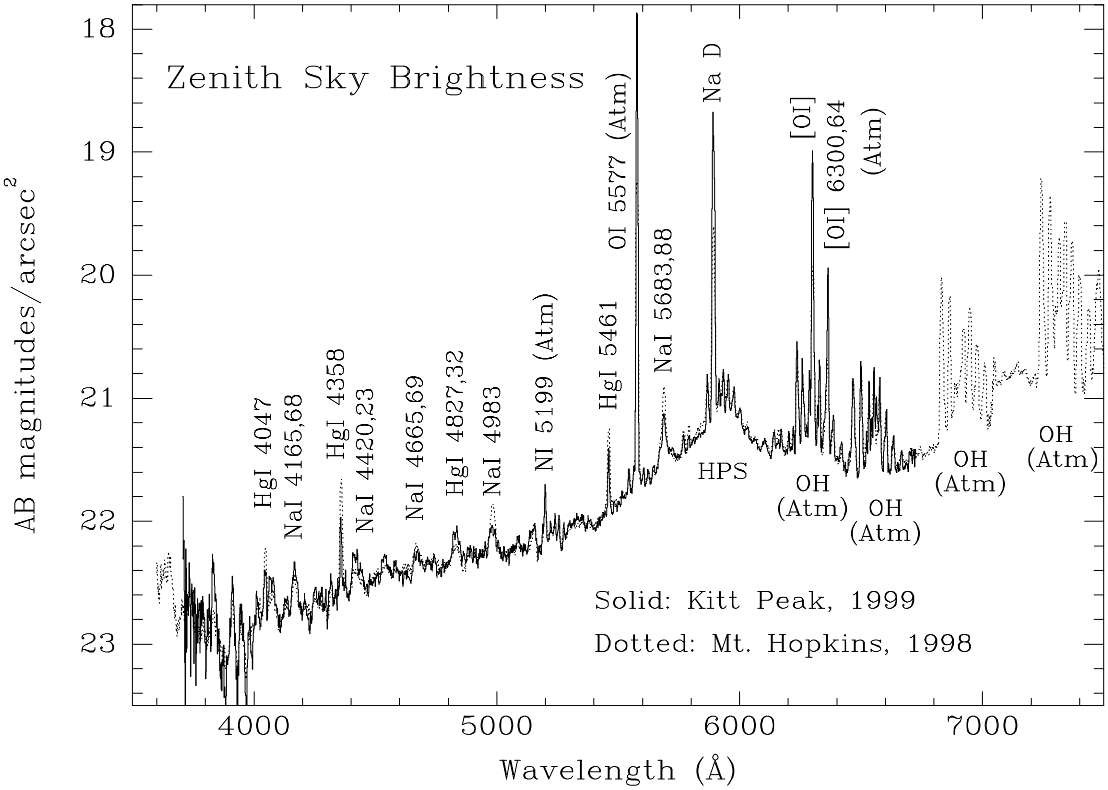

FIG. 1.—Second-epoch observations of the spectrum of the night sky at the zenith above Kitt Peak (*solid line*) and Mount Hopkins (*dashed line*). Emission features from natural and man-made sources are marked. High-pressure sodium (HPS) lamps are responsible for the broad feature extending from $\sim$5500 to 6500 Å.

0.05 mag), (2) the uncertainties in the slit width (0.01–0.02 mag), (3) the adoption of a mean extinction curve (0.01 mag), and (4) the uncertainties in calibration of the spectrophotometric standards themselves (0.02 mag). The exception is the 1988 Mount Hopkins observation, which could have a $\sim$0.1 mag color problem as described above.

We were naturally curious about what fraction of the V night-sky brightness was due to high-pressure sodium (HPS). We used the observations over Tucson to produce an HPS template spanning the range from 5250 to 6650 Å. Narrow features of atmospheric origin were excised individually by eye. (There is some underlying OH emission; see Louistisserand et al. 1987.) The template was then scaled and subtracted from the individual spectra until a linear continuum was achieved. Broadband V magnitudes were then computed for the corrected spectra and compared to those of the uncorrected data. The resulting estimates of the HPS contributions are tabulated in Table 1. At the zenith, HPS contributes about 0.17 mag arcsec^{-2} at each site; i.e., comparable to what is contributed by the O I λ5577 atmosphere line.

