LOCAL HELIOSEISMOLOGY OF INCLINED MAGNETIC FIELDS AND THE SHOWERGLASS EFFECT

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ABSTRACT

Direct evidence of the dependence of local helioseismic measurements on the orientation of near-surface magnetic fields is presented. MDI Doppler images are used to perform acoustic holography, with the focus placed in various positions within the penumbrae of two sunspots as the spots move across the solar disk. The computed ingression amplitudes are compared to the observed velocities, to determine the phase shifts produced in the penumbral photosphere. Significant phase changes from the acoustic ingression to the observed line-of-sight velocity are found to be sensitive to the line-of-sight direction in the plane of the tilted magnetic field. Modelling of the observational evidence for the influence of active region magnetic fields on acoustic signals will aid in understanding, and potentially ameliorating, the showerglass effect which obscures our view of deeper features.

1. INTRODUCTION

Magnetic fields on the solar surface have been shown to significantly scatter and reduce the energy of acoustic waves (Braun 1995). Consequently, Lindsey and Braun (2003, 2004) have discussed how a “showerglass” effect may play havoc with the coherency of near surface acoustic waves. It is critical to examine the effects of surface magnetic fields on the phase and amplitudes of p-modes, since to date, none of the local helioseismic techniques have adequately considered the role of these effects on inferences of subsurface structure. The correlation between the magnetic field strength and the phase perturbations of the showerglass effect are found to generally be high (Lindsey and Braun 2004). Considerable work has been done on the interaction of acoustic waves with the surface magnetic field. Crouch (2003) and Crouch and Cally (2003a,b) have shown that the interaction of the acoustic waves with the magnetic field depends on the angle between them. A uniform field absorbs more efficiently when the field is inclined from the vertical direction (Cally 2001; Crouch 2003), and so the overall perturbation of the acoustic wave is also thought to be enhanced. The purpose of this research is to gauge if and to what extent inclined magnetic fields are effecting the phase shifts of the acoustic waves, thereby contributing to the showerglass effect and potentially impairing seismic diagnostics of the shallow subphotosphere (Lindsey and Braun 2004).

In the quiet sun, the acoustic surface velocity is driven by a wave emerging from several Mm in depth with a predominantly vertical propagation. However, in the presence of strong surface magnetic field, the acoustic wave, converted to a slow magneto-acoustic mode, will produce photospheric motions with a velocity that, over a wave cycle, describes an ellipse whose major axis is tilted up to the inclination angle of the magnetic field. (e.g. Fig. 5). For simple polytropic models (Crouch and Cally 2003b), the degree to which this happens is dependent on magnetic field inclination and wave frequency. Observations of phase perturbations in a sunspot penumbra made at various viewing angles with respect to the magnetic field direction may allow us to confirm and quantify this effect. The properties of the velocity ellipse will depend on the magnetic field amplitude and the tilt of the field relative to the direction of the incident acoustic radiation. It might be expected, for example, that acoustic waves which propagate in the direction of the magnetic field will not be as greatly influenced by the presence of the field as waves for which the angle between the propagation direction and magnetic field is substantial.

Using Doppler observations from the MDI instrument, we examine phase perturbation in the penumbrae of two sunspots, as they possess a spreading sunspot field with various inclinations. The sunspots are viewed from different angles as they rotate across the solar disk from the east limb towards disk centre. The correlation of the ingression and the surface velocity within the penumbra is computed to determine the effect of the field on the acoustic wave. For one of the sunspots, vector magnetograph data is available and so the orientation and strength of the magnetic field can be directly assessed. In the next section, we briefly outline the principles of the holographic procedures and the correlation computation. This is followed by a description of the sunspots and the data employed in the analysis. A brief outline of the data reduction is included followed by a discussion of the results and concluding remarks.

2. PROCEDURE

Helioseismic holography has the ability to reveal subsurface features of the sun based on the observations of surface velocity (Lindsey and Braun 2000). The procedure infers the amplitudes of acoustic waves propagating through a focus placed within the solar interior, from which information about subsurface sources, sinks and scatters may be learned. For this study, the focal plane may be raised to the surface, allowing comparative observations of the surface velocities with acoustic waves propagating up to the surface through the interior (see Fig. 1). The amplitude of the incoming waves is what is called the ingression,

$$H_{-}(\mathbf{r},z,t)=\int_{a<|\mathbf{r}-\mathbf{r}'|<b} d^2\mathbf{r}\; G_{-}(|\mathbf{r}-\mathbf{r}'|,z,t)\psi(\mathbf{r}',t)\;, \tag{1}$$

which here is calculated at $z=0$. The Green's function represents the sub-surface disturbance at $(\mathbf{r},z,t)$ resulting from a unit acoustic impulse originating at surface co-ordinates $(\mathbf{r}',0,t')$. The computation is confined to an annulus or 'pupil' surrounding the focal point $\mathbf{r}$ with inner and outer radius a and b respectively. The ingression calculated in this way is essentially what *should* result from the incoming acoustic waves propagating from the pupil to the focal point, in the absence of magnetic fields or other surface perturbations.

