

# Sky Spectra at a Light-Polluted Site and the use of Atomic and OH Sky Emission Lines for Wavelength Calibration<sup>1</sup>

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**ABSTRACT.** Spectra of the night sky, taken at Lick Observatory in 1988 and 1989 as byproducts of nebular spectra, show the great increase of light pollution by sodium high- and low-pressure lamps in comparison with previous spectra taken in 1975. The usefulness of the emission lines of the night sky spectrum for wavelength calibration is mentioned. In the far-red and near-infrared regions, where there are only few atomic night-sky lines, the OH vibration-rotation spectrum may be used for this purpose. Accurate rest wavelengths for these lines, calculated from the best laboratory determinations, are tabulated, and the special suitability of the  $P_1$  (and to a lesser extent  $P_2$ ) lines is discussed.

## 1. INTRODUCTION

Lick Observatory is well known to be located at a site with severe light pollution, probably the worst of any telescope currently active full time on research. Its light-pollution problem may become increasingly relevant to other observatories in the southwestern United States. Osterbrock et al. (1976) published sky spectra taken at Mount Hamilton in 1975, as well as spectra of the mercury lamps then mainly in use in San Jose, and of the high-pressure sodium (HPS) and low-pressure (LPS) lamps that were coming into use at that time. They predicted that the future Lick Observatory night-sky spectrum would be increasingly dominated by these sodium lamps, and stated the astronomical advantages of the LPS lamps. More recently Massey et al. (1990) published spectra of sky spectra at Kitt Peak, taken in 1988, and of similar lamps. These spectra show that all three types of lamps are becoming apparent in the sky spectra at that site, particularly the LPS lamps. Walker (1991) has reviewed the continued slow increase in light brightness at Mount Hamilton until about 1978, its leveling off in the  $B$  band in the early 1980's as a consequence of the shift in street lights from mercury to HPS, with later some LPS, and its increase again since about 1984. Hence, it is of interest to compare the current night-sky spectrum at Lick Observatory with that of the mid-1970's. This is done in the present paper.

The spectrum of the sky, though a nuisance astronomically, has one redeeming feature. It automatically imposes on the spectrum of any object, while it is being taken, emission lines with accurately known wavelengths. These may be used as comparison lines, or as lines to fix the wavelength zero point if the dispersion curve is known from comparison-lamp spectra. In the red- and near-infrared spectral regions, the OH emission bands of the natural night-sky spectrum increasingly dominate over the light-pollution spectrum. In this paper we tabulate accurate laboratory wavelengths of the individual lines in these bands, and discuss their use as wavelength zero points.

## 2. OBSERVATIONAL DATA

The sky spectra on which this study was based were obtained at Lick Observatory in connection with a pro-

gram on the spectrum of NGC 1976, the Orion nebula (Osterbrock et al. 1991). They were taken with the UV-Schmidt spectrograph and a thinned Texas Instrument (TI) 800×800 three-phase CCD detector at the Cassegrain focus of the Shane 3-m telescope (Miller et al. 1988). The spectra were obtained with two gratings, each of 600 lines  $\text{mm}^{-1}$ , at seven different grating rotations, to cover the spectral range  $\lambda\lambda$  3000–11 000 (with some overlap). Each exposure covered approximately 1550 Å. The gratings were used in the first order, and glass filters were used to block the second order from the spectra with central wavelengths  $\lambda_c \geq 5580$  Å. Slit widths of 2" (in the optical region,  $\lambda \leq 7500$  Å), or 3" (in the near-infrared,  $\lambda \geq 7000$  Å) were used, giving spectral resolutions (FWHM) of about 5–7 Å. The slit length was 2' for all exposures. A journal of observations is given in Table 1.

The first two sky spectra, taken in 1988, came from regions on either end of the slit, well away from the objects being exposed at its center, BD + 26°2606 (March 21) and NGC 4151 (March 22). The other sky spectra were taken with the slit either 4 min due east of the bright region studied in NGC 1976 (1989 January) or 1.5 hr east of it (1989 April). The zenith distances at midexposure are listed in Table 1. The spectrum for  $\lambda_c = 7750$  Å was taken very near the zenith; all the others were taken to the west or southwest in azimuth. San Jose, Santa Clara, and the other Silicon Valley cities which are the main sources of light pollution at Lick Observatory, lie to its west.

The spectra were individually reduced to flux units as functions of wavelength following standard Lick Observatory procedures, as described by Osterbrock et al. (1991). Because of differences in zenith distance, azimuth, time of night, and thin cirrus on at least one night, the spectra contain different mixtures of natural and light pollution sky contributions, and no attempt was made to fit them together into one "mean" spectrum. However, these spectra are quite characteristic of "typical" observing conditions at Lick Observatory. These spectra are plotted in Figs. 1–7. Note that the wavelength scales were derived from comparison-lamp spectra, mostly taken at the beginning of the night with the telescope vertical, and have not been corrected for a wavelength zero-point shift due to flexure. These shifts are discussed below, in the next section.

