Propagating Magneto-Acoustic Waves in the Network

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**Abstract.** The analysis of spectroscopic data taken in the chromospheric network is interpreted as evidence for propagating waves. These waves are seen from the photospheric level propagating upward to the highest levels of the chromosphere at velocities around 40 km/s, suggesting a magneto-acoustic nature. We note the lack of an adequate one-dimensional model of the solar chromosphere to interpret these data.

1. Introduction

When looking for the propagation of waves, wavelet analysis is a perfectly suited method: it gives information on a signal both in time and frequency. This method is widely used in many domains of physics and has many applications. We applied it previously to study waves in the chromosphere at different heights, using CaII K and He I lines, allowing the study of these waves at different times and altitudes (Bocchialini & Baudin, 1995). Later results suggested an interpretation favouring upward propagating waves (Bocchialini & Koutchmy, 1995) when an additional photospheric Si I line was taken into account. New observations, additional analysis and a global re-interpretation is considered here.

2. Observations

The present work is based on two data sets: the first one, previously used in our first analysis, consists of spectra taken at the disk center in the chromospheric network, simultaneously in CaII K, He I (at 1083 nm) and Si I lines, obtained with the Dunn Telescope at the National Solar Observatory in March 1993 (Bocchialini et al. 1994). The second one is made of new observations obtained at the Dunn Telescope as well, in August 1998. They consist of simultaneous spectra in the same CaII K and He I lines taken at the limb.
Figure 1. Time/frequency analysis of the time series derived from SiI, HeI and CaII K spectra taken in the active network (AN). This analysis displays the power variation of the signal versus both time and frequency, showing very similar patterns in the three time series, and allowing the precise estimate of time lag between wave packets simultaneously observed at different heights.

3. Wavelet analysis

A general description of wavelet analysis can be found in Mallat (1998), and its application in the frame of helioseismology (p-modes oscillations) was given by Baudin et al. (1996). Here, we have used a wavelet analysis using the classical Morlet wavelet:

\[
\text{WT}(t_0, d) = \int S(t) O(\frac{t - t_0}{d}) \, dt \quad \text{and} \quad O(t) = e^{-\pi t^2} e^{-i\pi t} \quad (1)
\]

where \( S \) is the signal to be studied, \( t_0 \) the time of interest, \( d \) the dilation coefficient, and \( O \) the Morlet wavelet. Thus, each "wavelet coefficient" yields information on the signal at time \( t_0 \) and frequency \( \nu = 1/2d \).
4. Results

Bocchialini & Baudin (1995) found evidence for propagating waves in the chromospheric network. These results were based on a wavelet analysis of Doppler velocities observed in He I and Ca II K lines. We found similar patterns in the time/frequency analysis of these two time series, interpreted as wave packets (see Fig. 1). We derived time lags between the packets in both lines, showing that the packets observed in the He I line were \(~20\) s in advance on average of those seen in the Ca II K line. We first based our interpretation on the VAL model (Vernazza, Avrett & Loeser, 1992) which locates the formation height of the Ca II K line between 900 km and 1700 km in the solar atmosphere and the He I line between 1600 km and 1900 km, suggesting possibly downwardly propagating waves. A more definite comparison (Bocchialini & Koutchmy, 1995) with wave packets observed in a photospheric Si I line showed that these packets were also \(~50\) s in advance compared to He I and \(~70\) s compared to Ca II K, indicating without ambiguities an upward propagation.

The new observations at the solar limb in the same Ca II K and He I lines we use here give us new insights into the formation heights. From 100 spectra taken every arcsecond along the limb with the slit across the limb, we computed an average spectrum in which we selected two wavelengths corresponding to the center of the line of interest and to the continuum (see Fig. 2). In Fig. 3, we have plotted the averaged profiles of intensity at these wavelengths versus spatial position. The continuum profile shows the location of the limb and indicates clearly that we observe Ca II K emission at altitude significantly higher above the limb than the altitude where He I line is produced, contrary to the prediction of the one-dimensional models.

To observationally estimate heights of formation is not an easy task. The location of the limb, considered to be at \(~400\) km above the \(\tau_5 = 1\) level (Lites, 1983), was taken as the position of the maximum gradient in intensity at the wavelength of reference for the continuum (see Fig. 2 and 3). Since the plasma is supposed to be optically thin at the wavelength of the He I line, we took as an estimate of the formation height the position of the maximum of emission, itself estimated as the intensity difference between the center of the line and the continuum, yielding a value of \(~1600\) km above the limb for the He I line, in agreement with Koutchmy (1995). At the wavelength of Ca II K3 line, the plasma cannot be considered as optically thin. We took as a crude estimate of the formation height of this line the weighted average over height (or center of gravity) of the emission: \(~3000\) km. A more precise determination of the effective heights of formation based on modeling will be considered in a forthcoming work.

From this evaluation and the observed time delays, we can calculate the propagation speed of the waves from the Si I level (\(~200\) km above \(\tau_5 = 1\) level) to the He I level to be \(~32\) km/s, from He I to Ca II K to be \(~70\) km/s, with an average value of \(~45\) km/s between Si I and Ca II K levels. These values indicate that the nature of these waves is not acoustic but magneto-acoustic (fast mode). They also indicate an acceleration of the propagation speed of the wave with increasing height, which is understandable because of the increasing temperatures with increasing heights. However, these preliminary results must
Figure 2. Left: the observed spectrum in the He I line region at 1083 nm. The solid line indicates the reference wavelength used for the continuum, the dotted line the reference for the He I line center. Right: the observed spectrum of the Ca II K line, with the references for the continuum (solid), $K_3$ (dotted), $K_{2R}$ (dashed), $K_{2V}$ (dot-dashed).
Figure 3. Left: variation of the averaged intensity (with the same line styles as for Fig. 2) versus spatial position in a radial direction. The origin is set to the limb position in the continuum (defined by its inflection point). Right: the solid line shows the derivative of continuum intensity variation, its minimum showing the limb position. The other lines (same convention as for Fig. 2) show the intensity difference for He I, K3, K2R, and K2V lines, after subtracting the continuum intensity. The center of gravity of the resulting intensity variation above the limb is taken as a crude estimate of the contribution function of the effective height of formation of the corresponding line.
be complemented with more precise observations of the wave packets propagation at different heights in the solar atmosphere and, above all, more accurate measurements of the formation height of the studied lines. This must be completed as well with a proper modeling of the solar chromosphere in the magnetic network, which is not achieved by present models.

References