ABSTRACT

We present observations of solar infrared intensity variations at 50, 100, and 200 \( \mu \)m made simultaneously and cospatially with Doppler observations in the sodium D1 line \( \lambda 5896 \) Å. The infrared observations were made from the Kuiper Airborne Observatory; the Doppler observations were made from the Mees Solar Observatory. We found brightness temperature variations of several K in amplitude in our \( \sim 1.7' \) beam, highly correlated with five minute Doppler oscillations. We attribute the brightness variations to work done on the chromospheric medium by compression, driven by the five minute oscillations. The Doppler oscillations lead the brightness variations by \( \sim 47° \) in phase at 50 and 100 \( \mu \)m and by \( \sim 72° \) in phase at 200 \( \mu \)m (i.e., maximum redshift occurs from 47° to 72° in phase before maximum brightness). In an adiabatically responsive medium we expect a phase lead of 90° for five minute oscillations. The reduced phase shifts we see suggest thermal relaxation processes that are important in the dissipation of compressional energy.

Subject headings: infrared: sources — Sun: chromosphere — Sun: oscillations

I. INTRODUCTION

Far-infrared continuum observations of the Sun have provided important information for modeling the solar photosphere and chromosphere. Because the infrared continuum is emitted in LTE with a Planck source function simply proportional to temperature, it provides us with an excellent thermometer. It is only relatively recently that we have extended the unique advantages of the far-infrared continuum beyond diagnostics of the static structure of the solar atmosphere to study the dynamical behavior, in particular the thermal response, of the solar chromosphere to vertical motion in acoustic waves.

The first observations to show chromospheric intensity oscillations in the submillimeter continuum clearly were made at the NASA Infrared Telescope Facility by Lindsey and Kaminsky (1984) and Lindsey and Roellig (1987). Lindsey and Roellig (1987) observed 350 and 800 \( \mu \)m intensity variations from three to five minutes in period simultaneously in the same field of view. They found a high correlation between these two wavelengths, with the shorter-wavelength significantly leading the longer, by 25° to 35° in phase. They suggested that these phase shifts were due to thermal relaxation in the chromospheric medium, with a relaxation rate dependent on height.

In this work we report new measurements made from the NASA Kuiper Airborne Observatory (KAO), in which we observed intensity variations simultaneously at 50, 100, and 200 \( \mu \)m in one region of the Sun and at 200 and 400 \( \mu \)m in another region. Throughout this time we made Doppler observations from the Mees Solar Observatory (MSO) at Haleakala, Hawaii in a strong chromospheric line, the D1 line of neutral sodium, \( \lambda 5896 \) Å, cospatial with the 50 to 200 \( \mu \)m KAO observations. At the same time, cospatial Doppler observations were made at the Wilcox Solar Observatory at Stanford University in the photospheric line Fe I \( \lambda 5124 \) Å.

In this paper we will discuss only the 50, 100, and 200 \( \mu \)m observations made from the KAO and the sodium D1 Doppler observations made at MSO. According to standard chromospheric models (Vernazza, Avrett, and Loeser (VAL) 1976, 1981) the infrared wavelengths observed emanate from heights ranging from \( \sim 350 \) km (50 \( \mu \)m radiation) to \( \sim 500 \) km (200 \( \mu \)m), approximately the height of the temperature minimum. The sodium D1 line forms at about 600 km. More detailed analysis including the Stanford Doppler observations and the 400 \( \mu \)m KAO observations will be published later (Kopp 1989).

In the following section we describe the observations. In § III, we present the observational results. In § IV, we conclude with a brief discussion.

II. THE OBSERVATIONS

Because of absorption by terrestrial water vapor, the entire 30 to 300 \( \mu \)m decade of the infrared spectrum is inaccessible to ground-based telescopes. Solar photometry in this range must be done from the stratosphere, a task for which the KAO is well suited. The KAO is an aircraft-borne 1 m telescope flown at an altitude of 41,000 feet. We used a multichannel detector to observe radiation at 50, 100, and 200 \( \mu \)m, with all channels viewing the same place on the Sun. The beam diameters were \( \sim 1.7' \) FWHM (see Table 1).

