THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 106:165–169, 1996 September

INFRARED SPECTRAL ATLASES OF THE SUN FROM NOAO

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Received 1995 November 3; accepted 1996 March 6

ABSTRACT

We have prepared a series of four solar spectral atlases. The atlases illustrate the disk center photospheric spectrum from 0.7 to 22 μm and the sunspot umbral spectrum from 1.2 to 21 μm. The spectra were observed at high resolution ($\lambda/\Delta\lambda \sim 300{,}000$) with the Fourier transform spectrometer (FTS) at the McMath-Pierce solar telescope on Kitt Peak. When possible, solar observations at different air masses and on different days have allowed the less opaque telluric lines to be effectively removed from the program spectrum. The solar lines have been identified by searching the literature on atomic and molecular laboratory spectroscopy and when necessary by additional laboratory spectroscopy. Many new identifications have been made, including numerous SiO and hot water lines in the sunspot spectrum.

Subject headings: atlases — line: identification — Sun: infrared — sunspots

1. INTRODUCTION

In conjunction with our studies of the solar and terrestrial atmospheres, we have made extended analyses of infrared solar spectra obtained with the Fourier transform spectrometer (FTS) (Brault 1978) at the all reflecting, centrally unobscured McMath-Pierce telescope on Kitt Peak (Pierce 1964). This work was done initially for our own use, but we have since organized parts of it into atlas form. Some of the spectra used in these atlases were obtained by other observers for their own purposes, but the spectra are all in the archives of the National Solar Observatory (NSO) and part of the public domain. Spectra obtained at different air masses have allowed us to separate the solar and terrestrial components, provided the signal-to-noise ratio was adequate.

The atlases have been published as NSO technical reports on 8.5 by 11 inch pages with superimposed identifications of most of the stronger solar features. They have proven of value in both solar and stellar studies from ground-based observatories as well as laboratory spectroscopy. A list of the four atlases is given in Table 1. We have had numerous requests for both the paper as well as electronic versions of these atlases. We summarize this material here so that it can be made widely and permanently available through the AAS CD-ROM series, Vol. 7.

2. TELLURIC CORRECTIONS

We have had varying degrees of success in correcting the spectra for telluric absorption. With high signal-to-noise ratio, resolved telluric features and constant water vapor amount, two spectra at substantially different air masses are readily combined to obtain the corrected solar component by invoking Beer's law (Wolfe 1991). In the simple case where spectrum 2, $Sp_\nu(2)$, has twice the air mass of spectrum 1, $Sp_\nu(1)$, the corrected solar component at each frequency is

$$Sol_\nu = Sp_\nu(1) \times Sp_\nu(1)/Sp_\nu(2) ,$$

and the telluric spectrum for the smaller air mass is

$$Tell_\nu = Sp_\nu(2)/Sp_\nu(1) .$$

The telluric absorbers other than water vapor vary only a few percent during a 2 or 3 day observing run, but a complication arises because water vapor can vary by a factor of 2 over the same period. The result is that most spectra show too much water vapor variability to be useful, and those that are acceptable still require adjustments in the effective air masses to obtain compromise best fits to all the telluric absorbers.

3. PHOTOSPHERIC ATLASES

From short wavelengths to long, atlas 1 is "An Atlas of the Photospheric Spectrum from 8900 to 13,600 cm^{-1} (7350–11230 Å)" (Wallace, Hinkle, & Livingston 1993) (see Table 1). This wavelength region is the interface between the infrared and the well-known visible spectrum. Little research has been done on the spectral region around 1 μm because it is a region in which the detector technology switches from the visible to the infrared. The infrared InSb detectors used at the solar FTS are sensitive throughout this region. For this atlas, we were able to combine five spectra obtained by M. Brown for G Stokes in 1983 June. This region is dominated by telluric water vapor absorption, which is well compensated in the atlas. The spectral content is indicated in Table 2. There are more lines of the CN Red system in this region than in all the rest combined, but good lines of metals, C, N, and O, are also present. Our identifications of the strongest features in this atlas are not substantially different from those of previous analyses by Moore, Minnaert, & Houtgast (1966) and Swensson et al. (1970). Previous spectral plots have been given by Minnaert, Mulders, & Houtgast (1940), Delbouille & Roland (1963), Delbouille, Roland, & Neven (1973), and Kurucz et al. (1984).