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TABLE 1  
Journal of Observations

UT Date	$\lambda_c$ (Å)	Exposure (min)	Zenith Distance (deg)
1988			
March 21	7750	5	13
March 22	8990	60	28
1989			
January 29	10 210	30	47
January 30	5580	20	53
January 31	3700	20	47
April 11	6700	60	64
April 12	4400	60	64

3. IDENTIFICATIONS

On each spectrum the wavelengths of all the strongest, apparently single emission lines were measured, generally using only the peak 20% or so of the profile. With these wavelengths, and the sky and lamp spectra of Osterbrock et al. (1976), it is straightforward to identify nearly all the atomic lines. The natural sky-spectrum lines, including both atomic and molecular, in particular OH, can be identified out to  $\lambda = 10\,000$  Å from the excellent charts published by Broadfoot and Kendall (1968), based on spectra taken at Kitt Peak, apparently a year or two before the date of publication. The only light-pollution lines they show are very weak Hg I. The identifications of the OH lines can easily be extended beyond  $\lambda 10\,000$  using the wavelengths described below. Many of the identified lines are marked on Figs. 1–7.

Qualitatively, the very great relative increase in light pollution by sodium lamps can be seen by comparing Fig. 3 with Fig. 2 of Osterbrock et al. (1976). The very broad wings of Na I  $\lambda\lambda 5890, 5896$  from the HPS lamps now dominate the region  $\lambda\lambda 5700\text{--}6100$ , and the “narrow” component of this doublet, due to the LPS lamps, is so strong as to be saturated on this exposure. Many other Na I lines, mostly broad and chiefly due to the HPS lamps, can be seen in Figs. 3–6. The Hg I lines are now fainter in the Mount Hamilton sky spectra relative to Na I and to the natural [O I] lines than they were in 1975. Also,

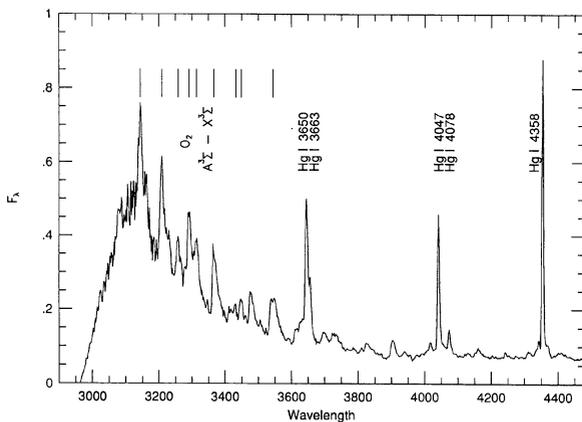


FIG. 1—Sky spectrum at Lick Observatory  $\lambda\lambda 3000\text{--}4400$ . Units are flux per unit wavelength (normalized) vs wavelength.

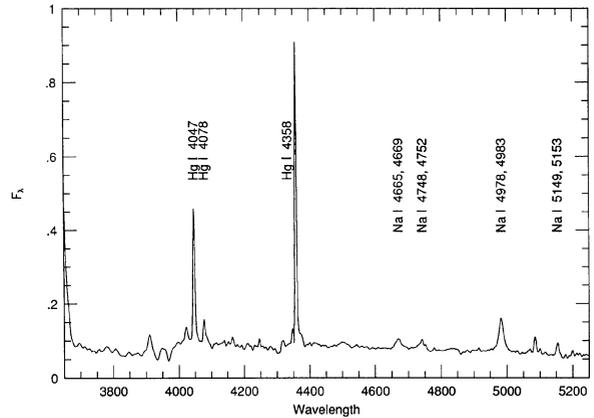


FIG. 2—Sky spectrum at Lick Observatory  $\lambda\lambda 3700\text{--}5200$ . Units as in Fig. 1.

several weak Ne I lines can now be seen in the Lick Observatory sky spectra in the  $\lambda_c = 6700, 7750$  Å spectral regions. They arise from advertising signs, and include most, but not all, of the brightest lines in our neon comparison lamp.

The measured wavelengths of the atomic lines were then used to calculate the wavelength offset,  $\Delta\lambda = \lambda_0 - \lambda_m$ , for each separate section of the spectrum, where  $\lambda_0$  is the known rest wavelength and  $\lambda_m$  is the measured wavelength. For the permitted lines the rest wavelengths are from the RMT (Moore 1945), except Hg I  $\lambda 4077.83$ , which comes from the *American Institute of Physics Handbook* (1957). The other Hg I wavelengths in this publication agree with those in the RMT to 0.01 Å. For the forbidden lines the rest wavelengths are from Kaufman and Sugar (1986). Most of the Na I lines are too broad, and blended also, to be used in these offset determinations, but Na I  $\lambda\lambda 8183, 8195$  (multiplet 4), and K I  $\lambda\lambda 7665, 7699$  (multiplet 1) are sharp and resolved, and were used. For each spectral region all the measured offsets from atomic lines were averaged with equal weight to find the best value. These are listed in the second column of Table 2, together with the probable errors and number of lines which went into the determination. It can be seen that the