Therefore, to ascertain the effect of a surface perturbation, such as a magnetic field, the ingression may be correlated with the surface velocity signal at the corresponding spatial position. In the space-frequency domain, the correlation is simply the product

$$C(\nu)=\langle\hat{H}_{-}(\mathbf{r},\nu)\hat{\psi}^{*}(\mathbf{r},\nu)\rangle_{\Delta\nu}. \tag{2}$$

where $\hat{\psi}$ represents the temporal Fourier transform of the surface disturbance ψ, and $\hat{H}_{-}$ represents the temporal Fourier transform of the ingression. The brackets indicate a summation over a frequency range $\Delta\nu$ of 1 mHz centred at 5 mHz. The magnetic influence is quantified by the phase of the correlation,

$$\Delta\Phi=\arg(C(\nu)). \tag{3}$$

The larger the deviation of the correlation phase (either negative or positive) from the mean, the larger the effect of the magnetic field upon the incoming acoustic wave.

Using MDI Dopplergram data sets (Scherrer et. al. 1995), two sunspots were studied, one in AR9026 and the other AR9033. The AR9026 sunspot was chosen as it was uniformly circular in the continuum image and had a fairly static magnetic field, making it quite a simple sunspot. It was observed from 3 June to 8 June 2000 as it crossed at a latitude of 20° from the east limb (heliocentric angle $\approx 60°$) to the central meridian. AR9033 has a more complex magnetic field topology making it interesting to see if the effect is preserved for a more capricious magnetic field. This sunspot was also located at about 20° latitude, observed from 7 June to 11 June 2000, both sunspots extant close to solar maximum.

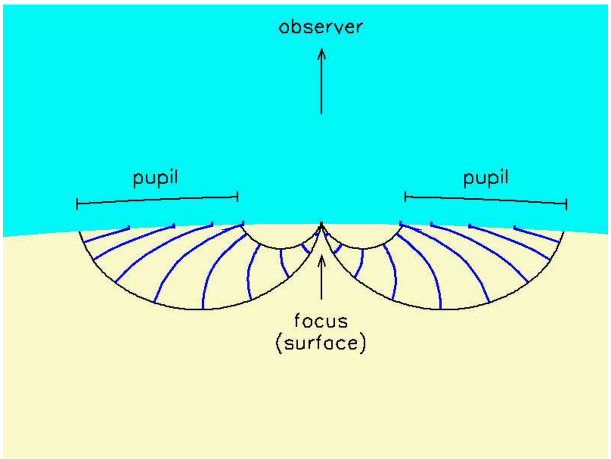

Figure 1. Holographic imaging of the surface. A cross-section of the Sun is represented, showing the acoustic radiation (blue wave fronts) which is observed in the pupil (annulus) and propagated numerically into the solar interior and up towards the surface. The ingression is compared with the velocity signal directly observed at the focal point in the centre of the pupil.

The full-disk MDI data were collated as 24 hour sets which were reduced to 60 degree square images centred on the active region in question. These were then Postel projected and Fourier transformed in time. From this the ingression was calculated and correlated to the surface Doppler signal. The pupil size in this case is $a=20.7$ Mm and $b=43.5$ Mm for the inner and outer radii respectively. A bias in the phase-shift, due to uncertainties in the Green's functions and measured from statistics of the quiet Sun, has been subtracted from the phase measurements.