Next is atlas 2, "An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm^{-1} (1.1–5.4 μm)" (Livingston

[1] NOAO is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

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TABLE 1

ATLAS SUMMARY

Atlas	Content	Wavenumber Range (cm^{-1})	Wavelength Range (μm)	Telluric Correction?
1......	Photosphere	8900–13600	0.74–1.12	yes
2......	Photosphere	1850–9000	1.1–5.4	yes
3......	Sunspot Umbra	1970–8640	1.2–5.1	yes
4......	Sunspot Umbra	717–1233	8.1–14	yes
4......	Sunspot Umbra	470–630	16–21	no
4......	Photosphere	460–630	16–22	no

& Wallace 1991). It is based on three spectra obtained by Livingston in 1990 December and shows very good compensation for all the telluric absorbers. This is the bread-and-butter region of the infrared in which InSb detectors work well, lines are isolated from each other, and the continuum level is well defined. The spectral content is indicated in Table 3. This region has hundreds of CN Red system lines at short wavelengths, hundreds of lines in the CO vibration-rotation bands, and lesser numbers of lines in the OH vibration-rotation bands. Figure 1 gives an example of the observed spectrum and the extracted solar component copied from the digital files and with identifications added. Previous identifications in this region have been by Mohler (1955). Many of the features we labeled as "unid" in NSO paper version of the atlas have since been identified by Geller (1992). Other spectral plots covering part or all of this region have been produced by Mohler et al. (1950), Delbouille et al. (1981), and Farmer & Norton (1989), the latter obtained from the shuttle Challenger.

TABLE 2

IDENTIFIED LINES IN ATLAS 1: PHOTOSPHERE, 8900–13600 cm^{-1} (7350–11230 Å)

Atom or Molecule	Number of Lines	Wavenumber Range (cm^{-1})	Wavelength Range (Å)
H I..............	7	9140–11425	8750–10938
He I.............	1	9231	10830
C I..............	30	9296–13372	7476–10754
N I..............	8	9884–13386	7468–10115
O I..............	8	10789–12863	7772–9266
Na I	5	9227–12217	8183–10835
Mg I............	51	9060–13534	7387–11035
Mg II	9	9128–12692	7877–10952
Al I[a]	15	9179–13580	7362–10891
Si I.............	171	8925–13559	7373–11201
P I..............	10	8940–10495	9526–11183
S I	34	9399–13018	7680–10637
K I..............	4	9070–13043	7665–11022
Ca I.............	30	9189–12139	8236–10880
Ca II	11	10066–12189	8202–9932
Ti I	68	9278–13587	7358–10775
Ti II.............	5	10805–13592	7355–9252
Cr I.............	42	8961–13591	7356–11156
Mn I............	5	11437–11490	8701–8741
Fe I.............	489	8991–13600	7350–11119
Fe II	21	8986–13553	7376–11125
Co I	21	11680–13530	7389–8559
Ni I.............	58	9105–13543	7382–10980
Cu I	2	12354–12602	7933–8092
Zn I.............	1	9044	11054
Sr II.............	3	9159–9961	10036–10915
CN $\Delta v = 0$......	138	8903–9150	10926–11229
CN $\Delta v = 1$......	421	9354–10975	9109–10688
CN $\Delta v = 2$......	390	11222–12699	7872–8909
CN $\Delta v = 3$......	27	13182–13583	7360–7584

[a] Mislabeled Al II in the NSO paper version of the atlas.

TABLE 3

IDENTIFIED LINES IN ATLAS 2: PHOTOSPHERE, 1850–9000 cm^{-1} (1.1–5.4 μm)

Atom or Molecule	Number of Lines	Wavenumber Range (cm^{-1})	Wavelength Range (μm)
H I	10	2149–7799	1.282–4.652
C I.................	55	2687–8604	1.162–3.721
Na I	9	2573–8767	1.140–4.043
Mg I...............	57	2433–8676	1.152–4.109
Al I	13	2556–7841	1.275–3.911
Si I	121	2413–8841	1.131–4.143
S I	29	3208–8777	1.139–3.116
K I	7	6591–8552	1.169–1.517
Ca I	35	2463–8362	1.196–4.059
Ca II...............	8	4665–8444	1.184–2.143
Ti I	30	4117–8474	1.180–2.428
Cr I................	27	3159–8961	1.116–3.165
Mn I	10	6550–7750	1.290–1.526
Fe I................	910	2339–8990	1.112–4.167
Ni I................	99	2869–8672	1.159–3.485
Zn I	1	7659	1.305
CN $\Delta v = -1$.....	165	6361–7102	1.408–1.572
CN 0–0...........	188	8018–9000	1.111–1.247
CO $\Delta v = 1$	Uncounted	1851–2194	4.557–5.401
CO $\Delta v = 2$	Uncounted[a]	3999–4360	2.293–2.500
OH 1–0...........	37	2730–3287	3.041–3.662