How do our zenith measurements compare with those of other dark sites? Such a comparison faces two obstacles. First, only broadband measurements are usually available for other sites, and these are misleading for the reasons stated in the Introduction, namely the inclusion of highly variable night-sky lines. Second, we expect that the natural sky brightness will depend, to some extent, on solar activity; we discuss why further below. Both our first-epoch and second-epoch data were obtained near a time of relatively high solar activity, and so we expect that the sky brightness to be elevated relative to solar minimum, possibly by several tenths of a magnitude (Pilachowski et al. 1989). However, we can offer two comparisons which may be meaningful. Absolute spectrophotometry has been published for the Palomar night sky by Turnrose (1974), although at much coarser resolution (80–160 Å) than that discussed here. At the time, Palomar was considered to be one of the finest dark observing sites. Turnrose's λ4540 flux is equivalent to a sky brightness of 22.30 mag arcsec^{-2}, which is about 0.1 mag arcsec^{-2} brighter than the corresponding Mount Hopkins and Kitt Peak narrowband sky brightness at λ4550 (Table 1). Thus the zenith sky brightness on Mount Hopkins and Kitt Peak at the end of the 1990s is still as dark as Palomar Observatory was in the early 1970s. (The Palomar data were obtained at a time nearly halfway between solar maximum and solar minimum, which simply underscores how well the two

Arizona sites are still doing.) We can also compare our values to the *predictions* of Garstang (1989) for 1980 for the two sites of $B = 22.93$ mag arcsec^{-2} for Kitt Peak and 22.87 mag arcsec^{-2} for Mount Hopkins. The synthetic B surface brightness at zenith at both sites is 22.63 mag arcsec^{-2}. Although the sky brightness at our two sites are elevated relative to these values, the predictions were explicitly computed for solar minimum. Clearly, additional data obtained at our two sites during the next solar minimum (circa 2005) would be of interest.

What changes have occurred over the past decade? In Figure 2 we show the first and second epoch observations at zenith plotted for each site. The strongest effects are the increase in the scattered light HPS light in the wavelength range from 5600–6300 Å, and an upturn in the UV flux relative to the 1988 Kitt Peak data. In general however, the agreement is very heartening. As can be seen in the figure and in the broadband synthesized magnitudes, the zenith sky brightness has changed by only about ± 0.1 mag arcsec^{-2} over Mount Hopkins. In fact, the B sky brightness appears darker in 1998 than in 1988, though we expect that this may be due to the instrumental calibration effect described in § 2.

The situation is much the same for Kitt Peak. Although the increase in sky brightness seems larger than for Mount Hopkins, $\Delta B = -0.17$ mag arcsec^{-2} and $\Delta V = -0.22$ mag arcsec^{-2}, these can be largely attributed to the increase in HPS and the turn-up in the UV. Examining the monochromatic magnitudes, one sees only an increase of about 0.1 mag arcsec^{-2} at wavelengths in the range 4000–5500 Å.

It is interesting to note that the strength of the Hg I $\lambda 4047$ and $\lambda 4358$ lines has decreased significantly between the two epochs. The sale of mercury vapor lamps is illegal in Pima County, so apparently some of the old fixtures have been replaced, presumably with HPS sources.

Are these changes over time representative, or could they be due to other causes? *Some* fraction of the natural night-sky brightness is composed of faint, unresolved stars, and *some* fraction is due to resolved, and unresolved, emission; Roach & Meinel (1955) estimate the relative contributions as 40% and 60%, respectively. (See discussion in Garstang 1989.) Care was taken to avoid observations near the