3. RESULTS

To ascertain the existence of a line-of-sight variation in the phase shift, we plot the correlation phase against the azimuthal angle, ξ, around the penumbra (see Figs. 2 and 3). The inner and outer radii of the penumbrae for both spots was determined from MDI continuum images; these are $7.3-16$ Mm for AR9026 and $10.1-18.9$ Mm for AR9033. The horizontal axis of the plots represents the azimuthal angle where $\xi=0°$ is defined from spot

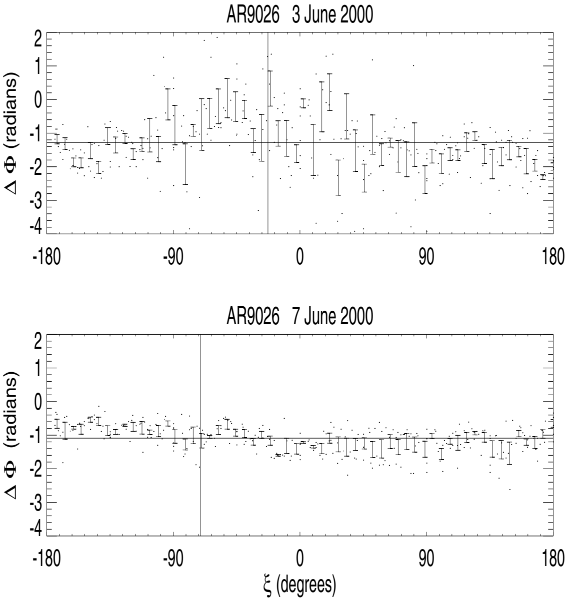

Figure 2. AR9026. The correlation phase $\Delta\Phi$ in the penumbra plotted against azimuthal angle ξ for AR9026 when the sunspot was: a) near the limb with disk centre in the direction of about $\xi = 22°$, and: b) closer to disk centre.

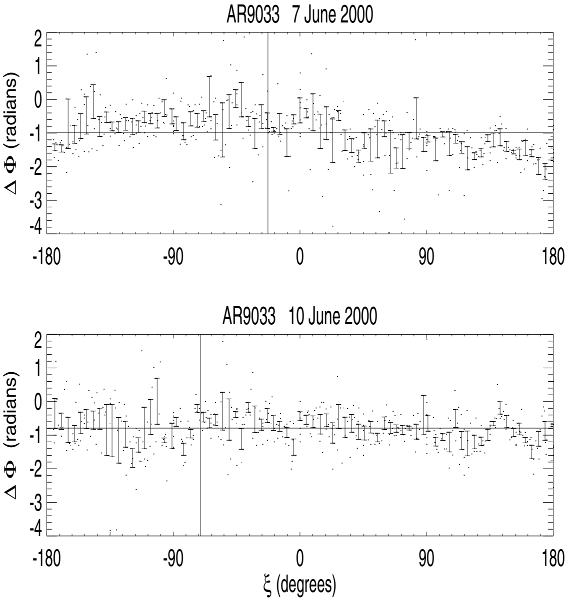

Figure 3. The same as Fig. 2, but for AR9033: a) near the limb with disk centre in the direction of about $\xi = 27°$, and b) closer to disk centre.

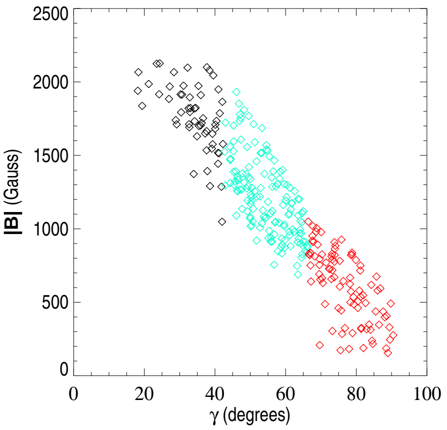

*Figure 4. Magnetic field strength vs. Inclination. The vertical axis is the magnetic field strength **B** (Gauss), the horizontal axis is the magnetic field's inclination from vertical γ (degrees)*

centre towards solar west, with a positive progression anti-clockwise. The top panels represent measurements obtained when both spots are $\approx$ 60° towards the east limb, and the bottom panels are obtained with the spots about 20° north of disk centre. The vertical lines represent the azimuthal direction to disk centre. The mean of the correlation phase is represented by a horizontal line to show the extent of the variation. The off-set of the mean from zero is consistent with previous determinations of the showerglass effect (Lindsey and Braun 2003, 2004) due to magnetic fields and represents a travel-time decrease relative to the quiet-Sun, possibly due to an acoustic Wilson depression and an underlying thermal perturbation (Braun and Lindsey 2000).

What is now observed for the first time is a clear variation of the phase shift with line-of-sight angle for both sunspots in the top panels of Figs. 2 and 3. At the limb the viewing angle is expected to change considerably with ξ around the sunspot. With a spreading penumbral magnetic field that is roughly axisymmetric, we might assume that when the sunspot is near the limb (top panels) the line-of-sight is significantly more aligned with the field in the direction towards disk centre than for the direction away from disk centre. When the spot is closer to disk centre, as in the bottom panels, the variation of the line-of-sight angle with respect to the field lines is more constant, which is true for both AR9026 and AR9033. This is consistent with the observations, which show significantly less variation of $\Delta\Phi$ with ξ when the spots are near disk centre. Figs. 2 and 3 show that the phase of the correlation is heavily dependent on the azimuthal direction around the spot and therefore, most likely, the line-of-sight angle.