[a] Files lost in disk crash

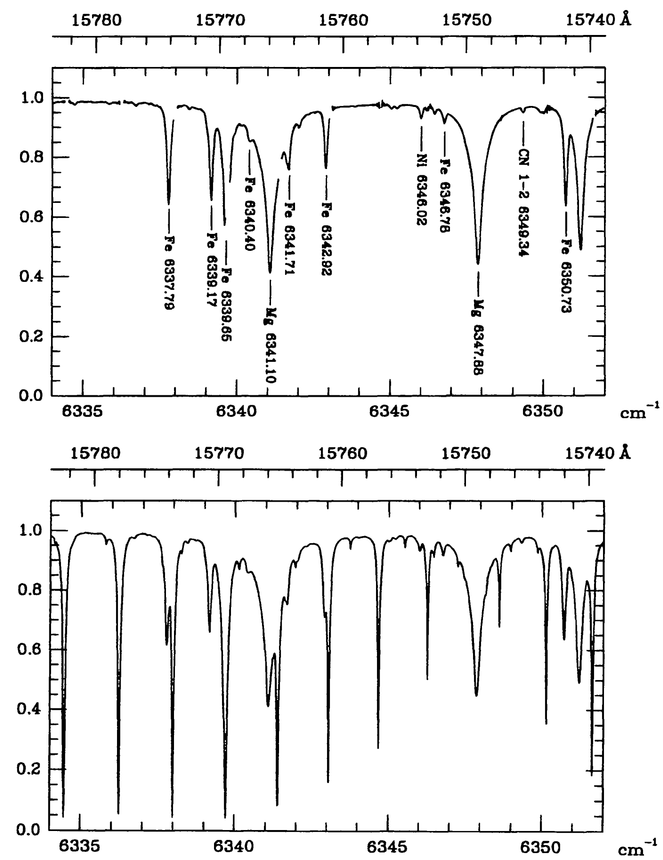

FIG. 1.—An example of observed and corrected photospheric spectra from atlas 2 (Livingston & Wallace 1991). A section of one of the observed spectra given in the bottom panel shows both solar lines and telluric lines of CO_2. The top panel shows the recovered solar component. The gaps and the occasional noise bursts adjacent to the gap results when the optical depth in the telluric lines prevents adequate recovery of the solar spectrum.

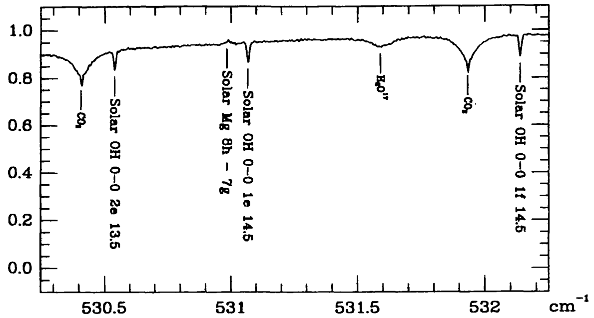

FIG. 2.—A section of the photospheric spectrum from atlas 4 (Wallace et al. 1994) from 18.78 to 18.85 μm. Of particular interest is the solar Mg line at 531.0 cm^{-1}. No correction was made for the telluric lines in this part of the spectrum. The CO_2 and $H_2{}^{17}O$ lines are telluric.

The next spectral region available to ground-based observers is the 8–22 μm window. The part from 460 to 630 cm^{-1} (16–22 μm) is in atlas 4 (Wallace, Livingston, & Bernath 1994). This atlas contains, as an afterthought, what were for some time the best spectra available in this difficult region in which the solar flux is decreasing and absorption by terrestrial water vapor is increasing. These are the sum of eight spectra obtained originally by J. Brault and R. Noyes in 1982 March. The signal-to-noise ratio in this region is not high enough to allow an adequate separation of the solar and telluric components. Other Kitt Peak spectra in this region taken during the warm part of the year tend to be obscured by water vapor. The strongest clear solar features (see Table 5), outside of the lines of the pure rotation bands of OH, and H (8–7) line at 524.6 cm^{-1} and the Mg (8*h*–7*g*) line at 531.0 cm^{-1}. The spectra were described by Brault & Noyes (1983); the identification of the Mg line and others was by Chang & Noyes (1983). A section showing the Mg line is given in Figure 2.

At wavelengths longer than about 22 μm, we on Kitt Peak are usually unable to observe the solar spectrum because of water vapor absorption. Observations from Jungfraujoch (altitude 3.58 km as opposed to Kitt Peak at 2.12 km) reported by Farmer et al. (1994) have less water vapor and extend to 35 μm. ATMOS spectra (Farmer & Norton 1989), obtained from Spacelab 3, cover 2.1 to 15.5 μm without large gaps due to telluric absorption bands.