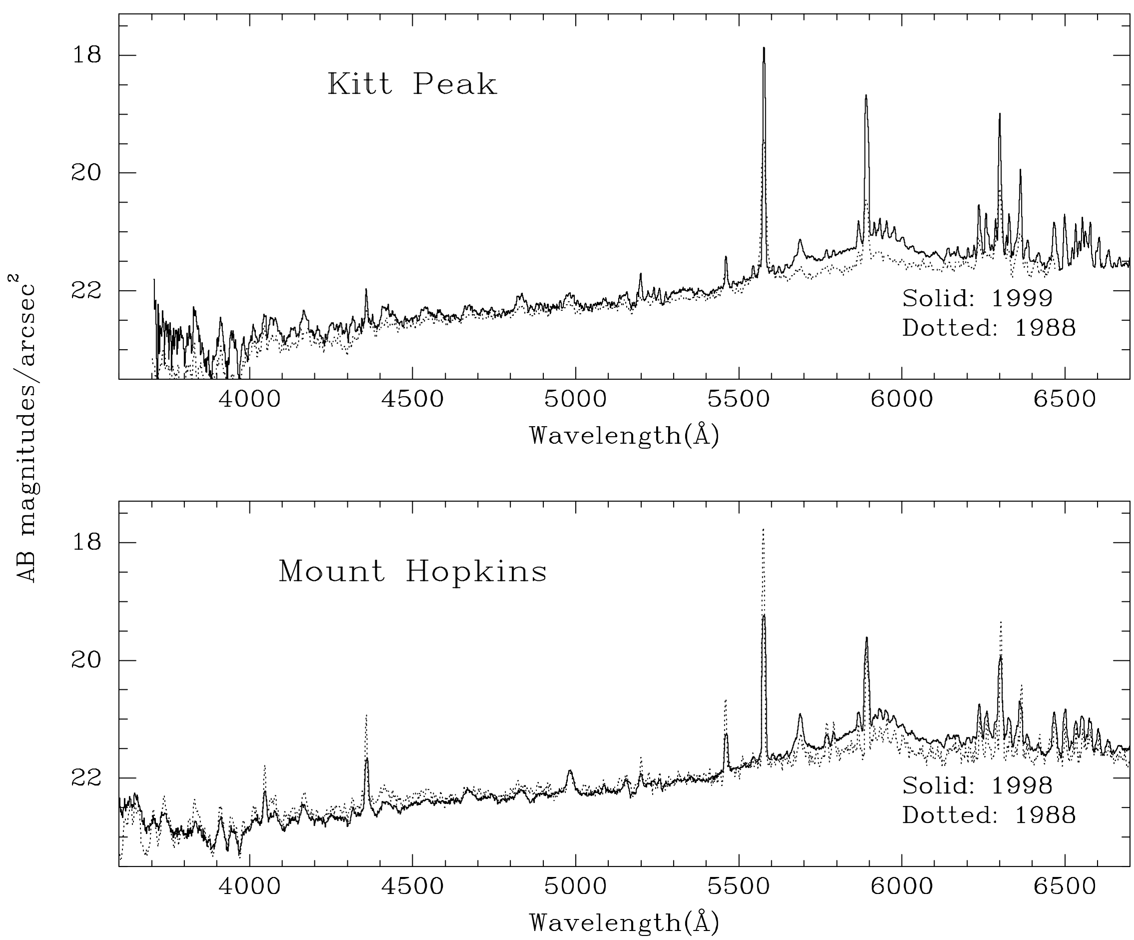

FIG. 2.—Comparison of the zenith sky brightness measured roughly 10 years apart for each site. Note the increase in the strength of HPS relative to the increase in the continuum. Quantitative assessment of the differences may be inferred from Table 1.

Galactic plane, as discussed above. We expect that the amount of solar activity will affect the latter component, as increased flux from the Sun excites additional atmospheric emission. The size of the effect is unclear, although some evidence suggests it may be as much as 0.5 mag arcsec^{-2} at the extremes of solar activity (Pilachowski et al. 1989; see also Fig. 2 of MGP). It is therefore fortunate, although not completely coincidental, that the second-epoch observations are separated from the first by roughly one 11 year solar cycle at each observatory, 10.5 years for the Mount Hopkins data and 11.7 years for the Kitt Peak data. Thus we believe that our comparisons over time are little affected by solar activity.

What happens then at intermediate zenith angles? For Mount Hopkins we have measurements toward the cardinal directions for the 1998 data only; for Kitt Peak we have observations made toward directions we thought would be interesting at a zenith distance of 60° in both 1988 and 1999.

In Figure 3 we compare the 1999 observation toward Tucson with that obtained at zenith for Kitt Peak. As the numbers in Table 1 suggest, this is the worst of any of direction. The photometry is about 0.5 mag arcsec^{-2} brighter here than at zenith.

