

THE SPECTRUM OF LIGHT POLLUTION AT MOUNT HAMILTON*

D. E. OSTERBROCK, M. F. WALKER, AND A. T. KOSKI

Lick Observatory, Board of Studies in Astronomy and Astrophysics
University of California, Santa Cruz*Received 1976 February 2*

Observed spectra of the night sky above Lick Observatory are presented, showing the light pollution due to lights in San Jose and other communities in the Santa Clara Valley. Spectra of several types of street lights are shown, and of these the low-pressure sodium lamp would cause the least additional light pollution if it were adopted for all future installations.

Key words: light pollution — Lick Observatory — street-lamp spectra

The problem of light pollution is becoming increasingly severe at essentially all major observatories in the continental United States (see e.g., Riegel 1973; Hoag, Schoening, and Coucke 1973; Walker 1973). In particular, the growth of San Jose and other communities in the Santa Clara Valley is causing an increase in the sky brightness over Lick Observatory at a rate of approximately 1 magnitude per 25 years (Walker 1973). We therefore thought it appropriate to measure the present spectrum of the light pollution at Mount Hamilton, and the spectra of various lights which may contribute to future additional light pollution.

The measurements were made with the image-tube scanner (Robinson and Wampler 1972; Miller, Robinson, and Wampler 1976) on the 120-inch (3-m) telescope, in the course of regular observations of the spectra of radio and Seyfert galaxies. In this instrument the spectrum of the galaxy plus sky is measured in one slit, and the sky alone in the other slit, 35" away, at the same time. Ordinarily the sky spectrum is then subtracted from the galaxy plus sky, leaving the spectrum of the galaxy alone. However, for the measurements reported here, the sky spectra were simply reduced to energy units, using the instrumental sensitivity function derived from measurements, the same night, of standard stars that had been used to reduce the galaxy spectrum. Spectra, taken with the dark slide closed immediately before and after the sky spectra (while moving the telescope to the next object) were subtracted from the sky spectra to eliminate the contribution of the dark current.

The sky spectra were obtained on 1975 August 2/3, one in the blue spectral region, totaling 64 minutes exposure centered about 23:37 PST, at a mean zenith distance 19° and azimuth 130°, a relatively dark part of the sky, and the other in the red spectral region,

totaling 48 minutes exposure centered about 21:50 PST, at a mean zenith distance 53° and azimuth 248°, approximately in the direction of San Jose. These spectra are shown in Figures 1 and 2, respectively, plotted in units of energy flux per unit frequency interval and to the same scale, so that the increase in brightness in the red scan due to lower altitude and closeness to San Jose is shown by the increased amplitude in the wavelength region common to both spectra. Note that our calibration procedure does not give the absolute value of the energy unit in Figures 1 and 2 since the amount of light from the standard star that enters the slit is somewhat seeing-dependent.

As can be seen in these figures, the blue scan is contaminated by Hg I lines from city lights, while the red scan shows in addition the many OH lines in the near infrared (Meinel 1950, 1951). Note that the [O I] $\lambda 5577$ line is fainter in the blue scan, partly because of the higher altitude and probably also because of the diurnal (or nocturnal) variation of this line, while the ratios of Hg I $\lambda\lambda 5461, 5770, 5791$ to [O I] $\lambda 5577$ show how much stronger the light pollution due to city lights is at low altitudes in the direction of San Jose. The Na I $\lambda 5893$ feature seems to be almost entirely due to night-sky emission, as judged by its strength with respect to [O I] $\lambda\lambda 5577, 6300, 6364$, and we do not see any signs of Ne I light pollution in the red-sky spectrum. In comparison with the present Mount Hamilton sky as shown in these scans, the relatively unpolluted Kitt Peak sky of ten years ago had much weaker Hg I lines and in fact $\lambda\lambda 5770, 5791$ were barely detected (Broadfoot and Kendall 1968). Considerably lower resolution scans of the night sky at Palomar and Mount Wilson have also been published by Turnrose (1974).

In both the red and the blue regions of Figures 1 and 2 the contributions of all the lines together is about one-third the total flux, while the contribution of the continuum, made up of pollution and natural skylight, is approximately two-thirds the total flux.

* *Lick Observatory Bulletin*, No. 730.

