

# HIGH- $n$ HYDROGEN LINES IN SOLAR INFRARED SPECTRA FROM BALLOON-BORNE, MAUNA KEA, AND ATMOS OBSERVATIONS

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**Abstract.** This paper reports the observation of high- $n$  lines in emission from  $n = 12-11$ ,  $13-12$ ,  $14-13$  and  $16-15$  Rydberg transitions in H, Mg and Si in solar far IR spectra taken from balloon altitudes, in which the H I line intensities are found to exceed those from the heavier elements. Tentative identification is also made of the  $n = 8-7$  hydrogen line in emission on  $20 \mu\text{m}$  spectra taken from Mauna Kea. The characteristics of the hydrogen lines are compared with lower- $n$  transitions seen in the Space Shuttle *ATMOS* spectra, in which Brackett, Pfund and  $n = 6$  lines with  $\Delta n = 1, 2, 3$  and  $4$  are seen as broad absorption features, while the  $n = 7-6$  line shows a small emission peak within a broader absorption line and the  $n = 9-7$ , and possibly the  $11-8$ , transitions appear as weak emission lines. These results indicate that the transformation from absorption to emission occurs at longer wavelengths for hydrogen lines than for those of heavier elements.

**Key words:** H I – infrared: stars – line: formation – line: identification – Sun: atmosphere

## 1. Background

The discovery in the early 1980's of intense emission lines in the  $10 \mu\text{m}$  solar spectrum (Murcray *et al.*, 1982, Brault and Noyes, 1983) and their subsequent identification as lines from  $n = 7-6$  Rydberg transitions in Mg I, Si I and Al I (Chang and Noyes, 1983; Chang, 1984) has opened up a new and important avenue in the study of the sun's high photosphere and chromosphere. These initial discoveries prompted a search for equivalent lines in far IR spectra taken from balloon altitudes with the University of Calgary balloon-borne telescope and the tentative identification of complexes of emission lines from  $n = 16-15$  and  $14-13$  (Boreiko and Clark, 1986).

In the meantime, the *ATMOS* spectrometer was flown on the Space Shuttle in 1985 to study the Earth's high atmosphere by rapid absorption spectroscopy during occultation of the Sun by the Earth's atmosphere. During these experiments, *ATMOS* also produced a series of superb high-resolution near-IR spectra of the Sun taken at high elevation angles which are almost devoid of atmospheric absorption features but which show a wealth of solar spectral lines. Among these, a series of hydrogen lines from various transitions are clearly seen to follow a trend from strong absorption at  $n = 5-4$  to weak emission at  $n = 9-7$ .

In view of this trend within the limited spectral range of *ATMOS* and the obvious importance to solar atmospheric modeling of further and more extended spectral information of this kind, a search for lines from the  $n = 8-7$  transitions in the solar spectrum was also undertaken through the highly structured and variable  $20 \mu\text{m}$  atmospheric window from Mauna Kea.

## 2. Experimental Details

The 0.23 m University of Calgary balloon-borne solar telescope (Boreiko, 1985; Boreiko and Clark, 1987) was flown to altitudes of 30-35 km from Gimli, Manitoba, Canada in 1982 and 1985 to measure the far IR ( $50$  and  $160 \text{ cm}^{-1}$ ) spectrum of the central 8 arc minute region of the Sun. A rapid-scanning Michelson interferometer with an apodized resolution of  $0.015 \text{ cm}^{-1}$  was used to make these radiometric measurements. Absolute calibration was performed with reference to a 1160 K black-body source, under the same thermal conditions as for the solar measurements. Direct measurements of the background were obtained by offsetting the telescope by several solar diameters.

A Michelson interferometer (Naylor and Clark, 1986), fed by a heliostat and 0.15-m optics, was used on Mauna Kea (4200 m) in Dec 1989 to explore the  $20 \mu\text{m}$  ( $490-540 \text{ cm}^{-1}$ ) solar and atmospheric spectra to an apodized resolution of  $0.01 \text{ cm}^{-1}$  and to search for solar atomic lines from  $n = 8-7$  transitions.

