Precise Stellar Radial Velocities
ASP Conference Series, Vol. 185, 1999
J. B. Hearnshaw and C. D. Scarfe, eds.

Convective Lineshifts in the Infrared Region of the Solar Spectrum

Devon Hamilton

Department of Astronomy, University of Toronto, 60 St. George St., Toronto, Ont., M5S 3H8

J. B. Lester

Erindale College, University of Toronto

Abstract. Convective motions in the photospheres of the Sun and solar-type stars can be studied using spectral line asymmetries via line bisectors and line shifts. Over the past few years there has been an improvement in the precision of the line positions for Fe I, CO and OH. These improved positions can be combined with recent high resolution infrared spectra of the Sun to examine how their convective line asymmetries behave with respect to observable line parameters, such as wavenumber and depth. We have completed a survey of convective line shifts for over 650 Fe I lines, 1320 CO lines and 80 OH lines, between 0.9 and 11 μm. The behavior of the distributions of these features, with respect to observed characteristics, is examined. The use of different species allows for an exploration of convective motions at different levels in the solar atmosphere. The large size of the sample allows for a more complete statistical understanding of the distributions. This work complements surveys of line asymmetries in the visible region of the Solar spectrum, and provides a foundation for further studies of convective motions in the spectra of other stars.

1. Motivation

Recent numerical simulations and theoretical models are challenging our traditional conceptions of convection in stellar atmospheres (Spruit 1997). These new models require improved observational diagnostics to test their predictions. Shifts in line cores reflect the convective motions (Dravins 1985), but they do require high precision laboratory wavelengths. These are now available, and it has been shown previously (Hamilton & Lester 1998, 1999), that it is possible to observe these lineshifts in the visible spectrum of the Sun at a wide range of resolutions.

Past work on the Solar spectrum has concentrated on studying the line asymmetries of Fe I and Fe II in the visible part of the spectrum (Dravins, Lindegren, & Nordlund 1981; Dravins, Larsson, & Nordlund 1986; Hamilton & Lester 1998). Here, we examine solar convection using line positions of Fe I, CO, OH and CN in the near-infrared and infrared.

2. Data and Analysis

• **Fe I**: Laboratory wavenumbers and χ_l for Fe I are available from Nave et al. (1994). Lines with positional uncertainties of < 0.005 cm^{-1} were examined in three solar atlases. Blends were excluded. Any remaining abnormal lines were checked against the lists of Ramsauer, Solanki, & Biémont (1995), Solanki, Biémont, & Mürset (1990), and Swensson et al. (1970), as well as against synthetic spectra computed with Kurucz's Atlas9 suite.
• **CO**: Calculated line positions for the fundamental and first overtone transitions for CO were taken from Goorvitch (1994) and lines were selected as described for Fe I.
• **CN and OH**: Laboratory wavelength positions were obtained from Abrams et al. (1994) and Davis (1997) and were screened as above.
• **Atlases**: Three primary atlases, each recording central intensity with an FTS, were used in this study: the KPNO NIR (Wallace, Hinkle, & Livingston 1993), the KPNO IR (Livingston & Wallace 1991), and the NASA ATMOS (Abrams et al. 1996). Each atlas was calibrated to a common wavelength scale.

The number of unblended lines of each species were: 685 Fe I, 1323 CO, 179 CN, and 81 OH. For each line, the position was calculated by averaging the bisectors of the two lowest non-minima points. These positions were then converted to radial velocities relative to the laboratory position using

$$V(\mathrm{m/s}) = c[k_\mathrm{l}(\mathrm{cm}^{-1}) - k_\mathrm{s}(\mathrm{cm}^{-1})]/k_\mathrm{s}(\mathrm{cm}^{-1}) - 636^1 \quad (1)$$

3. Results

3.1. Fe I

Wavenumber Dependence
• At a given line depth the lineshifts of lines in the NIR show a clear dependence on wavenumber (Fig. 1), just as in the visible (Hamilton & Lester 1998). The size of the dependence decreases with decreasing wavenumber, disappearing by the 5 μm region. *The wavenumber dependence could be reflecting the contrast* between granules and the intragranular lanes.
Linedepth Dependence
• The lineshifts have a clear dependence upon linedepth (Fig. 1), similar to the that found for Fe I lines in the visible (Hamilton & Lester 1999).
• In the NIR, each particular wavelength has a distinct offset, while retaining a similar linedepth-lineshift distribution. Much of the scatter for a particular depth in the overall distribution is due to this 'overlap' of the different wavelength bins.

3.2. CO

Unlike the Fe I in the near-infrared, the CO lineshifts show very little scatter. It is actually possible to 'follow' a particular transition in parameter-velocity

[1]The factor of 636 is the sun's gravitational redshift in m/s.

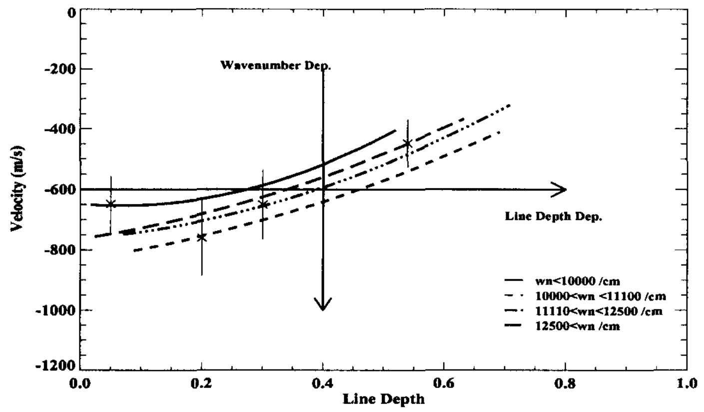

Figure 1. The wavenumber and line depth dependences of the Fe I distribution in the NIR. The curves are parabolic fits to four wavenumber bins. The error bars are the standard deviations for each one of these bins.