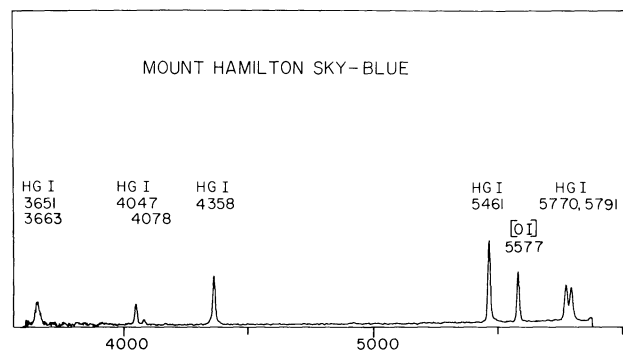


FIG. 1—The blue region of the night-sky spectrum observed from Mount Hamilton on 1975 August 2/3. The exposure was 64 minutes centered about 23:37 PST at a mean zenith distance 19° and azimuth 130° ($\alpha = 21^{\text{h}}22^{\text{m}}$, $\delta = +25^\circ$; $l = 75^\circ$, $b = -18^\circ$). The relative flux per unit frequency interval is plotted against wavelength to the same scale as Figure 2.

Furthermore, we find that in the east (represented by Fig. 1) approximately 60% of the continuum is due to light pollution, while in the west (represented by Fig. 2) approximately 80% of the continuum is due to light pollution. These figures were derived by assuming that in the region of overlap between Figures 1 and 2 (about $\lambda\lambda 5000$ to 5800) the strength of the light pollution continuum is proportional to the strength of Hg I $\lambda\lambda 5461$, 5770 , 5791 , and that the strength of natural skylight (composed of unresolved atmospheric emission features and faint background stars) has the same zenith-distance dependence as the sky brightness measured with a V filter at the dark-sky Junipero Serra site (Walker 1973).

The Public Works Department in San Jose, as in many other cities, is considering adopting new types of lights that are more efficient in luminous output per unit electrical energy consumed. These lights, as they are introduced, may significantly alter the spectrum of light pollution. We therefore obtained, through the cooperation of the Public Works Department and of Drath-Jacobs, samples of three types of lights and recorded their spectra. These spectral measurements were made in the daytime, by shining the lights onto the inside of the closed and otherwise darkened dome. The spectra were reduced to energy units using the conversion obtained from standard stars observed at night in the course of regular spectrophotometric observing programs. For each lamp, scans taken in several different spectral regions covering the range from the near ultraviolet to the near infrared were pieced together and are plotted in Figure 3.

The top scan of this figure shows the spectrum of a Norelco 35-watt low-pressure sodium lamp type SO X 35W. According to the manufacturer's figures this is the most efficient type of lamp commercially available, with a visual output of approximately 183 lumens per

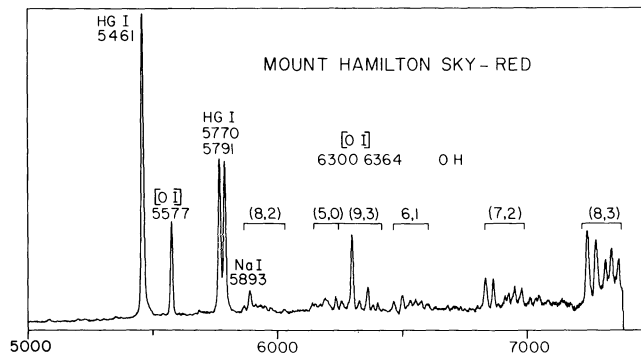


FIG. 2—The red region of the night-sky spectrum observed from Mount Hamilton on 1975 August 2/3. The exposure was 48 minutes centered about 21:50 PST at a mean zenith distance 53° and azimuth 248° ($\alpha = 15^{\text{h}}14^{\text{m}}$, $\delta = +70^\circ$; $l = 10^\circ$, $b = +50^\circ$). The relative flux per unit frequency interval is plotted against wavelength to the same scale as Figure 1.

watt of electrical energy consumed. The spectrum shows that nearly all the light is concentrated in the Na I D lines in the visible and Na I $3^2\text{P}-3^2\text{D}$ $\lambda\lambda 8183$, 8195 in the infrared. Broad spectral regions in the blue, green, and red are free of any appreciable emission from this lamp.

The middle scan of Figure 3 shows the spectrum of a 250-watt General Electric Lucalox high-pressure sodium lamp, type LU 250/BD. This lamp has an intense pinkish-yellow color, and its luminous efficiency is 93 lumens per watt (General Electric 1975), approximately half that of the low-pressure sodium lamp. The spectrum of the high-pressure lamp is dominated by the very strong, very broad Na I D lines, with a central reversal about 100 \AA wide. Numerous other Na I lines contribute significantly to the spectrum, as well as the K I $\lambda\lambda 7665$, 7699 doublet marked. High-dispersion spectrograms show many weaker lines of Na I, K I, Sr I, and Hg I. As can be seen in the figure, this lamp does not emit much blue light, and in particular the Na I $\lambda\lambda 3302$, 3303 doublet does not show at all on another spectrum of the lamp that we obtained with an ultraviolet-sensitive image tube. No doubt this ultraviolet radiation is absorbed by the glass envelope of the lamp.