The *ATMOS* instrument and operating mode are described in Farmer and Norton (1989). Individual spectra between  $600$  and  $4700 \text{ cm}^{-1}$  ( $2.3-16 \mu\text{m}$ ), were measured to  $0.01 \text{ cm}^{-1}$  apodized resolution with a rapid-scanning Fourier transform spectrometer from the Space Shuttle, at both high and low tangent angles through the Earth's atmosphere.

## 3. The Spectra

### 3.1. BALLOON MEASUREMENTS

The balloon-borne spectra were analyzed using standard Fourier spectroscopy techniques. Notable features of the spectra were several emission line complexes along with the expected absorption lines from stratospheric molecules, particularly  $\text{H}_2\text{O}$  and  $\text{O}_3$ . Sections of these spectra have been analyzed, corrected for instrument transmission and calibrated in terms of solar continuum intensity to yield the emission complexes shown in Figures 1a-d. Stratospheric absorption lines are seen to dominate the  $n = 14-13$  and  $16-15$  regions but are absent or weak in the other two regions. The expected positions of H, Mg and Si lines from  $\Delta n = 1$  transitions as well as positions and relative heights of the stratospheric absorption lines are shown on these graphs. It can be seen that the strongest feature in each complex is a peak at the H line position. At the longer wavenumbers, there is evidence of both the Mg line and the 6-fold emission from Si, although the positions of these features do not appear to correspond precisely with the expected line positions.

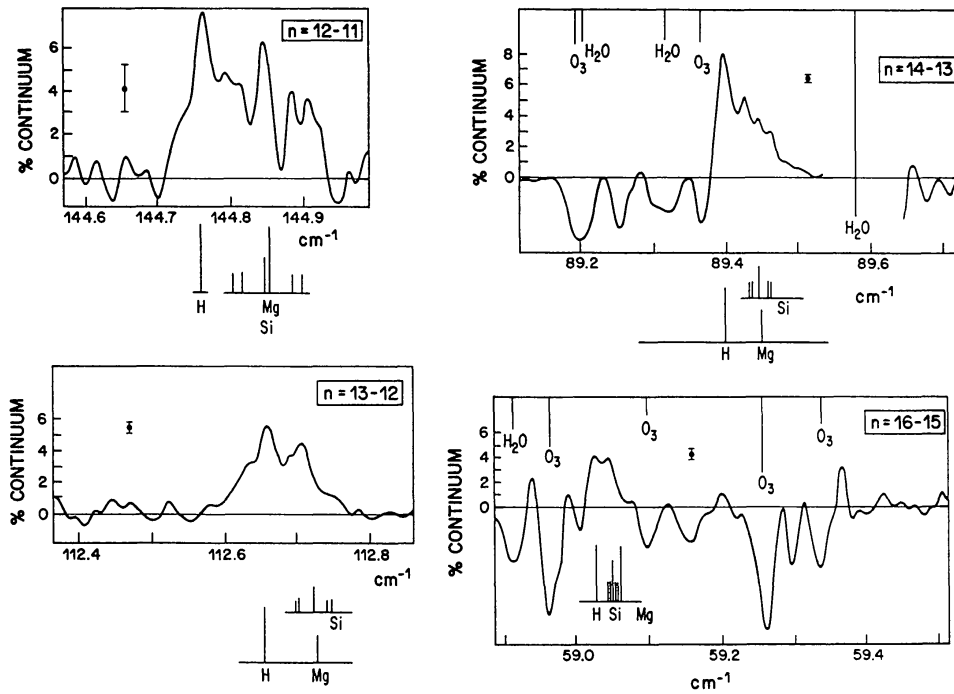


Fig. 1. *a-d*: Emission line complexes from transitions between high- $n$  states of H, Mg and Si. Error bars represent  $\pm 1$  standard deviation on the mean continuum intensity.