We are heartened that in other directions the increase relative to zenith is only about 0.15–0.30 mag arcsec^{-2} in the 1998/1999 data, although it slightly higher than what we expect just from the natural sky brightness. Roach & Meinel (1955) measured the natural sky brightness in a line-free band centered at about 5300 Å from a site at about 5000 feet (1500 m) elevation and found that the natural sky brightened by about -0.06 mag arcsec^{-2} at 40° zenith distance to -0.14 mag arcsec^{-2} at 60°. Indeed, this increase away from the zenith is about all we observed in our 1988 data. Adopting these values as somewhat liberal estimates, we estimate that, with the exception of directions over Tucson, the sky brightness observed from Mount Hopkins and Kitt Peak is elevated over that expected due to natural airglow by less than 0.2 mag arcsec^{-2}.

Nevertheless, the contrast between the zenith and the Tucson direction is dramatic, especially as viewed from Kitt Peak. Furthermore, this contrast has increased more than it has in other directions during the 1988–1999 time interval. In 1988 the difference between 55°–61° and zenith was only 0.13–0.20 mag arcsec^{-2} at Kitt Peak, and not very dependent upon azimuth.

The most glaring difference (so to speak) between the two sites is the different contrasts between the Tucson and zenith directions. The sky appears 0.46 and 0.54 mag arcsec^{-2} brighter in B and V, respectively, at a ZD of 58°–60° from Kitt Peak (compared to zenith), while it is 0.24 and 0.27 mag arcsec^{-2} brighter from Mount Hopkins at a ZD of 48°. Why are the Kitt Peak Tucson values so high com-

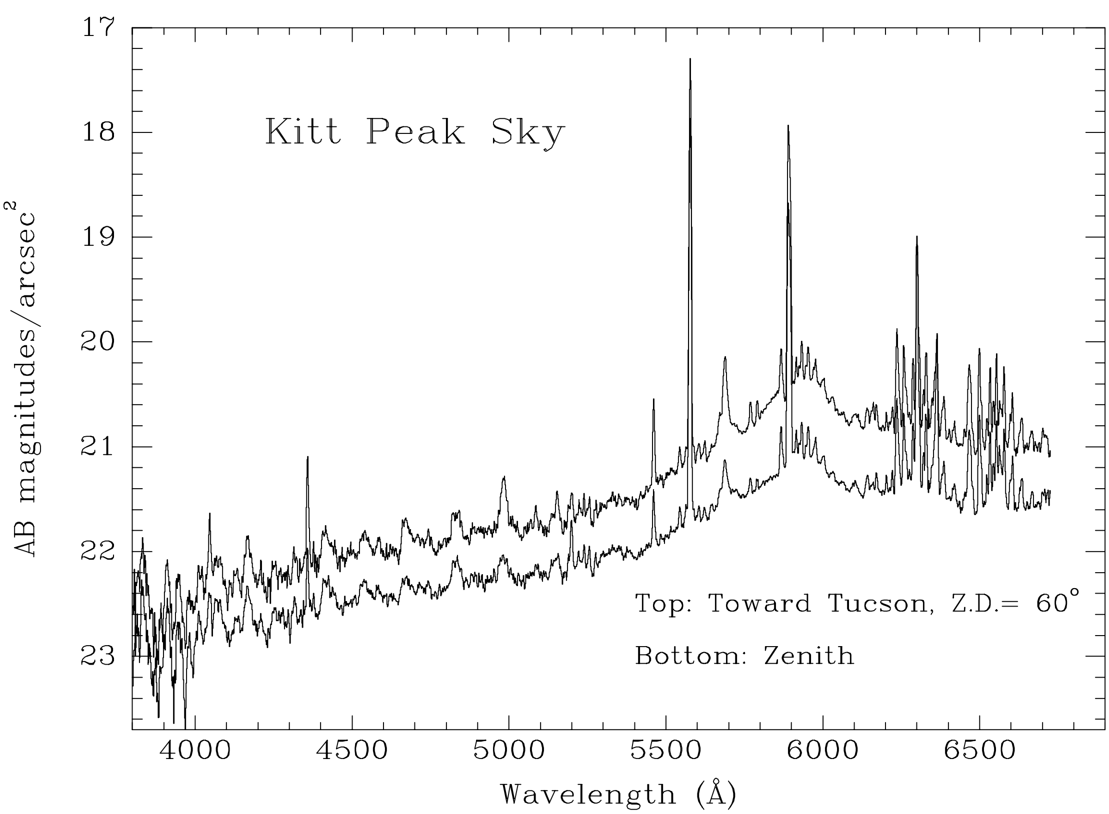

Fig. 3.—Comparison of the Kitt Peak zenith sky brightness with that at a zenith distance of 60° in the direction toward Tucson