The bottom scan of Figure 3 shows the spectrum of a General Electric "color corrected" 250-watt Deluxe White Mercury lamp, type GE H250 DX37-5. This lamp has an average efficiency of 30 lumens per watt, about a factor of three smaller than the efficiency of the high-pressure sodium lamp, but is considerably more efficient than incandescent lamps, which average around 17 lumens per watt (General Electric 1975). The mercury lamp's spectrum in the blue and yellow consists almost entirely of Hg I lines, with very little continuum. In the red there are several broad features, due to a phosphor described by the manu-

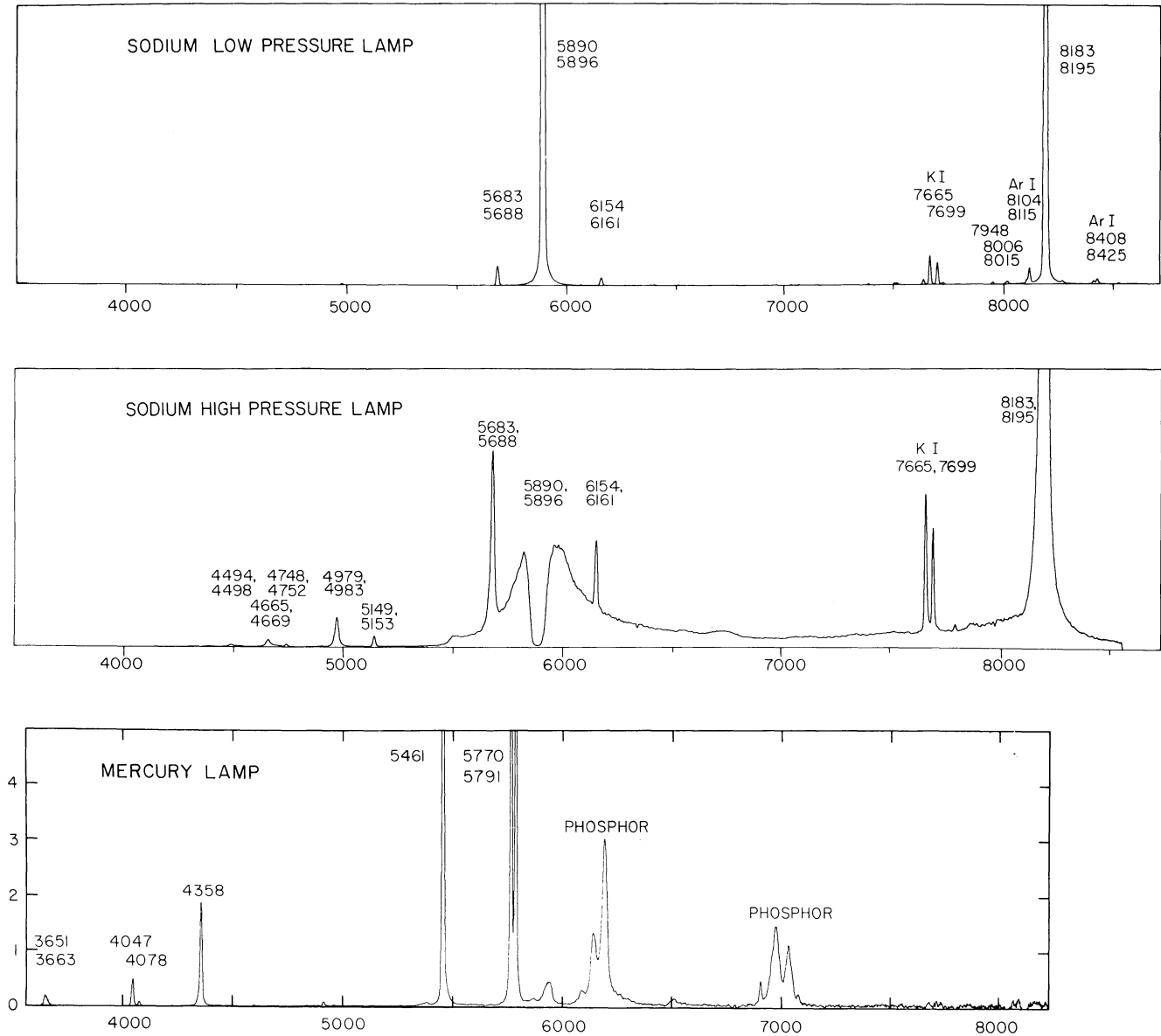


FIG. 3—Spectra of three street lamps. Relative flux per unit frequency interval is plotted against wavelength. Each spectrum is scaled so that they each have approximately the same total visual effect as the sky spectrum shown in Figure 2. *Top scan.* Norelco 35-watt low-pressure sodium lamp type 50X 35W. The Na I D lines $\lambda\lambda 5890, 5896$ are unresolved in this scan and extend 10 times higher than shown. Na I $\lambda 8183$ and $\lambda 8195$ extend 1.2 and 1.6 times higher, respectively. *Middle scan.* General Electric Lucalox 250-watt high-pressure sodium lamp, type LU 250/BD. The Na I lines $\lambda 8183$ and $\lambda 8195$ extend 4.6 and 4.1 times higher, respectively, than shown. *Bottom scan.* General Electric 250-watt mercury lamp, type Ge H 250 DX37-5 (Deluxe White Mercury Lamp). The Hg I lines $\lambda\lambda 5461, 5770,$ and 5791 extend 2.5, 1.6, and 1.5 times higher, respectively, than shown.

