Travel-Time Analyses of an Emerging-Flux Region

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Abstract.

Travel-time analyses of a newly-formed plage region are presented. The dataset has been obtained from the 12-hr Hinode observation of an emerging-flux region (to be NOAA AR 10975) close to the disc center on 23 November 2007. The SOT provides data in Ca ii H line and in Fe i 557.6nm line; we use both chromospheric intensity oscillation data and photospheric Dopplergrams for travel-time measurement by a cross-correlation method. In the plage region, we have detected a travel-time anomaly in the chromospheric data, but not in the photospheric data. This can be interpreted as a signature of downflows in the chromosphere. This result illustrates how time-distance techniques can be used to study chromospheric flows.

1. Introduction

Helioseismology provides us with the only way to investigate the subphotospheric structure and dynamics of the Sun. However, its usefulness is not limited to studying subsurface layers. We report on the detection of chromospheric flows by a helioseismology analysis in an emerging flux region.

Emerging flux regions are the place where the magnetic flux tubes generated in the convection zone are first observed directly, and their dynamics are manifestations of subphotospheric interaction between plasma and magnetic field. Therefore, to understand those processes that are key to solar dynamo mechanisms, studying dynamics of emerging flux region is highly important. Indeed, numerous studies about such regions have been done so far from both observational and theoretical points of view. It is generally thought that there are plasma downflows along the flux tube. The observed speed is 30 – 50 km s⁻¹ in the chromosphere and 1 – 2 km s⁻¹ in the photosphere (e.g., Tajima and Shibata 2002); the plasma decelerates as it descends into layers with higher densities.

We have detected such a chromospheric downflow in an emerging flux region using a local helioseismological technique. This result may open new possibilities of time-distance analysis of chromospheric dynamics. More details about this work are found in Nagashima et al. (2009).

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417
2. Observation

The Solar Optical Telescope (SOT; Tsuneta et al. 2008) on Hinode (Kosugi et al. 2007) observed an emerging flux region near the disc center on 23 November 2007 for 12 hours (11:17–23:55 UT). In this region (later to be NOAA Active Region 10975) a plage and small sunspots appeared just before the observation began. During the observation, the Broad-band Filter Imager (BFI) took Ca II H images, while the Narrow-band Filter Imager (NFI) took non-magnetic Fe i 557.6 nm filtergrams. The Fe filtergrams consist of blue-wing and red-wing intensities, and we obtained Doppler velocity by dividing the (blue-red) intensity by the (blue+red) intensity. The field of view used is $218\times109$ arcsec, and the pixel scale is about 0.2 arcsec, both of which are different from the original ones due to a trimming and a pixel summing. The top panels in Figure 1 show sample images. Note that in the photospheric (Fe i line) Dopplergram, the plage region exhibits a weak redshift; this indicates a few hundred m s$^{-1}$ downflow in the photosphere.

![Figure 1. Top row: A sample Ca II H line intensity image (left) and an Fe i 557.6 nm Dopplergram (right). In the Dopplergram, black indicates a blueshift and white indicates a redshift. Bottom row: Outward-inward travel-time difference maps. The gray scale corresponds to the range from $-0.5$ min (black) to $+0.5$ min (white).](image)

3. Time-Distance Analyses

A time-distance technique for local helioseismology (Duvall et al. 1993) has been used to analyze the 12-hour dataset. First, we applied three filters in Fourier space: i) an f-mode filter; we used p-mode waves only, ii) low-wavenumber filters and a Gaussian frequency filter with 1-mHz width, peaking at 3.3 mHz, to remove artifacts due to filter problems (see below), and iii) a phase-speed filter with a width of 4.4 km s$^{-1}$ centered at a speed of 22 km s$^{-1}$; these waves travel to a distance of 14.86 Mm, chosen for this study.

The images from the NFI contain artifacts caused by air bubbles inside the tunable filter (Tsuneta et al. 2008). Since the bubbles move around in the field
of view with the orbital period (\(\sim 98\) min, or \(0.17\) mHz), the artifacts show this periodicity. Lower-wavenumber components (up to \(\ell \sim 400\)) are also affected by the artifacts. In this analysis, therefore, we removed lower-wavenumber components as well as lower-frequency components by the filter (ii).