4. SUNSPOT ATLASES

In the spectra of sunspots, the atomic lines are generally broadened or split by the Zeeman effect, and many are difficult to recognize for that reason. Molecular features, on the other hand, are not so much influenced by the Zeeman effect and are generally stronger than the same lines in the photosphere. Also, the Zeeman effect in molecular spectra is usually smaller for the vibration-rotation bands than for electronic transitions.

Spectra exist for the production of an atlas in the 1 μm region which contains the very interesting FeH band and the CN Red system. Some of the CN lines show shifts due to the Zeeman effect (Harvey 1973), and some of the FeH lines show a clear Zeeman doubling. However, to date we have not undertaken an atlas for this region.

The most heavily observed region is covered by atlas 3, "An Atlas of a Dark Sunspot Umbral Spectrum from 1970 to 8640 cm^{-1} (1.16–5.1 μm)" (Wallace & Livingston 1992). It is derived from two umbral spectra obtained by Livingston in 1991 July. The compensation for telluric absorption is good but not as good as in atlas 2. The spectral content (see Table 4) shows that atomic features are present but dominated by the vibration-rotation bands of CO, OH, H_2O, HCl, and HF and the CN Red system. Some of the Q-branch lines of OH show Zeeman doubling. Toward the long-wavelength end of this atlas, the density of weak unidentified lines increases markedly. The previous work in this region was by Hall (1970, 1974).

Our longest wavelength sunspot atlas is atlas 4, "An Atlas of the Sunspot Spectrum from 470 to 1233 cm^{-1} (8.1–21 μm) and the Photospheric Spectrum from 460 to 630 cm^{-1} (16–22 μm)" (Wallace et al. 1994). The primary sunspot spectrum here was also obtained by J. Brault and R. Noyes in 1982 March.

In the short-wavelength region from 717 to 1233 cm^{-1} (8.1–14 μm), the best we were able to do for correction due to telluric absorption was division of the umbral spectrum by the penumbral spectrum of the same spot. The penumbral spectrum is similar to a photospheric spectrum except that the atomic lines show a Zeeman effect. In the long-wavelength region from 470 to 630 cm^{-1} (16–21 μm), the penumbral spectrum did not have high enough signal-to-noise ratio to give a useful division.

The umbra observed for atlas 4 was, rated among other sunspot umbra that have been studied, dark and cold, producing lines much deeper and clearer than in other spectra that we have seen. We estimate an excitation temperature of 3200 K from SiO, as opposed to the more common value of 3700 K. This whole region is filled with lines. For example, we count 54 lines in the 2 cm^{-1} interval 789–791 cm^{-1}, and by extrapolation we estimate that more than 10,000 lines need to be accounted for in the observed 8.1–21 μm interval.

The $\Delta v = 1$ SiO vibration-rotation bands are the only feature in this region that had already been identified. These

TABLE 4

IDENTIFIED LINES IN ATLAS 3:
SUNSPOT UMBRA, 1970–8640 cm^{-1} (1.6–5.1 μm)

Atom or Molecule	Number of Lines	Wavenumber Range (cm^{-1})	Wavelength Range (μm)
H I	1	7799	1.282
Na I	9	2473–8115	1.232–4.043
Mg I	19	2586–8452	1.183–3.866
Al I	9	2556–7618	1.312–3.911
Si I	24	2704–8342	1.198–3.697
K I	7	6591–8552	1.169–1.517
Ca I	31	4381–8496	1.177–2.282
Sc I	6	4349–4583	2.181–2.299
Ti I	44	4117–8465	1.181–2.428
Cr I	6	7353–8610	1.161–1.320
Mn I	9	6550–7750	1.290–1.526
Fe I	108	4420–8623	1.159–2.262
Ni I	4	5880–7730	1.293–1.700
CN 0–0	59	8092–8635	1.158–1.235
CO $\Delta v = 1$	342	1971–2199	4.546–5.072
CO $\Delta v = 2$	469	4002–4360	2.293–2.498
CO $\Delta v = 3$	489	5690–6418	1.558–1.757
^{13}CO $\Delta v = 1$	120	1971–2198	4.548–5.072
^{13}CO 2–0	19	4211–4263	2.345–2.374
$H^{35}Cl$ 1–0	10	2516–2799	3.572–3.973
$H^{37}Cl$ 1–0	6	2570–2650	3.772–3.890
HF 1–0	10	4039–4368	2.289–2.475
10 H_2O Bands	892	1982–7449	1.342–5.004
OH $\Delta v = 1$	265	2397–3194	3.130–4.171
OH $\Delta v = 2$	397	5541–6866	1.456–1.804
SiO $\Delta v = 2$	508	2381–2497	4.004–4.199