facturer as europium-doped yttrium vanadate phosphate, which converts ultraviolet line radiation, chiefly $\lambda 2537$ but also including some of the $\lambda\lambda 3651, 3663$ photons, to lower frequencies, and gives the emitted light its white color. Note that the ultraviolet and violet Hg I lines $\lambda\lambda 3651, 3663, 4047, 4358$ are much weaker in this lamp with respect to the yellow Hg I lines $\lambda\lambda 5461, 5770, 5791$ than in the Mount Hamilton sky, no doubt due to absorption by the phosphor in the lamp.

All the scans of Figure 3 have been normalized so they have the same total visual effect as the present Mount Hamilton sky spectrum shown in Figure 2. More accurately, the integral of each of the spectra shown in Figures 2 and 3 convolved with the response function of the V filter (Johnson and Morgan 1951) is the same. Thus, if in the next 20 years the sky brightness over Mount Hamilton increases by a factor of two through the addition of further lighting in the Santa Clara Valley, the resulting spectrum of light pollution

will approximate the sum of Figure 2 (extended to the blue by Figure 1 scaled up by a factor of about three) plus one of the scans of Figure 3, or by a linear combination of the three of them.

While scans have not been obtained of the "Multi-Vapor" or metal-halide type of high-intensity discharge lamps, it is clear from published data (General Electric 1975) that these would have an even greater impact on astronomical observations than the types just considered. The emitted spectrum of this type of lamp contains numerous strong emission features, plus an irregular continuum throughout the region from 3500 Å to 7500 Å.

Certainly, if at all possible, new observatory sites should be chosen to combine clear weather, good-seeing dark skies, and the possibility of controlling future development of artificial illumination in the vicinity. Communities near existing large research observatories should be encouraged to control light pollution by reducing nonessential lighting and installing shields on new lights to prevent wasting energy by illuminating the sky. In addition, whatever lighting increases are necessary should be in the form of low-pressure sodium lamps, which minimize the resulting light pollution. If low-pressure sodium lamps cannot be used, then the next best choice is clear mercury lamps rather than high-pressure sodium or metal-halide lamps, for the increase will then occur in spectral regions that are more or less polluted already, rather than introducing new sources of pollution that would seriously affect nearly the entire yellow and red spectral regions. We are therefore recommending that

all new lights installed in San Jose and the Santa Clara Valley be low-pressure sodium lamps, or if other types of lamps must be used, that they be shielded or shaped so that no light is emitted above the horizontal, and equipped with filters to absorb the visually unimportant radiation at wavelengths shortward of 4400 Å.

We are greatly indebted to J. Baldwin, M. Cohen, R. Costero, S. A. Grandi, E. A. Harlan, S. A. Hawley, G. H. Herbig, L. Kuhl, and M. M. Phillips for their assistance in various stages of obtaining and reducing the data, and to the San Jose Public Works Department and Mr. Bill Drath of Drath-Jacobs for making the lamps available for these tests. We are also very grateful to the National Science Foundation for partial support of this research under grant MPS 73-08981 A02.

REFERENCES

- Broadfoot, A. L., and Kendall, K. R. 1968, *J. Geophys. Res.* **73**, 426.
 General Electric Co. 1975, *High Intensity Discharge Lamps*, Booklet TP-109R.
 Hoag, A. A., Schoening, W. W., and Coucke, M. 1973, *Pub. A.S.P.* **85**, 503.
 Johnson, H. L., and Morgan, W. W. 1951, *Ap. J.* **114**, 522.
 Meinel, A. B. 1950, *Ap. J.* **111**, 433.
 — 1951, *ibid.* **114**, 120.
 Miller, J. S., Robinson, L., and Wampler, E. J. 1976, *Adv. Electronics Electron Physics* (New York: Academic Press).
 Riegel, K. W. 1973, *Science* **179**, 1285.
 Robinson, L., and Wampler, E. J. 1972, *Pub. A.S.P.* **84**, 161.
 Turnrose, B. E. 1974, *Pub. A.S.P.* **86**, 545.
 Walker, M. F. 1973, *Pub. A.S.P.* **85**, 508.