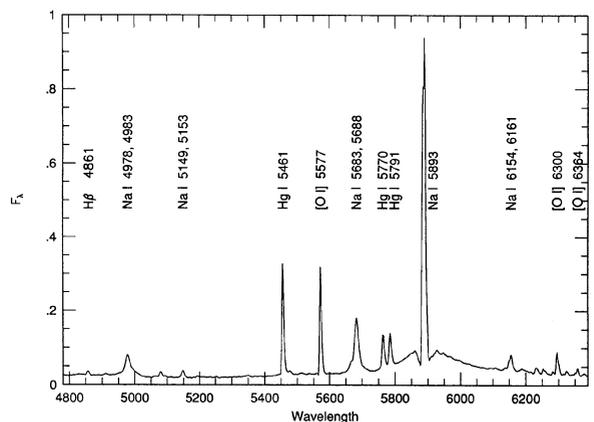


FIG. 3—Sky spectrum at Lick Observatory  $\lambda\lambda 4800\text{--}6300$ . Units as in Fig. 1.

TABLE 2  
Wavelength Offsets from Sky,  $\Delta\lambda = \lambda_0 - \lambda_m$

Central Wavelength $\lambda_c$	Atomic Lines		OH P Lines		OH All Lines		All Lines	
	$\Delta\lambda$	$n$	$\Delta\lambda$	$n$	$\Delta\lambda$	$n$	$\Delta\lambda$	$n$
3700	$+5.02 \pm 0.29$	4	—	—	—	—	$+5.02 \pm 0.29$	4
4400	$-0.15 \pm 0.22$	3	—	—	—	—	$-0.15 \pm 0.22$	3
5580	$+5.63 \pm 0.09$	6	$+5.36 \pm$	—	$+5.36 \pm$	—	$+5.59 \pm 0.09$	7
6700	$+0.15 \pm 0.12$	11	$-0.17 \pm 0.08$	11	$-0.10 \pm 0.13$	13	$+0.01 \pm 0.09$	24
7750	$+4.18 \pm 0.26$	5	$+4.25 \pm 0.10$	15	$+4.28 \pm 0.09$	18	$+4.26 \pm 0.09$	23
8990	$+1.29 \pm 0.53$	2	$+1.38 \pm 0.18$	12	$+1.45 \pm 0.11$	24	$+1.44 \pm 0.10$	26
10 210	—	—	$+2.41 \pm 0.08$	16	$+2.46 \pm 0.06$	36	$+2.46 \pm 0.06$	36

offsets are well determined, in most cases to within 0.1–0.3 Å, but that more sky lines are desirable to improve the determinations particularly in the longer wavelength spectral regions. In particular there are no identified atomic sky lines in the  $\lambda_c = 10\,210$  Å region.

A few other atomic lines, which were not used in the determination of the offsets, are also worthy of mention. Their wavelengths, namely the wavelengths measured on these sky spectra, corrected by the best values of the offsets as listed in the last column of Table 2, are  $\lambda\lambda$  6707.84, 6563.98, 4862.46. The first and strongest of these can be seen from Fig. 4 to be blended with a weaker line at longer wavelength, almost certainly Ne I  $\lambda$ 6717.04. The line itself is very likely the unresolved Li I  $\lambda\lambda$  6707.74, 6707.89 doublet, multiplet (1), with mean laboratory wavelength  $\lambda$ 6707.82. The other two, weaker lines, appear to be H $\alpha$  and H $\beta$  with redshifts  $+1.16$  and  $+1.13$  Å, respectively. Note that H $\beta$  is visible only in Fig. 3 ( $\lambda_c = 5580$  Å), but not in Fig. 2 ( $\lambda_c = 4400$  Å), which also includes this wavelength. However, the latter spectrum was taken with more moonlight in the sky (as can be seen from the Ca II H and K absorption lines), and the resulting H $\beta$  absorption line the sky spectrum would have weakened the emission feature. Both Li I  $\lambda$ 6708 and H $\alpha$  have been reported as possibly present in the night-sky or twilight spectra by Chamberlain (1961). It is also possible that the observed Li I  $\lambda$ 6708 arises as an impurity in sodium lamps (as K I  $\lambda\lambda$  7665, 7699 do), but it did not appear in the lamps whose spectra were measured by Osterbrock et al. (1976),

nor in Phillips SOX and Osram A  $3 \times 6$  LPS lamps also used in San Jose, of which we obtained spectra of in 1991. Courteau (1991) has not detected Li I  $\lambda$ 6708 in the sky on any of his galaxy spectra taken in this wavelength region, but closer to the zenith than our exposure.