pared to Mount Hopkins? Without detailed sky brightness models we can only speculate. Certainly, the somewhat larger zenith distance of the Kitt Peak observation will lead to a brighter measurement. Another factor may be that the Tucson metropolitan area is more extended in the east-west direction than it is north-south, making the sky appear brighter from Kitt Peak, which is west-southwest of Tucson, than from Mount Hopkins to the south. Finally, it is possible that the meteorological conditions may have been substantially different on the nights of the two observations. Mount Hopkins is at higher elevation (2605 m or 8550 feet) than Kitt Peak (2120 m or 6950 feet) and is often above the inversion layer that forms over the desert floor and entrains dust. It may be that this was the case during the 1998 Mount Hopkins measurements and not during the 1999 Kitt Peak observations. Whatever the reason, the need for additional sky brightness measurements at both sites, both to resolve this issue and to establish better statistics on the sky brightness, is clearly indicated.

4. DISCUSSION

We have found that the zenith sky brightness over Kitt Peak and Mount Hopkins increased only modestly during the period between 1988 and 1999, with the largest changes being seen for Kitt Peak. There the zenith sky has brightened by $\approx$0.1–0.2 mag arcsec^{-2} in the blue-optical region. At large zenith distances (ZD $\approx 60°$) away from the direction toward Tucson, the sky has brightened by approximately 0.2–0.35 mag arcsec^{-2} throughout this wavelength region. Toward Tucson the change has been larger, approximately 0.5 mag arcsec^{-2}.

Eastern Pima County, Arizona, is an area of substantial urban growth. The impact of this growth has been ameliorated by a fairly strict outdoor lighting code (International Dark Sky Association 1994).[3] We can ask if this code has been effective in minimizing the impact of light pollution on the two observatories. Between 1988 and 1999, the population of Tucson and surrounding municipalities has increased from approximately 405,000 to 510,000 persons (Huckelberry 1998),[4] a 26% increase. Including the unincorporated land, the population of the county as a whole increased from 641,000 persons to 824,000, a 29% increase. Since much of the population density in Pima County is concentrated near Tucson, it is probably safe to assume that the increase in the population in areas affecting the observatories is probably closer to the latter number than to the former.

Both observatories are also affected by light pollution from the twin cities of Nogales, Arizona (in Santa Cruz County), and Nogales, Sonora, Mexico. We have no estimate of the increase in the population of the latter. During this period, however, the population of Santa Cruz county increased from approximately 27,000 persons to just under 38,000 (Arizona Department of Economic Security 1999),[5] a 40% increase.

The implication of these numbers is that in most directions from the two observatories, the increase in sky brightness has lagged behind the increase in population of the major metropolitan centers in Pima and Santa Cruz county. This is very good news. However, both observatories are feeling the pressure from development as Tucson grows to the west, toward Kitt Peak, and to the south, toward Mount Hopkins. Since the effect of artificial illumination on sky brightness varies roughly as distance$^{-2.5}$ (Walker's law; International Dark Sky Association 1996),[6] the impact of this development extending in some cases literally to the foot of the mountains will be commensurately greater. Preservation of these and other sites will require assiduous attention to lighting plans and outdoor lighting codes and frequent, diligent interaction with local elected officials and planning and zoning boards.

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[3] Published in electronic form at http://www.darksky.org/ida/ida_2/info91.html.

[4] Published in electronic form at http://www.dot.co.pima.az.us/county/urban/ubntblcon.htm.

[5] Published in electronic form at http://www.de.state.az.us/links/economic/webpage/.

[6] Published in electronic form at http://www.darksky.org/ida/ida_2/info11.html.

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