HELIOSEISMIC OBSERVATIONS OF SUBPHOTOSPHERIC DYNAMICS OF SUNSPOTS AND DEVELOPING ACTIVE REGIONS

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ABSTRACT

New methods of time-distance helioseismology provide us unique information about the structure and dynamics of sunspots and active regions in the upper convection zone. We present three-dimensional maps of the sound-speed perturbations and flow velocities obtained from the SOHO/MDI data for sunspots, emerging flux events and evolving active regions. The results reveal complex dynamics of magnetic structures below the solar surface, and shed light on the mechanisms of sunspots and active regions, and magnetic field dynamics. One interesting case that includes a fast spinning sunspot accompanied with subphotospheric vortex motions and twisting coronal loops represents an intriguing example of magnetic coupling between the subphotospheric processes and the atmospheric activity. The evolution of a large active region, NOAA 9393, has been studied for almost 3 solar rotations in March-April 2001, including the periods of emergence, maximum activity and decay. It is concluded that this active region was formed by fragmented magnetic flux tubes emerging during an extended period of time rather than by a single large Ω-loop broken into smaller flux tubes near the surface.

Key words: helioseismology, solar interior, solar activity, solar cycle, sunspots.

1. INTRODUCTION

The new methods of helioseismology allow us to investigate the coupling between the internal dynamics and the evolution of active regions in the solar atmosphere. The key questions are: How fast do the active regions erupt? Why do new active regions tend to appear in places where previous active regions existed? How deep in the convection zone are the active regions formed? Is there retraction of magnetic flux during the active regions decay? What is the role of convective mass flows in the formation and evolution of sunspots and active regions? Answering these questions will help to understand the mechanisms of solar activity and develop space weather forecasts.

Figure 1. A sample of raypaths of acoustic waves propagating through the solar interior.

In this paper, we review some initial results of the diagnostics of the flow patterns in sunspots, and evolving active regions. The results are obtained by time-distance helioseismology from the SOHO/MDI data.

2. METHOD

Time-distance helioseismology measures travel times of acoustic or surface gravity waves propagating through the interior (Duvall et al. 1993). The travel times depend on subphotospheric conditions - the flow velocity and sound speed along the ray path:

\[ \delta \tau = - \int_{\Gamma} \frac{k}{c} \frac{\delta c}{\omega} ds - \int_{\Gamma} \frac{(\mathbf{n} \cdot \mathbf{U})}{c^2} ds, \quad (1) \]

where \( \delta \tau \) is the variation of the travel time due to the sound-speed perturbation, \( \delta c/c \), and flow velocity, \( \mathbf{U} \); \( k \) is the wave number, \( \omega \) is the wave frequency, \( \mathbf{n} \) is the unit vector tangential to the ray path, \( \Gamma \) (Fig.1).

The effects of the sound-speed and velocity perturbations are separated by taking the mean and the difference of the travel-time measurements along the same ray path in two opposite directions. Then, the distributions of \( \delta c/c \) and \( \mathbf{U} \) are obtained by inversion techniques (Kosovichev & Duvall, 1997). So far, most results have been obtained...
Figure 2. a) The sound-speed perturbation in a large sunspot observed on June 20, 1998, are shown as vertical and horizontal cuts. The horizontal size of the box is 13 degrees (158 Mm), the depth is 24 Mm. The positive variations of the sound speed are shown in light gray, and the negative variations (just beneath the sunspot) - in dark. The upper semitransparent panel is the surface intensity image (dark colour shows umbra, and light colour shows penumbra). b) A different projection of the sunspot shows long narrow structures ('fingers') connecting the main sunspot structure with surrounding pores A and B of the same magnetic polarity as the spot (the lower horizontal sound-speed plane located at the depth of 4 Mm). Pores of the opposite polarity (e.g. C) are not connected to the spot. (Kosovichev et al. 2000).

Figure 3. The axisymmetrical component of mass flows in a sunspot area at the depth of 0–12 Mm. The arrows show the magnitude and directions of the flows. The longest arrow represents 1.6 km/s. The upper panel shows the sunspot umbra and penumbra. In the dark subsurface region, the sound speed is lower than in the surrounding plasma by approximately 10%; in the lower gray region the sound speed is higher than in the surrounding plasma. The white horizontal line separating the lower and higher sound-speed regions is approximately 4 Mm deep.

using the ray approximation. More accurate techniques based on the wave propagation theory are being developed (Birch & Kosovichev, 2000; Jensen et al., 2000; Gizon & Birch, 2002).