#### 4. OH WAVELENGTHS

More sky lines with accurately known rest wavelengths are needed in the red- and near-infrared spectral regions, to calibrate the wavelength offsets in those regions. As the spectral plots show, many OH emission features are present in the sky spectra in these regions. Some observers have disregarded these OH features, incorrectly supposing that they are all blends (Osterbrock et al. 1990). Others have used the OH features as comparison lines, obtaining wavelengths for them from various sources (Rubin et al. 1980; Rubin et al. 1985; Courteau 1991). Chamberlain (1961) published an early list of wavelengths, based on combined laboratory and low-dispersion sky spectra, and later values for some of the lines in some of the bands, also based on sky measurements have been published by Blackwell et al. (1960), Krassovsky et al. (1962), Doan (1963), and Louistisserand et al. (1987).

However, considerably more accurate laboratory wavelengths are now available for all the OH lines. Coxon (1980) made a very complete discussion of all the best laboratory measurements of electronic, vibration-rotation and microwave transitions in OH, and calculated from them highly accurate energy levels for all the levels of the ground  $X^2\Pi$  term with vibrational quantum number  $v \leq 5$ . Additional high-resolution laboratory measurements of the OH vibration-rotation spectrum by Coxon and Foster (1982) gave the higher energy levels with  $6 \leq v \leq 10$ . From the measured energy levels they derived highly accurate molecular constants, which they then used to calculate all the energy levels on a consistent basis.

We have used these published energy levels to calculate the rest (air) wavelengths of all the OH vibration-rotation lines expected in the sky spectrum, to provide wavelength standards for the red- and near-infrared spectral regions. The notation has been described by Herzberg (1950). The ground electronic term of OH has electronic angular momentum projection on the internuclear axis  $\Lambda = 1$  and spin angular momentum  $\Sigma = 1/2$ . It is thus a  $^2\Pi$  term, and the lower ground term is  $^2\Pi_{3/2}$ , with electronic total angular momentum  $\Omega = 3/2$ , while the first excited term has  $\Omega = 1/2$ . The total rotational angular momentum of the molecule  $J$  is then the vector sum of  $\Omega$  and  $N$ , the angular

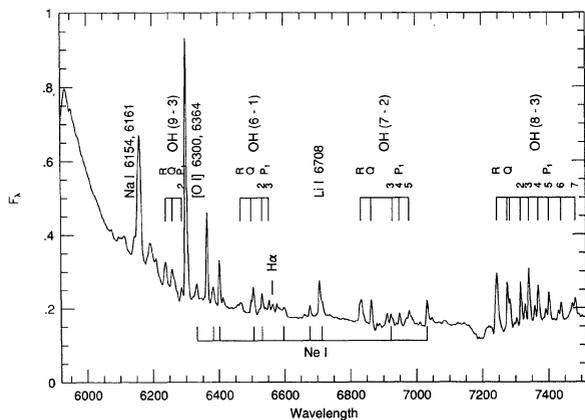


FIG. 4—Sky spectrum at Lick Observatory  $\lambda\lambda$  6000–7500. Units as in Fig. 1.

momentum of nuclear rotation, so  $J = \Omega, \Omega + 1, \Omega + 2, \dots$ . The vibrational quantum number  $v = 0, 1, 2, \dots$ . A vibration-rotation transition occurs between an upper level  $v', J'$  and a lower level  $v'', J''$  of the same electronic term, that is, either within the ground  $X^2\Pi_{3/2}$  term [these transitions are labeled  $R_1(J'')$ ,  $Q_1(J'')$ , or  $P_1(J'')$ ] or within the first excited  $X^2\Pi_{1/2}$  term [these are labeled  $R^2(J'')$ ,  $Q_2(J'')$ , or  $P_2(J'')$ ]. The  $R$  transitions connect levels  $J' - J'' = 1$ , the  $Q$  transitions  $J' - J'' = 0$ , and the  $P$  transitions  $J' - J'' = -1$ . Each rotational level is further split by  $\Lambda$ -type doubling into a  $+$  level and a  $-$  level; the selection rule is that  $R$  and  $P$  transitions connect  $+$  levels only with  $+$ , and  $-$  only with  $-$ , while  $Q$  transitions connect only  $+$  with  $-$  and vice versa. Each band is further labeled by its  $(v' - v'')$ .

Although the above describes the standard spectroscopic notation used by Coxon (1980), Coxon and Foster (1982), and Maillard et al. (1976), who also measured high-precision laboratory wavelengths of the OH vibration-rotation bands, it has not been used in most published astronomical papers. Instead Chamberlain (1961), following Meinel (1950), who first identified the bands, used the quantum number  $K$ , the total angular momentum apart from spin  $= \Lambda, \Lambda + 1, \Lambda + 2, \dots$ . Hence  $K = J - 1/2$  for the  $R_1, Q_1$ , and  $P_1$  transitions of  $^2\Pi_{3/2}$ , but  $K = J + 1/2$  for the  $R_2, Q_2$ , and  $P_2$  transitions of  $^2\Pi_{1/2}$ . This notation has been subsequently used in the published astronomical papers.