TABLE 5

IDENTIFIED LINES IN ATLAS 4:
SUNSPOT UMBRA, 470–1233 cm^{-1} (8.1–21 μm) AND
PHOTOSPHERE, 460–630 cm^{-1} (16–22 μm)

Atom or Molecule	Number of Lines	Wavenumber Range (cm^{-1})	Wavelength Range (μm)
Sunspot Umbral Section			
HF 0–0	10	553–1004	9.959–18.081
H_2O................	4007	482–1233	8.108–20.744
OH $\Delta v = 0$	210	478–997	10.025–20.929
^{28}SiO $\Delta v = 1$......	1713	898–1233	8.108–11.136
^{29}SiO $\Delta v = 1$......	411	986–1233	8.110–10.142
^{30}SiO $\Delta v = 1$......	311	997–1233	8.110–10.023
Photospheric Section			
H I	1	525	19.057
Mg I.................	1	531	18.828
OH $\Delta v = 0$	30	497–623	16.041–20.110

bands were analyzed by Glenar et al. (1985) in a warmer sunspot spectrum, which showed fewer lines than ours. The additional lines required remeasurement and an extended analysis, which resulted in identifications of all SiO lines from 898 to 1233 cm^{-1} (Campbell et al. 1995). The observed SiO transitions included the 1–0 to 13–12 vibrational bands for the main ^{28}SiO isotopomer and the 1–0 to 6–5 bands for the minor ^{29}SiO and ^{30}SiO isotopomers.

Approximate positions for the pure rotational OH lines were obtained from a variety of sources, including remeasurement of the photospheric spectrum. A few weak lines of the pure rotational HF fundamental band (Le Blanc, White, & Bernath 1994) are also present.

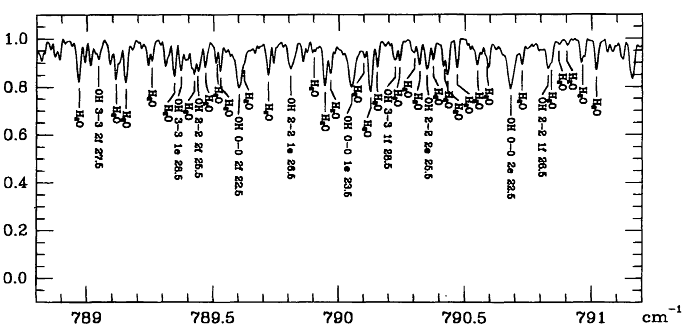

FIG. 3.—A section of the umbral spectrum from 12.636 to 12.674 μm from atlas 4. The unidentified lines in this region are probably H_2O. The telluric lines were divided out with a penumbral reference spectrum similar to a photospheric spectrum.

A larger problem than that posed by SiO is the identification of the solar H_2O lines. The only previous identification of the water molecule in a sunspot umbra was by W. S. Benedict (Hall 1970, 1973) in the 4040–5060 cm^{-1} region (2.0–2.5 μm). Positions for the lines in the 8.1–21 μm region calculated from published laboratory work were inadequate. Studies based on high-precision low-temperature measurements did not include enough high-excitation lines, while those based on high-temperature flames at atmospheric pressure are not extensive enough or of high enough precision because of pressure shifts. To overcome these limitations, Bernath and coworkers have obtained spectra of H_2O at low pressure in high-temperature furnaces with both the Brault FTS on Kitt Peak and a Bruker FTS at Waterloo. With these, we have found several thousand lines in common with the umbra (see Table 5). A more complete summary of the hot water problem is given by Wallace et al. (1995). A full analysis is going to require a detailed study of the laboratory spectra. We estimate that between 2000 and 4000 more lines remain to be identified in this region, and we expect that most of them will prove to be H_2O.

A small section of this spectrum, which is dominated by H_2O, is displayed in Figure 3. In the section from 789 to 791 cm^{-1}, 40 features are labeled, mostly H_2O, out of the total estimate of 54.

No sunspot spectra have been obtained at wavelengths longer than 21 μm.

5. AVAILABILITY OF THE ATLASES

Paper versions of the atlases are available at no charge from the Office of the Director of the National Solar Observatory. The digital form is available on Volume 7 of the AAS CD-ROM series. The README files contain a description of the file structure as well as simple MONGO code for plotting pages of the atlas without the line identifications. Line identifications are given separately in the line list files.

P. B. wishes to thank the NASA Laboratory Astrophysics Program for support.

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