The observing techniques we used in this experiment are basically the same as those in other airborne solar infrared observations (Lindsey et al. 1984). Two-beam chopping was used to correct for atmospheric transparency variations; this procedure is described in Lindsey and Roellig (1987). The point is to observe the intensity difference in two separate regions on the Sun, subtracting one from the other. This is accomplished by alternating the secondary mirror back and forth between two orientations at a frequency of \( \sim 30 \) Hz, and using phase-switched electronics to extract the resulting 30 Hz signal variation. We assume in our analysis that this two-beam difference is the superposition of two statistically independent time series. In this observation one beam was placed at Sun center, while the other was placed horizontally 4' left of Sun center, which was 136° counter clockwise from celestial north. The beam positions were checked every 20 minutes by offsetting to the solar limb at two positions and were found to stay within 10' of their nominal positions throughout the observation.
TABLE 1

AMPLITUDE AND PHASE RELATIONSHIP BETWEEN RED SHIFT AND INFRARED BRIGHTNESS VARIATIONS

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Beamwidth (km)</th>
<th>Height of Formation* (km)</th>
<th>Rms Brightness Temperature, b (K)</th>
<th>Phase Lead c</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>110</td>
<td>350</td>
<td>1.0</td>
<td>46° ± 10°</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>450</td>
<td>1.8</td>
<td>48 ± 10</td>
</tr>
<tr>
<td>200</td>
<td>95</td>
<td>500</td>
<td>2.4</td>
<td>72 ± 30</td>
</tr>
</tbody>
</table>

* See Val 1981.

b Rms variation of the two-beam brightness difference is tabulated. Assuming that the brightness variations in both beams are statistically independent, the rms brightness variation attributable to a single beam is the tabulated variation divided by the square root of 2.

c Doppler redshift leads brightness temperature variation by the phases tabulated.

Over the 90 minute duration of the observation the image of the Sun rotated ~ 3° due to rotation of the Earth and motion of the airplane across the Earth's surface. This resulted in a motion of the offset beam across the solar image during the observation of ~ 12°, a distance small compared to the beam diameter.

Doppler observations in the sodium D1 line (15896 Å) were made at the Mees Solar Observatory at Haleakala, Hawaii, using the Stokes Polarimeter (Mickey 1985). We used the polarimeter to measure the intensity (I) profile of the sodium D1 line, with no discrimination of polarization (Q, U, or V). Each I profile was fitted to a Lorentzian to determine the Doppler shift. The polarimeter was defocused to a total beam width of 3' for this observation. We settled on this full diameter as the best match to an infrared beam whose full width at half-maximum was 1.7 but whose wings extended significantly beyond this width. The polarimeter was programmed to observe alternately in the same two regions the KAO monitored in 50, 100, and 200 μm radiation, switching between the two with a period of 10 s. The Doppler velocity measurements in these two regions were subtracted, one from the other, to give the net velocity difference between the two regions. This procedure gave us a data set analogous to the two-beam differences we obtained in the infrared in the same two regions, so that the velocity data could be compared directly with the infrared data.

III. RESULTS

a) Brightness Time Series

Our two-beam difference infrared brightness data are shown in Figure 1 with zero time set at 21:00 UT of 1987 May 14. The entire time series is ~ 1.5 hours in length. We used the absolute photometry of Rast, Kneubuehl, and Mueller (1978) to normalize our two-beam signal variations to brightness temperature.

In all the time series shown in Figure 1 there are strong five minute oscillations. It is immediately clear that the signal variations at any two wavelengths correlate closely with each other. Some correlation is inevitable, of course, since the weighting functions for different wavelengths overlap considerably. (The overlap between the 50 and 200 μm weighting functions is ~ 22%.) However, such a strong correlation as we find implies that the temperature variations between two different heights in the chromosphere are strongly correlated.