The calculated wavelengths, corrected to air by the standard formula given in the *Handbook of Chemistry and Physics* (1974) are listed in Table 3. Note on this table, to save space the  $Q_1(K'')$  wavelengths are listed opposite  $K''$ , but the  $Q_2(K'')$  wavelengths are listed opposite  $K'' + 4$ , so that for instance  $Q_2(2)$  is always listed opposite  $K'' = 6$ . Note also that each line is actually double, but the calculated separations are small, and the expected relative intensities of the two components nearly equal, so we have listed the mean wavelengths only. Typical separations of the two components of the  $P_1(K'')$  lines range from  $\sim 0.3$  Å for  $P_1(4)$  near  $\lambda 7500$  and  $\sim 0.7$  Å for  $P_1(8)$  near the same wavelength, to  $\sim 0.5$  Å for  $P_1(4)$  and  $\sim 1.3$  Å for  $P_1(8)$  near  $\lambda 11\,000$ . The separations of the  $P_2$  components are much smaller, as they are for all the  $Q$  and  $R$  lines tabulated. Though the table extends from  $\lambda 6000$ , where all the OH lines are quite weak in the sky spectrum, to  $\lambda 12\,000$ , near the limit of sensitivity of the CCDs currently used at Lick Observatory, we can supply wavelengths beyond these limits to interested users. Likewise we can supply tables with the separations listed for each component. The expected accuracy of the listed wavelengths is about  $0.01$  Å for transitions with  $v' \leq 5$ , up to perhaps  $0.04$  Å for transitions with  $v' > 5$ . For the  $(3 - 0)$  and  $(4 - 1)$  bands the measured frequencies of the individual components have been published by Maillard et al. (1976), and there is no difference between them and the calculated values (for the  $P$  lines, the only ones we checked systematically)

TABLE 3  
Meinel OH Rotation-Vibration Bands Air Wavelengths

$v' - v''$	$K''$	$Q_1/Q_2$	$R_1$	$R_2$	$P_1$	$P_2$	$v' - v''$	$K''$	$Q_1/Q_2$	$R_1$	$R_2$	$P_1$	$P_2$
5 - 0	1	6170.64	6144.48	6150.92			8 - 3	1	7276.41	7244.92	7253.15		
	2	6176.29	6139.47	6143.37	6202.72	6192.94		2	7284.45	7240.19	7245.12	7316.29	7303.75
	3	6184.41	6136.79	6138.99	6221.77	6213.06		3	7295.95	7238.79*	7241.43*	7340.89	7329.17
	4	6136.56*	6137.64*	6243.64	6236.01			4	7240.86	7241.96	7240.86	7369.38	7358.68
	5	6169.53	6138.87	6139.22	6268.41	6261.76		5	7275.14	7246.53	7246.60	7401.87	7392.22
	6	6174.19	6143.78	6143.67	6296.11	6290.30		6	7281.59	7255.91	7255.30	7438.49	7429.80
	7	6181.85	6151.37	6150.95	6326.79	6321.68		7	7292.23	7269.09	7268.04	7479.33	7471.49
	8	6161.67	6161.06	6161.06	6360.51	6355.96		8	7286.18	7284.83	7284.83	7524.50	7517.39
9 - 3	1	6257.97	6235.95	6241.69			4 - 0	1	7523.99	7483.48	7493.67		
	2	6265.22	6234.30*	6237.41	6287.44	6278.09		2	7530.71	7473.68	7480.25	7571.75	7557.49
	3	6275.60	6235.68	6237.00*	6306.93	6297.90		3	7540.38	7466.61	7470.71	7598.44	7586.09
	4	6240.21	6240.34	6329.85	6321.40			4	7462.43	7464.87	7464.87	7628.63	7618.05
	5	6256.94	6248.02	6247.38	6356.32	6348.54		5	7522.66	7461.24*	7462.59*	7662.36	7653.32
	6	6262.73	6259.20	6258.07	6386.44	6379.32		6	7528.23	7463.14	7463.77	7699.71	7691.91
	7	6272.30	6273.86	6272.41	6420.32	6413.82		7	7537.38	7468.20	7468.34	7740.70	7733.92
	8	6292.08	6292.08	6290.44	6458.06	6452.10		8	7476.47	7476.28	7476.28	7785.38	7779.43
6 - 1	1	6498.72	6470.97	6477.91			9 - 4	1	7750.65	7716.91	7726.04		
	2	6504.99	6465.95	6470.14	6533.04	6522.42		2	7760.00	7712.63	7718.05	7794.12	7780.43
	3	6513.99	6463.52*	6465.85	6553.61	6544.02		3	7773.38	7712.23*	7715.06*	7821.51	7808.46
	4	6463.80	6464.90*	6577.28	6568.78			4	7715.86	7716.93	7716.93	7853.37	7841.27
	5	6497.52	6466.90	6467.19	6604.13	6596.64		5	7749.42	7723.70	7723.58	7889.87	7878.79
	6	6502.66	6472.89	6472.65	6634.23	6627.63		6	7756.86	7735.86	7734.96	7931.14	7921.05
	7	6511.09	6481.84	6481.26	6667.63	6661.77		7	7769.14	7752.48	7751.06	7977.35	7968.15
	8	6493.81	6493.00	6704.40	6699.16			8	7773.69	7771.93	7771.93	8028.61	8020.21
7 - 2	1	6863.94	6834.42	6841.94			5 - 1	1	7913.71	7870.73	7881.68		
	2	6870.98	6829.48	6834.00	6900.82	6889.29		2	7921.12	7860.66	7867.73	7964.65	7949.20
	3	6881.07	6827.45*	6829.92	6923.21	6912.62		3	7931.77	7853.61	7857.99	7993.33	7979.76
	4	6828.46	6829.56*	6949.03	6939.52			4	7849.73	7849.73	7852.31	8025.81	8014.06
	5	6862.68	6832.63	6832.82	6978.40	6969.92		5	7912.25	7849.15*	7850.53*	8062.18	8052.02
	6	6868.39	6840.05	6839.65	7011.40	7003.85		6	7918.35	7851.97	7852.54	8102.50	8093.68
	7	6877.79	6850.80	6850.01	7048.11	7041.35		7	7928.36	7858.27	7858.30	8146.84	8139.11
	8	6864.96	6863.92	7088.60	7082.52			8	7868.11	7867.78	7867.78	8195.25	8188.42