3. STRUCTURE AND DYNAMICS OF A DEVELOPED SUNSPOT

The typical sunspot structure revealed by the time-distance technique consists of a 4-Mm deep layer of a decreased sound speed immediately beneath the sunspots and a zone of higher sound speed in the deeper interior (Fig. 2). This zone is visible at least up to the depth of 20-30 Mm. The observed changes in the sound speed could be due to variations of both, magnetic field and temperature. The temperature variations appear because the magnetic field of sunspots affects the convective energy flux. The sound-speed variations range from 0.3 to 1 km/s. At a depth of 4 Mm, this corresponds to 3-18 kG magnetic field or 900-2800 K temperature change. The time-distance results also show ‘fingers’ - long narrow structures connecting the sunspot with the surrounding pores of the same polarity at a depth of 4-5 Mm. There is no such connections to the pores of the opposite polarity.

Figure 3 illustrates the typical flow pattern beneath the sunspots. It appears that the convective flows form converging vortices beneath the surface, and diverging ones in the deeper interior (Zhao, et al. 2001). These observations confirm Parker’s (1979) idea about sunspots as clusters of magnetic flux tubes held together by converging flows.

4. FLOW PATTERNS UNDER A SPINNING SUNSPOT

Simultaneous observations of a rapidly rotating sunspot in active region NOAA 9114 in August 7-10, 2000, by MDI and TRACE provide an interesting example of magnetic coupling between the interior and corona. During these three days the leading spot rotated counterclockwise by approximately 200°. In the corona, this resulted in twisting magnetic flux tubes connecting this sunspot with the following sunspot (Fig.4).
Figure 5. Vortex flows beneath the rapidly rotating sunspot of August 8-10, 2000. a) a continuum intensity image of the sunspot from SOHO/MDI; b) and c) the horizontal flow maps in two layers, 0–3 Mm and 9–12 Mm beneath the surface (the longest arrows correspond to the maximum velocity of about 1 km/s in panel b) and 1.5 km/s in panel c). The background images in b) and c) show the boundary of sunspot magnetic field from the MDI magnetogram.

Figure 6. Emergence of active region NOAA 9393 (March 4, 2001): a) the photospheric magnetic field and the horizontal velocity field at a depth of 2 Mm; b) the vertical velocity (the grayscale map) and the horizontal velocity field at the same depth.

Figure 7. The maximum activity phase of AR 9393 (March 27, 2001): a) the photospheric magnetic field and the horizontal velocity field at a depth of 2 Mm; b) the vertical velocity (the grayscale map) and the horizontal velocity field at the same depth.
Figure 8. The decay phase of AR 9393 (April 26, 2001): a) the photospheric magnetic field and the horizontal velocity field at a depth of 2 Mm; b) the vertical velocity (the grayscale map) and the horizontal velocity field at the same depth.

Figure 5 shows the observations of the internal mass flows in the sunspot region on August 8 when the sunspot rotated most rapidly. It is found that in the subsurface layer, 0-3 Mm deep, the solar plasma rotated in the same direction as the sunspot surface structure (counterclockwise), but in the deeper layer, at 9-12 Mm, the plasma motion was in the opposite direction (clockwise). The sound-speed maps provide evidence that the sunspot structure was twisted in the interior (Zhao & Kosovichev, 2002). Finding whether the vortex flows resulted in the magnetic field twisting and the rapid rotation or were the result of untwisting of the magnetic flux is important for understanding the mechanisms of solar activity.

5. DEVELOPMENT OF A LARGE ACTIVE REGION

The evolution of the largest active region of the current solar cycle (NOAA 9393) has been studied by time-distance helioseismology for three solar rotations from its emergence through the decaying phase, in March-April, 2001. The spatial resolution was about 5 Mm, and the temporal one - 8 hours. Figure 6 shows the distribution of the photospheric magnetic field and the horizontal and vertical flow maps in the subsurface layer 2 Mm deep. Beside the usual supergranular flows (Duvall et al. 1997) these maps do not show any specific flow pattern that could be associated with emergence of a large-scale structure, e.g. a large-scale outflow or upflow. Soon after the emergence the dominant flow pattern consists of converging downflows around the active regions (see also, Kosovichev, 1996). Figure 7 shows the dynamics during the maximum activity phase. The flow structure is quite complicated. In addition to the converging downflows surrounded by upflows we see a diverging flow around a rapidly evolving leading spot. Also, there is evidence for strong shear flows in the central part of this region where a very strong flare occurred 3 days later, on April 2. The decaying phase shown in Fig.8 is characterized by predominant outflows. The sound-speed maps reconstructed up to a depth of 60 Mm reveal that the subsurface structure of the active region is as complicated as its surface structure, and also rapidly evolving.

From these observations, we find no evidence for a large magnetic Ω-loop emerging from the interior and forming this active region. The active region was rather formed by a very fragmented magnetic flux emerging during an extended period of time.

Further investigations of the dynamics of active region and the magnetic coupling between the interior and the atmosphere will shed more light on the physics of solar activity.

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