A close examination of Figure 1 also shows that 5 minute variations at 50 and 100 μm significantly lead those at 200 μm. Such a phase shift cannot arise artificially from overlap in weighting functions or a discrepancy in beam sizes. We are seeing the result of a phase shift of temperature variations with height in the chromosphere.

The rms brightness amplitudes of the oscillations are listed in Table 1. They increase by ~ 50% going from 50 to 200 μm. This increase could be due in part to a narrower beam for the longer wavelengths. Tannenbaum et al (1969) find that velocity amplitudes for visible lines are inversely proportional to the square root of beam diameter for beam diameters greater than ~ 10". The observed increase in brightness amplitude with wavelength well exceeds the 15% increase we expect on the basis of beam diameter alone. We feel that this indicates a considerable increase in temperature amplitude of the oscillations with height in the solar chromosphere.

![Fig. 1.—Two-beam intensity differences for 50, 100, and 200 μm radiation. The 50 and 200 μm plots are displaced upward and downward, respectively to separate them from each other and the 100 μm plot. We had to interrupt our measurements at disk center periodically to check guiding and measure the signal difference across the solar limb for calibration. The intensity is interpolated linearly in the missing intervals. Note the predominance of five minute period variations and the strong correlation between different wavelengths.](image-url)
**b) Doppler Observations**

Figure 2 shows the Doppler measurements (top curve) made in the sodium D1 line together with the 100 μm brightness measurements (bottom curve). Positive velocity corresponds to redshift, i.e., motion into the Sun. There is a strong correlation between velocity and infrared brightness, particularly for five minute variations.

**c) Power Spectral Analysis**

To evaluate the phase shifts evident in the time series we multiply the Fourier transform of the first time series by the complex conjugate of the second, giving a "cross-power spectrum." The argument of this complex function at a given frequency is the phase shift between the two time series at that frequency (cf. Lindsey and Roellig 1987). The cross-power spectra between velocity and infrared brightness variations for 50, 100, and 200 μm are shown in Figure 3. The solid curves show the real parts, while the dashed curves show the imaginary parts; a zero imaginary part indicates no phase shift. The real parts are consistently positive, reflecting the high correlation between velocity and brightness at all wavelengths seen in Figure 2. The imaginary parts are predominantly positive between 2.5 and 3.5 mHz, indicating that redshift velocity leads brightness variations. Table 1 lists the phase lead of redshift velocity ahead of brightness in the 2.5 to 3.5 mHz band for the cross-power spectra of Figure 3. The lead is ~47° for 50 and 100 μm, but for 200 μm, the phase shift appears greater (72°), although the uncertainty is increased. Direct cross-correlations between 100 and 200 μm corroborate with much higher significance that the phase lead of velocity ahead of brightness increases with wavelength (Kopp 1989). The ground based observations of Lindsey and Roellig (1987) in 400 and 800 μm radiation show this same trend, i.e., shorter wavelength variations leading longer wavelengths, as do the 200 and 400 μm variations observed separately in this flight (Kopp 1989).

**IV. DISCUSSION**

The high correlation we have found between velocity and infrared brightness confirms a strong relationship between infrared brightness and Doppler oscillations. Our basic interpretation of this relationship has, heretofore, been relatively simple: During the five minute oscillations, the chromospheric medium experiences compression; the work done on the medium by this compression is sufficient to vary the temperature of the medium, averaged over our 2' beam, by several K if the compression is adiabatic. The brightness variations basically reflect this temperature variation directly.

Prevailing models of five minute oscillations as p-modes have portrayed them in the low chromosphere as evanescent waves in an adiabatically responsive fluid. Evanescent waves carry no energy flux vertically, and their energy density attenuates rapidly with height. They appear to be trapped with the great bulk of their energy localized below the chromosphere. Evanescent waves are characterized by motion that is in phase at all heights, with adiabatic temperature variations in phase with compression at all heights. We therefore expect redshift velocity to lead compression by 90° for five minute oscillations.