TABLE 3  
(Continued)

$v'-v''$	$K''$	$Q_1/Q_2$	$R_1$	$R_2$	$P_1$	$P_2$	$v'-v''$	$K''$	$Q_1/Q_2$	$R_1$	$R_2$	$P_1$	$P_2$
6-2	1	8344.59	8298.89	8310.72			9-5	1	10 012.82	9956.59	9972.35		
	2	8352.86	8288.59	8296.24	8399.16	8382.39		2	10 025.46	9946.53	9956.66	10 082.48	10 060.71
	3	8364.71	8281.68	8286.39	8430.17	8415.23		3	10 043.53	9941.67*	9947.76	10 124.02	10 103.60
	4		8278.30*	8281.03	8465.35	8452.25		4		9942.23	9945.49*	10 171.72	10 152.98
	5	8343.03	8278.59	8279.99*	8504.84	8493.38		5	10 011.34	9948.41	9949.73	10 225.81	10 208.79
	6	8349.77	8282.68	8283.17	8548.71	8538.67		6	10 021.33	9960.39	9960.37	10 286.51	10 271.10
	7	8360.85	8290.64	8290.52	8597.05	8588.19		7	10 037.87	9978.37	9977.43	10 354.03	10 340.06
	8		8302.56	8302.02	8649.94	8642.06		8		10 002.52	10 000.95	10 428.59	10 415.87
7-3	1	8827.07	8778.31	8791.18			4-1	1	10 286.64	10 211.05	10 230.66		
	2	8836.42	8767.89	8776.20	8885.83	8867.58		2	10 296.02	10 189.71	10 203.05	10 372.88	10 347.29
	3	8849.79	8761.29	8766.39	8919.61	8903.11		3	10 309.52	10 172.11	10 181.04	10 418.36	10 396.54
	4		8758.70*	8761.59*	8958.06	8943.38		4		10 158.48	10 164.38	10 468.96	10 450.50
	5	8825.45	8760.25	8761.64	9001.33	8988.35		5	10 284.77	10 149.01	10 152.83	10 524.77	10 509.13
	6	8832.99	8766.09	8766.46	9049.52	9038.04		6	10 292.52	10 143.81	10 146.22	10 585.86	10 572.51
	7	8845.42	8776.31	8776.00	9102.76	9092.54		7	10 305.25	10 143.00*	10 144.42*	10 652.29	10 640.76
	8		8791.04	8790.25	9161.16	9152.00		8		10 146.65	10 147.39	10 724.13	10 714.06
8-4	1	9375.97	9323.74	9337.90			5-2	1	10 831.32	10 750.97	10 772.10		
	2	9386.72	9313.36	9322.49	9439.66	9419.78		2	10 841.72	10 728.77	10 743.20	10 923.43	10 895.69
	3	9402.10	9307.39	9312.94	9476.87	9458.57		3	10 856.65	10 710.74	10 720.41	10 972.32	10 948.34
	4		9306.02*	9309.09*	9519.37	9502.85		4		10 697.11	10 703.47	11 026.79	11 006.27
	5	9374.36	9309.41	9310.79	9567.36	9552.57		5	10 829.28	10 688.07	10 692.16	11 086.98	11 069.42
	6	9382.95	9317.73	9317.95	9620.99	9607.76		6	10 837.80	10 683.76*	10 686.28	11 152.98	11 137.86
	7	9397.13	9331.11	9330.54	9680.41	9668.53		7	10 851.81	10 684.30	10 685.73*	11 224.87	11 211.73
	8		9349.69	9348.56	9745.77	9735.04		8		10 689.78	10 690.44	11 302.77	11 291.22
3-0	1	9791.12	9719.83	9738.09			6-3	1	11 436.78	11 351.11	11 374.01		
	2	9799.67	9699.34	9711.71	9872.14	9848.48		2	11 448.45	11 328.07	11 343.77	11 535.61	11 505.46
	3	9811.98	9682.25	9690.50	9914.67	9894.74		3	11 465.17	11 309.75	11 320.26	11 588.49	11 562.08
	4		9668.77	9674.24	9961.93	9945.26		4		11 296.35	11 303.24	11 647.54	11 624.65
	5	9789.41	9659.09	9662.66	10 013.99	10 000.00		5	11 434.62	11 288.09	11 292.45	11 712.93	11 693.13
	6	9796.54	9653.32	9655.60	10 070.88	10 059.03		6	11 444.10	11 285.13*	11 287.74*	11 784.80	11 767.60
	7	9808.21	9651.55*	9652.94*	10 132.65	10 122.48		7	11 459.68	11 287.60	11 289.00	11 863.27	11 848.19
	8		9653.85	9654.62	10 199.35	10 190.52		8		11 295.64	11 296.16	11 948.47	11 935.13

