INFRARED HELIOSEISMOLOGY: DETECTION OF THE CHROMOSPHERIC MODE

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1. INTRODUCTION

We have observed solar oscillations using a new instrumental technique in a relatively unexplored region of the solar spectrum. We obtained a 2-day sequence of line profiles, at 30 second intervals, for a pure rotation line of OH at 11.065 μm, using a laser heterodyne spectrometer to view a 2 arc-sec portion of the quiet Sun at disk center. The continuous opacity of the solar atmosphere increases with wavelength longward of 1.6 μm, so 11 μm lines are formed in the upper photosphere, near h = 250 km. In this region the OH rotational transitions have $\Delta J=1$ collisional rates which are two orders of magnitude larger than their radiative rates. Hence the OH lines have source functions which are equal to the Planck function, and the high spectral purity provided by the laser heterodyne technique makes their line profiles especially appropriate for investigating the dynamics of the solar atmosphere. We have recently reported (Deming et al. 1986) that oscillations in this OH line show evidence of a resonance due to a cavity in the solar chromosphere.

2. CHROMOSPHERIC MODELS AND THE CHROMOSPHERIC RESONANCE

It has long been known that oscillatory power shifts to higher frequencies with increasing height in the solar atmosphere (e.g. Frazier 1968). However, little attempt has been made to relate observations of higher frequency oscillations to the eigenfrequencies of model chromospheres. Most of the relevant observations are of relatively short duration, but are probably sufficient to resolve the frequency response of the chromosphere. However, the chromosphere is spatially inhomogeneous, and time variable. For this reason, long duration data are also desirable, so as to better define the average frequency response of a variable chromosphere. Figure 1 shows results from 18.7 hours of heterodyne line profile data, obtained using the McMath telescope of the National Solar Observatory. Figure 1a shows the power spectrum of the line center velocity. The familiar 3 mHz band from the sub-photospheric cavity is dominant, but a secondary feature is seen

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near 4.3 mHz. This secondary feature is quite close to the chromospheric eigenfrequency calculated by Ando and Osaki (1977) and Ulrich and Rhodes (1977). Construction of a k-ω diagram for an 11 μm line is not yet feasible. However, because we have line profile data, we can examine the dynamics of the oscillation as a further clue to its origin. Figure 1b shows the power spectrum of the line depth, which is primarily determined by the temperature in the line-core-forming region. In this spectrum the 3 mHz sub-photospheric cavity is barely detectable; instead the 4.3 mHz feature dominates the spectrum. Temperature fluctuations associated with oscillations are damped by radiation in the solar atmosphere (Stix 1970). The weakness of the 3 mHz band in Figure 1b is consistent with the rapid radiative damping which is expected to occur in the photosphere. The integrated power in the 4.3 mHz feature gives a temperature fluctuation of order 20 Kelvins, and velocity of order 50 meters/sec, in the wave. These values are consistent with a γ=5/3 adiabatic oscillation from the upper solar atmosphere, where radiative damping is less important. Thus the dynamics of the oscillation supports our identification of the feature as a chromospheric resonance. We note that the far-infrared continuum intensity of the Sun, formed at chromospheric altitudes, shows brightness temperature fluctuations which are also centered at 4.3 mHz (Lindsey and Kaminski 1984).

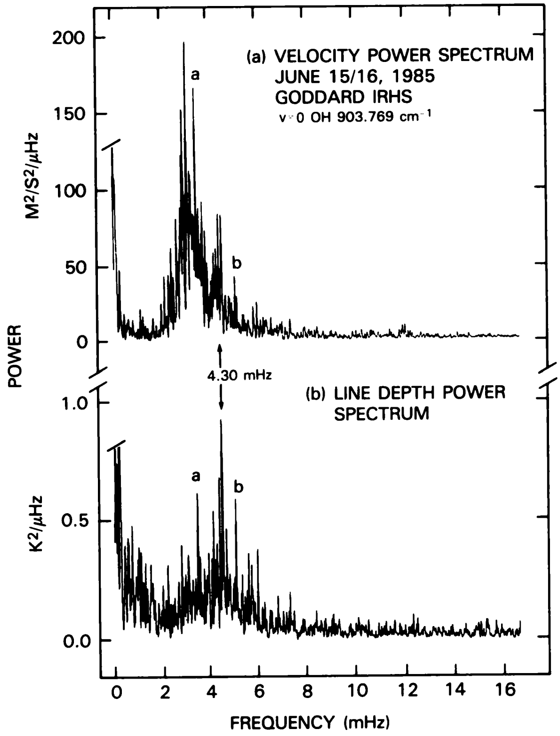

Figure 1. Power spectra of the OH line center velocity and line depth.