The phase shift we observe between velocity and brightness is considerably less than 90°. This strongly suggests the possibility of thermal relaxation. When we introduce thermal relaxation, the simple adiabatic picture described above changes. Thermal relaxation is irreversible, thus in no way adiabatic. The simplest thermal relaxation model, the Newton cooling law, assumes that temperature variations caused by compression of a volume, V, of the medium relax toward thermal equilibrium at a rate proportional to the magnitude, ΔT, of the perturbation

\[
\frac{d\Delta T}{dt} = -\frac{p}{c_v} \frac{dV}{dt} - \omega_R \Delta T .
\]

Here \(c_v\) is the heat capacity of the atmospheric medium at constant volume and \(-p dV/dt\) is the rate of compressional work done on the medium. The constant \(\omega_R\) is the thermal relaxation rate. Thermal relaxation, has two main effects:

1. It attenuates the thermal response to compression. A thermal relaxation rate, \(\omega_R\), decreasing with height could explain the rapid growth in temperature amplitude of the oscillations with increasing wavelength.
2. It shifts the phase of the thermal response forward in time. A thermal relaxation rate \(\omega_R\) results in temperature...
leading compression by a phase \( \phi \) given by

\[
\phi = \cot^{-1} \left( \frac{2\pi v}{\omega_R} \right),
\]

where \( v \) is the frequency of the compression, i.e., the oscillation frequency.

The phase shift we see between velocity and infrared brightness appears consistent with thermal relaxation in the low chromosphere. Lites and Chipman (1979) and Lites, Chipman, and White (1982) find a similar phase shift between velocity and line-center brightness in their observations of the calcium triplet, which form in the high photosphere. To have redshift velocity leading temperature by \( \sim 45^\circ \) suggests that temperature leads compression by \( \sim 45^\circ \), a result consistent with thermal relaxation of the chromosphere following compression. By equation (2), a relaxation process with a characteristic time of order 50 s would result in such a phase shift for five minute oscillations.

Various relaxation processes have already been considered at different levels in the solar atmosphere (Giovanelli 1978, 1979; Noyes and Leighton 1963; Spiegel 1957). These mechanisms generally depend on cooling because of the escape of continuum radiation and generally give relaxation rates considerably slower than our observations indicate. Recent very detailed work by Anderson and Athay (1989), shows that moderately strong chromospheric lines are important in radiative cooling, and appear to cause relaxation fast enough to account for the infrared phase shifts. They find a relaxation time, \( 2\pi/\omega_R \), of 60 s for the chromospheric plateau overlying the temperature minimum. Also, there may be other aspects of thermal relaxation, e.g., relaxation of hydrogen to local ionization equilibrium (cf. Lindsey 1981) that do not depend on the rapid escape of radiation.

Thermal relaxation can be expected to result in strong dissipation of compression waves. It is important to emphasize that in a dissipative medium our picture of oscillations as evanescent modes at the temperature minimum must be greatly revised. Strong energy dissipation implies an energy flux with a nonzero divergence, and therefore prohibits strictly evanescent modes. The results presented here indicate the need for a thorough reexamination of the hydrodynamics of \( p \)-modes in the chromosphere from the standpoint of waves in a dissipative medium.
We wish to thank L. Haughney and the entire NASA Airborne Astronomy Division for their enthusiasm and hard work on this particularly demanding project. We particularly thank J. McClenahan for going far out of his way to accommodate our special demands. We thank Mike Robinson for the late hours he spent in the CAVE to satisfy the special software requirements of this project. We greatly appreciate Phil Scherrer and the staff of the Wilcox Solar Observatory, who supported us with excellent photospheric Doppler velocity data. We regret that space does not allow us to thank individually the many other dedicated people who went far beyond the boundaries of obligation to make this project a success. This work was supported by NASA grants NAG-2-418 and NAGW 723 to the University of Hawaii.

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