which corresponds to a wavelength error greater than 0.01 Å.

Inspection of the chart of the sky spectrum by Broadfoot and Kendall (1968), or of Figs. 4-7 of the current paper together with Table 3, shows that the structure of the OH molecule is such that all the vibration-rotation bands have similar structures. Each  $R_1$  and  $R_2$  branch is

a head at short wavelength. These heads are marked with asterisks in Table 3. They are generally within a few angstroms of each other, and hence these bands are unresolved at resolutions similar to that used here. The resulting blend is marked  $R$  in the figures; its effective wavelength and profile depend critically on the resolution of the spectrograph and the intensity distribution of the various  $R_1$  and

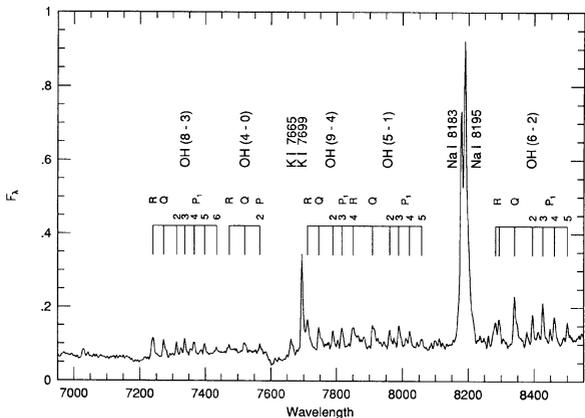


FIG. 5—Sky spectrum at Lick Observatory  $\lambda\lambda$  7000-8500. Units as in Fig. 1.

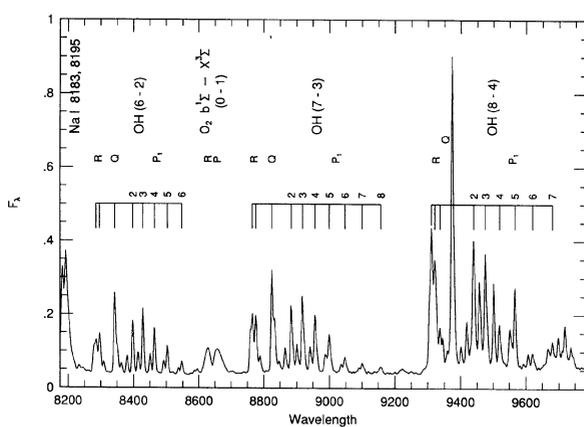


FIG. 6—Sky spectrum at Lick Observatory  $\lambda\lambda$  8200-9700. Units as in Fig. 1.

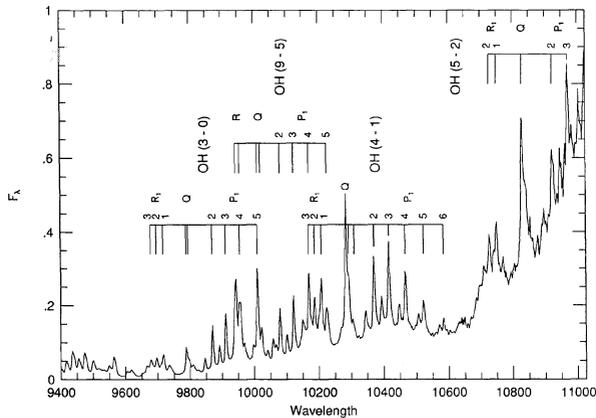


FIG. 7.—Sky spectrum at Lick Observatory  $\lambda\lambda$  9400–11 000. Units as in Fig. 1.