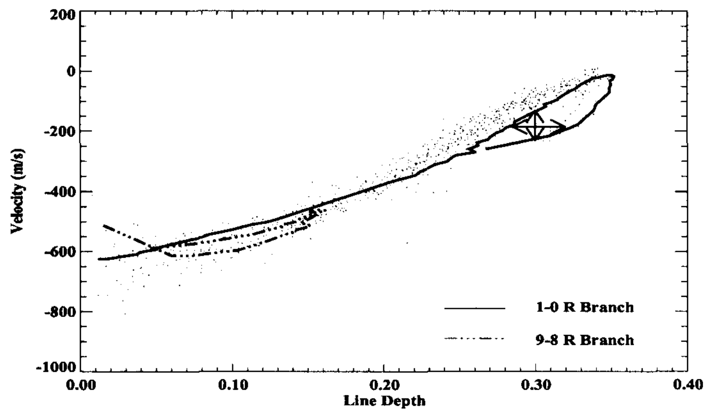

Figure 2. The line depth - velocity lineshift distribution for CO δv = 1 in the IR. The 9-8 and 1-0 R Branch transitions are traced out. Note how the distribution for particular transitions 'double back'.

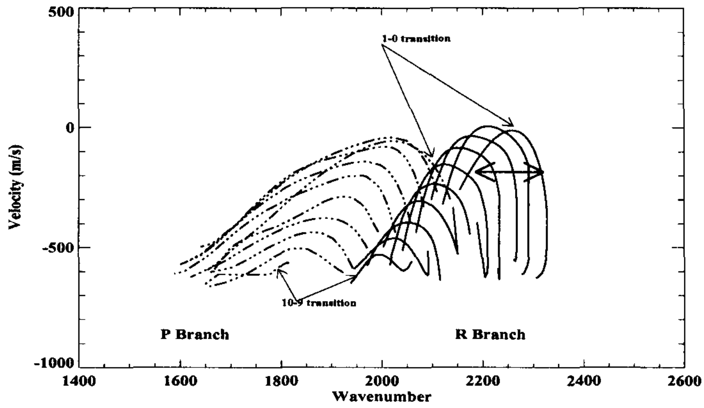

Figure 3. The wavenumber-velocity lineshift distribution for CO δv = 1. The curves trace out fits (in order of J) to all the points for the band transitions.

space (see Figs. 2-4). The δv = 2 sample is of limited use in the Solar spectrum because almost all of the lines are weak, but the δv = 1 sample has a very wide range of linedepths.

Linedepth Dependence

- The velocity-linedepth distribution is similar in shape to that of Fe I, but much narrower and steeper. Most of the width of the distribution (at a particular linedepth) can be accounted for by the different transitions (e.g. 2-1 vs 1-0) and branches (Fig. 2).
- If any particular transition is traced out (by J), its distribution can be seen to 'double back'. For a particular line depth and transition there may be two different corresponding lineshifts, the lines with lower J having larger shifts towards the blue.

Wavenumber Dependence and Energy Dependence

- For a given transition of δv=1 CO, the wavenumber-velocity and energy-velocity distributions are shaped like arches. As before, we see a duplication in wavenumber and in lower energy level for particular velocities (Figs. 3 and 4).
- If we cull all the lines with similar J-values (e.g. $J > 45$), no significant dependence on wavenumber is seen.

4. Conclusions and Future Work

The dependence of the Fe I lineshifts upon wavenumber decreases with increasing wavelength. However, the depth sensitivity continues, for both Fe I and CO. The CO results show that the linedepth sensitivity is extremely strong and that the lower excitation energies and the particular transitions within the bands influence the shifts of the line cores. Future work will involve using these species to examine convective motions in stars both slightly hotter and cooler than the Sun.

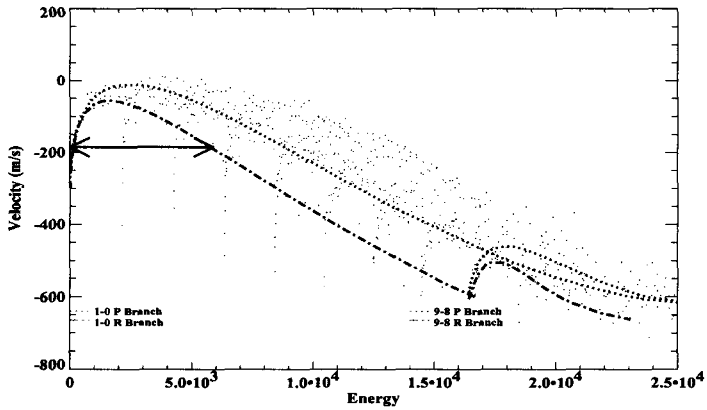

Figure 4. The energy-velocity lineshift distribution for CO $\delta v = 1$. The curves trace out sample transitions in order of J.

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Discussion

Hearnshaw: The solar continuous opacity has a minimum at about 1.6 μm, so convective cells are presumably more visible at that wavelength. Is the wavelength effect that you discussed related to the continuous opacity?

Hamilton: We do see a wavelength dependence in the visible, and have shown that it is still present in our Fe I data. The dropoff can also be related to contrast, however. I would expect it to vanish beyond 1.6 μm for Fe I. I plan to go back and look for the inversion in the OH lines.