### 3.2. 20 $\mu\text{m}$ SPECTRA FROM MAUNA KEA

Figure 2 shows sections of two representative solar spectra between 523 and 526  $\text{cm}^{-1}$ , taken under very dry conditions, along with the FASCOD/HITRAN synthetic transmission spectrum, which indicates the positions and strengths of major absorption features. An emission peak is seen on each of these spectra, of intensity about  $4 \pm 1.5\%$  of continuum, at the position of the  $n = 8-7$  transition of H I. Equivalent Mg I and Si I lines from this transition are predicted to occur on the steep side or in the center of the major H<sub>2</sub>O line at 526  $\text{cm}^{-1}$ . No such features have yet been identified. The large uncertainty in measured H I line intensity reflects the lack of accurate knowledge of the underlying spectral envelope. Thus, this result is regarded as preliminary only and a final conclusion must await further calibration.

### 3.3. ATMOS SPECTRA

The sequence of H I lines from high level transitions between  $n = 5-4$  to  $9-7$  have been measured on the *ATMOS* spectra. Of particular interest are the 2 sections of the spectrum shown in Figure 3 for lines showing the transition between absorption and emission. The  $n = 7-6$  line shows a small emission peak superimposed upon a broader, offset, absorption feature while the  $n = 9-7$  line is a weak, broad, emission peak upon which two solar OH absorption lines are superimposed.

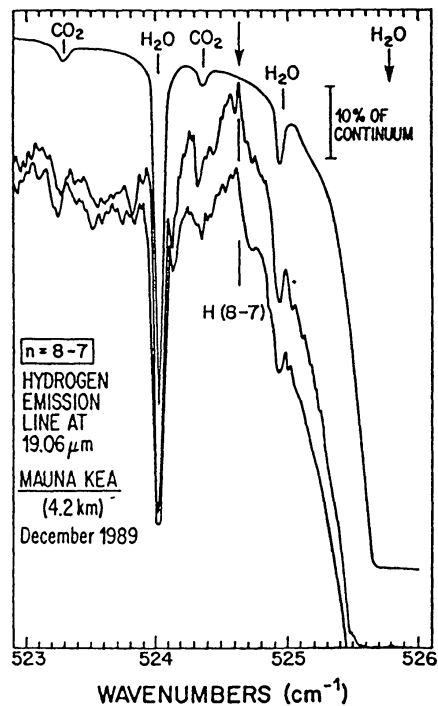


Fig. 2. Two representative 20  $\mu\text{m}$  solar spectra taken from Mauna Kea, Hawaii.

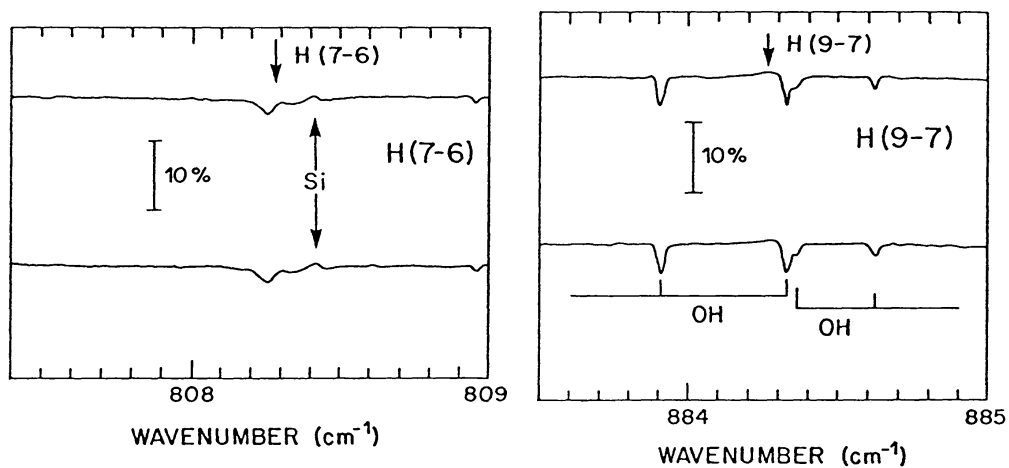


Fig. 3. Two sections of the *ATMOs* spectra, showing emission lines from  $n = 7-6$  and  $9-7$  transitions in H I.