$R_2$  lines. An example is the OH (8–3)  $R$  head at  $\lambda$ 7244 in Fig. 4. At longer wavelengths some of the lower individual  $R$  lines can be resolved; since the  $R_1$  lines are two to three times as strong as the  $R_2$  lines (this depends on the excitation mechanism), generally the  $R_1$  lines are seen. Examples are OH (8–4)  $R_1(1)$ ,  $R_1(2)$ , and  $R_1(3)$  near  $\lambda$ 9700 marked in Fig. 6, which were measured on it and Fig. 7.

The  $Q_1$  and  $Q_2$  lines with the same  $K$  are generally very close in wavelength and unresolved. Again, each  $Q_1$  line is approximately two to three times as strong as the corresponding  $Q_2$ . The intensities in the  $Q$  branches fall off very rapidly with increasing  $K$ , while in OH the wavelengths increase slowly with  $K$ . The result is a blended feature, with a maximum at short wavelength, going down in steps toward longer wavelength, as for instance the OH (7–3)  $Q$  feature at  $\lambda$ 8825 in Fig. 6. (Note that the wavelengths used in this discussion are measured wavelengths, not corrected for the offsets of Table 2, and hence not comparable with Table 3 until this offset has been applied.) Like the  $R$  heads, the  $Q$  branch effective wavelengths depend critically on the resolution of the spectrograph and on the relative intensities of the individual lines. Both the  $R$  heads and the  $Q$  branches are blends, whose accurate wavelengths cannot be determined from calculated values, although of course an effective wavelength may be *measured* with any particular spectrograph, slit, grating, detector, etc. and used as a wavelength standard on other exposures taken with the same instrumental setup.

Finally, the  $P$  branches do not have heads, but instead the individual lines are well separated. Again each  $P_1(K'')$  line is approximately two to three times as strong as the corresponding  $P_2(K'')$ . The wavelengths are such that each  $P_2(K'')$  is at a shorter wavelength than  $P_1(K'')$ , but at a longer wavelength than  $P_1(K'' - 1)$ . In the figures the  $P_1$  lines are marked, and the  $P_2$  lines, which fall between them, can be easily recognized. Almost all these  $P_1$  and  $P_2$  lines are unblended. Hence they are very good lines to measure for wavelength calibration, using the calculated OH wavelengths. The  $P_1$  lines, being stronger, are easier to measure, but particularly at longer wavelengths many  $P_2$  lines can also be used. Typically the strongest  $P$  lines in each band are around  $K'' = 3-5$ , although absorption by  $H_2O$  and  $O_2$  in the atmosphere modifies the relative inten-

sities greatly in some cases, as for instance in the OH (8–4) band in Fig. 6 near  $\lambda$ 9450. A particularly graphic example of this same effect is provided by the K I  $\lambda\lambda$  7665, 7669 doublet, which the HPS spectrum published by Osterbrock et al. (1976) shows with relative intensities  $\sim 1.3:1$ , but in the sky spectrum are modified by absorption to  $\sim 1:5$ . The OH (4–0) band near this same region is so strongly absorbed and modified as to be almost unrecognizable.

To test the suitability of the OH lines for determining the wavelength offset, the measurements originally made to identify the lines in these sky spectra were used. All of the stronger, apparently single lines had been measured. Eliminating the  $R$  heads and  $Q$  branches, plus a very few accidental blends, left a good number of  $P_1$  lines, several  $P_2$ , a few  $R_1$ , and one  $R_2$  line. Solutions were carried out separately for the offset from the  $P_1$  lines alone, all the measured single OH lines (including  $P_1$ ,  $P_2$ ,  $R_1$ , and  $R_2$ ), and for all the lines, atomic and OH. The results are listed in Table 2. It can be seen that wherever there is a good overlap of atomic and OH lines, they agree well in determining the offset. In the longer wavelength regions, the OH lines improve the accuracy of the offset appreciably, and at the longest wavelengths to which the CCD is sensitive, they provide the only determination of it. From the probable errors of the offsets listed in Table 2, it appears that  $P_2$  and  $R$  lines, which on the average are weaker than the  $P_1$  lines, do not add greatly to the accuracy of the determination of the offset, but neither do they weaken it. It certainly is preferable to identify and use the unblended OH lines in determining the wavelength offset, than to ignore them.

It might be possible to use the OH and other sky lines to determine the wavelength scales themselves. However, with the comparison lamps we use, there is a good distribution of lines in wavelength, except for  $\lambda > 10\,410$  Å, while the unblended sky lines, particularly the OH lines, are more concentrated in specific regions. Hence we have used the sky lines only to determine the offsets, or zero-point corrections due to flexure. At longer wavelengths, it may be more convenient and accurate to determine the wavelength calibration directly from the sky lines.

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