Second, we cross-correlated the filtered signals and measured the acoustic travel time by fitting a Gabor-wavelet function to the cross-correlation functions (Kosovichev et al. 2000). The bottom panels in Figure 1 show maps of the travel-time difference between the outward and inward wave components. In the Quiet-Sun (QS) region, the similar pattern of flow divergence due to supergranulation is seen in both the chromospheric (Ca \(\Pi\)) and the photospheric (Fe \(I\)) maps. In the plage region, however, only in the chromospheric data the outward travel time is shorter than the inward travel time. The difference is about half a minute on average, while the typical travel time for the distance of \(14.86\) Mm is \(\sim 21.5\) min.

We measured the outward-inward travel-time difference in the averaged cross-correlation functions in both the plage and the QS region. In the plage region, the difference was \((-6.72 \pm 0.04) \times 10^{-1}\) min for the chromospheric data and \((-0.78 \pm 0.03) \times 10^{-1}\) min for the photospheric data, while in the QS region, it was \((0.63 \pm 0.04) \times 10^{-1}\) min for the chromospheric data and \((1.33 \pm 0.03) \times 10^{-1}\) min for the photospheric data.

Finally, we checked temporal variation of the travel-time anomaly, noting that the shape of the plage significantly changed during the observation (see Fig. 2). We divided the 12-hr dataset in Ca \(\Pi\) H line into two 6-hr segments and measured the travel times for each 6-hr segment. The averaged cross-correlation functions in Ca \(\Pi\) H line are shown in Figure 2. In the plage region, the outward-inward travel-time difference changed from \((-5.90 \pm 0.04) \times 10^{-1}\) min to \((-7.38 \pm 0.04) \times 10^{-1}\) min, while in the QS region, it was \((0.85 \pm 0.03) \times 10^{-1}\) min in the first 6 hours and \((0.39 \pm 0.03) \times 10^{-1}\) min in the last 6 hours. The weak variation in travel-time difference in the QS region is interpreted as the variation of the supergranular pattern.

Figure 2. Left: Ca \(\Pi\) intensity images averaged over the first (A) and the last (B) 6 hours. Middle and Right: Mean cross-correlation functions from Ca \(\Pi\) H data in the plage (middle) and in a QS region (right), normalized by the maximum value in the QS region.
4. Discussions

In this analysis, we used only acoustic (p-mode) waves with the central frequency of 3.3 mHz. Although stationary p-mode waves around such frequency are evanescent in the chromosphere, perturbations caused by the subphotospheric sources do propagate upward with the chromospheric sound speed (see e.g., Lamb 1975). Therefore, a chromospheric signal is observed after the corresponding photospheric signal is observed, and the delay time is the acoustic travel-time between the two layers. We appreciate that more care may be required to study the effect of filters, but we adopt this simple picture for this initial analysis.

If the delay time is constant at all points, the photospheric and the chromospheric travel-times are the same; this is consistent with what measurements in QS region show. However, if some kinds of flow locally exists in the chromosphere, the delay time at a point can differ from that at another point, and only in the chromospheric observation outward-inward travel-time difference shows up.

The outward-inward travel-time difference in the chromosphere can be estimated by \( \Delta t_{ch} = -2(LV/c^2) \), where \( c \) is the sound speed in the chromosphere, \( L \) is the formation height difference between the Fe I 557.6 nm line and the Ca II H line, and \( V \) is the downflow speed in the chromosphere. Assuming \( c \sim 10 \text{ km s}^{-1} \) and \( L \sim 250 \text{ km} \) (Carlsson et al. 2007), we obtain 8 km s\(^{-1}\) for the downflow speed \( V \) from the travel-time difference of \(-0.67\) min. As we mentioned in \$3., the travel-time difference in the plage changed as the plage evolved: \(-0.59\) min for the first 6 hours and \(-0.74\) min for the last 6 hours. They correspond to the downflow of 7 and 9 km s\(^{-1}\), respectively. This temporal variation is consistent with the behavior of an emerging flux region in the developing phase. Further works are required to investigate spatial structure of the downflow.

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