We interpret the chromospheric resonance in Figure 1b as showing a nearly Lorentzian response from a low-Q cavity, centered at 4.3 mHz, overlaid by noise and by two additional components (labelled "a" and "b" on Fig. 1) which may represent resonances from different components in an inhomogeneous chromosphere. Gouttebroze (1986) finds that the frequency of the n=1 mode is more strongly affected by the geometric thickness of the chromosphere than by the chromospheric temperature structure. Based on Gouttebroze's calculations, a 4.3 mHz eigenfrequency implies a transition region near 2650 km, in qualitative agreement with the sub-millimeter limb extensions observed by Lindsey et al. (1983). However, Ando and Osaki (1977) calculated a 4.3 mHz mode frequency using the HSRA with 1800 km thickness. An examination of other calculations (Gurman and Leibacher 1984; Christensen-Dalsgaard and Frandsen 1983) shows large differences in mode frequency calculations which appear unrelated to the thickness of the chromospheric model. Clarification of these differences is necessary before we can use our data to infer the geometric thickness of the chromosphere.

3. ENERGY FLOW

The sub-photospheric and chromospheric cavities can exchange energy by tunneling through their common boundary at the temperature minimum. We are observing a region (h=250 km) where the chromospheric mode begins to emerge as a traveling wave after tunneling through the temperature minimum. The average wave energy flux is $\langle \delta P \delta V \rangle$, where δP is the pressure perturbation and δV is the wave velocity. $\langle\ \rangle$ denotes the time average over many wave periods. We propagate a wave through a model atmosphere to infer δT from the observed line depth, and we deduce δP from the adiabatic relation: $\delta \ln P = \gamma / (\gamma - 1)\ \delta \ln T$. Since brightenings in the line correspond to redshifts (see also Lites and Chipman 1979), the wave energy flow we observe is downward.

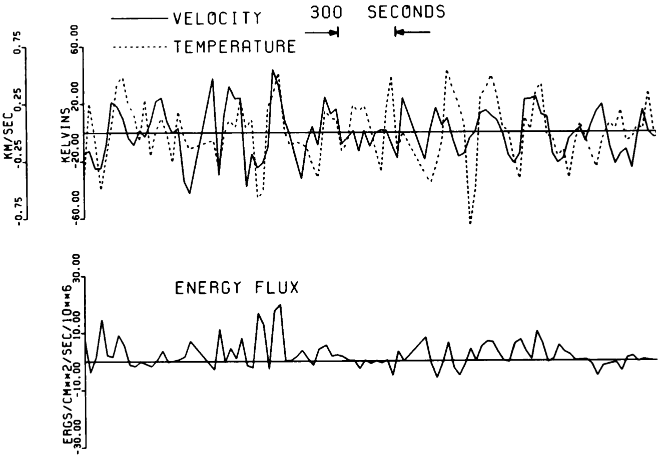

Figure 2. Velocity and temperature perturbations obtained from the 11.065 μm OH line (top), and the wave energy flux (bottom), versus time. Downward propagating energy is positive on the figure.

Figure 2 shows δT, δV and the $\delta P \delta V$ product for a small portion of the data; the average flux from the full data set is 2×10^6 ergs/cm^2/sec (uncertain to a factor of 2). The p-mode energy in the sub-photospheric cavity is of order 10^{34} ergs (Libbrecht et al. 1986), so the downflow we observe can excite it to full amplitude in 8×10^4 seconds, which is comparable to the lifetime of the sub-photospheric modes. We have not, however, observed the net flow, because the 3 mHz temperature perturbation is damped, and the upward flow is presumably more nearly isothermal (hence less visible to us). There are two possibilities as regards the upward flow, both of which are interesting. If the upward flow is comparable to, or greater than, the downflow we observe, then exchange with the chromosphere can provide a damping which limits the coherence, and possibly the energy content, of the sub-photospheric cavity. In this case, leakage to the chromosphere fills the need for a high frequency damping found by Libbrecht et al. (1986). If the upward flow is negligible in comparison to the downflow, then we would have to conclude that acoustic energy is generated within the chromospheric cavity itself, and that leakage from the lower boundary of this cavity provides a significant source of acoustic excitation for the sub-photospheric cavity. In this respect it would be interesting to search for solar-type p-mode oscillations in dwarf stars with active chromospheres, where surface activity could excite the interior to the greatest amplitude.

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