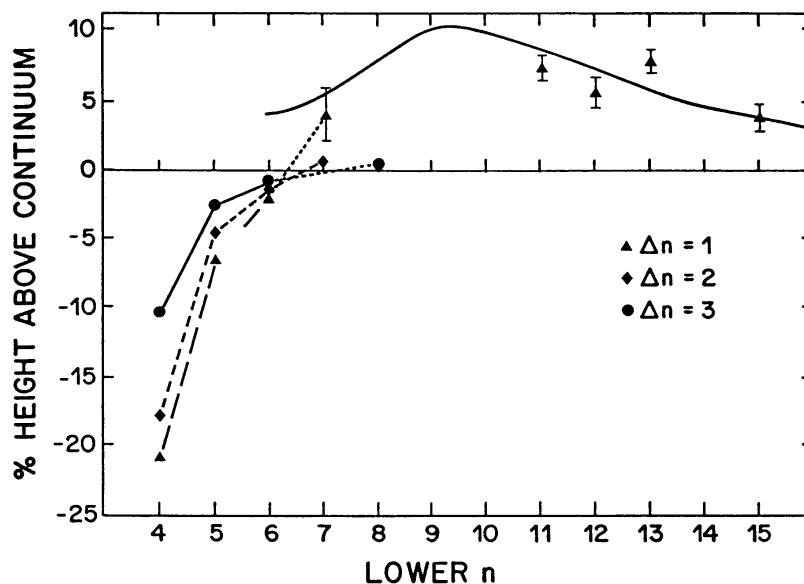


Fig. 4. Summary of the H I line peak intensities as a function of lower  $n$  value. The solid line above  $n = 7$  shows the prediction of Hoang-Binh (1982).

#### 4. Discussion and Conclusions

Figure 4 summarizes the trend of line depth or height of all of the observed H I recombination lines as a function of lower  $n$  value. The higher  $n$ -value lines are compared with the model prediction of Hoang-Binh (1982). The uncertainties in these line intensities arise from the correction for atmospheric and instrumental background emissions. There is a clear trend from absorption to emission in this H line sequence where the transition occurs at a higher  $n$  than for the Mg I lines, a fact which has been successfully explained by the modeling of Carlsson *et al.* (1992). Figure 5 shows the equivalent trend in line width, from very broad to relatively narrow H I lines as  $n$  increases, in the *ATMOS* data. The high- $n$  emission lines are also relatively narrow, with FWHM of about  $0.05 \text{ cm}^{-1}$ , but with relatively wide outer wings, particularly on the  $n = 12-11$  and  $13-12$  H I lines. This trend, from deep, wide absorption features to relatively narrow emission peaks, with the cross-over for  $\Delta n = 1$  between  $n = 7-6$  and  $8-7$ , and the relative behavior of the H I and heavier element lines, has been explained, at least qualitatively, by Carlsson *et al.*, (1992) and, in these proceedings, by Rutten and Carlsson and by Avrett. The further refinement of line intensity and width measurements of these and other high- $n$  lines should serve to tighten the solar atmospheric model parameters within the line source region.

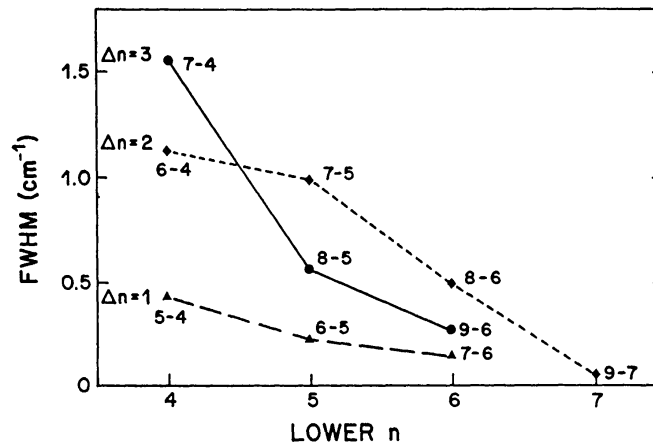


Fig. 5. Line width as a function of lower  $n$  for lines in the *ATMOS* spectrum.

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