For AR9026, data from the Imaging Vector Magnetograph (IVM) at the University of Hawaii Mees Solar Observatory (Mickey et. al. 1996) is available which provides the orientation and strength of the surface magnetic field in the sunspot. The IVM observations were made

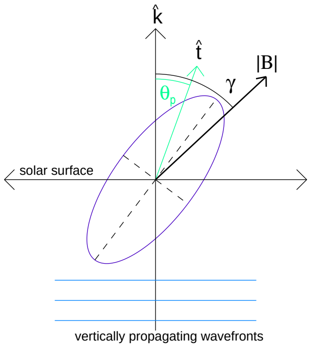

Figure 5. A simple pictorial view of the effect of an inclined magnetic field upon acoustic waves. Upcoming vertical waves impinge on the solar surface from below. The magnetic field vector **B***, the vertical vector,* $\hat{k}$ *and the line-of-sight vector* $\hat{t}$ *all lie in the same plane. The velocity has been inclined and developed a transverse component due to the presence of the magnetic field.*

during a 28 minute interval starting at 18:29 UT on 5 June 2000. Rotation and scaling was applied to align the IVM data to the line-of-sight MDI magnetogram. The magnetic field shows that the sunspot generally has a spreading field, but is not entirely symmetric. Fig. 4 exhibits the relationship between the magnetic field inclination, γ, and the magnetic field strength in the penumbra of AR9026. An inverse relationship between inclination and field strength is obvious; the more vertical field is stronger and the more inclined field is weaker. From the tight correlation in Fig. 4 it is evident that it is difficult to independently determine the variation of the phase shift with both field strength and inclination. Consequently, we divide the penumbral region into three bins, indicated by different colours. These bins define different values of the magnetic field inclination from vertical: $\gamma < 42°$, $42° < \gamma < 66°$ and $\gamma > 66°$, and largely correspond to increasing distance from the centre of the sunspot. The mean magnetic field strengths in the three bins are 1900, 1400 and 600 Gauss. We have assumed, supported largely by available line-of-sight MDI magnetograms, that there was no significant evolution of the magnetic field in the sunspot in AR9026 during the three days, June 3 - 5 2000.

Basic considerations of the interaction of acoustic waves with magnetic fields suggest that, for a uniform (but tilted) magnetic field, only the wave components of displacement (or velocity) in the plane defined by the magnetic field and the direction of propagation are on average non-zero. We define θ_p as the angle of the line-of-sight $\hat{t}$ from vertical, projected into the plane containing the magnetic field **B** and $\hat{k}$. We expect that the phase shift between the ingression and surface amplitude should depend only on the magnitude and inclination of the field as well as the projected line-of-sight angle θ_p.

Having the full vector magnetic field allows us to study the effect of the phase shifts with line-of-sight angle, independently of considerations or assumptions of the field symmetry (as in Figs 2 and 3). However, it is useful to see how, for most penumbrae, the variation of azimuthal angle with a sunspot away from disk centre maps into a variation of θ_p. For the typical spreading penumbral field, when the plane defined by the magnetic field and the vertical direction is aligned with the plane defined by the line-of-sight and vertical directions, then θ_p has either a large positive or negative value, corresponding to the direction towards or away from disk centre, respectively. When the magnetic field is in a plane perpendicular to the line-of-sight plane, then θ_p will be zero. In addition, the maximum value of $|\theta_p|$ is the heliocentric angular distance of the sunspot from disk centre.

The three panels of Fig. 6 show the variation of $\Delta\Phi$ with θ_p for the three bins of γ to get a general idea of the behaviour with increasing inclination (or magnetic field strength). Three days data for AR9026 are represented by different colors in each of the panels; 3 June (black), 4 June (green), 5 June (blue). Along the horizontal axis is the projected angle θ_p in degrees and the vertical axis is the correlation phase $\Delta\Phi$ in radians. For 3 June, when the sunspot is near the limb, there is a larger spread in θ_p than for 5 June when it has moved closer to disk centre.

It is apparent from Fig. 6 that for the top two panels, there is a significant variation of $\Delta\Phi$ with θ_p. The effect is cleanest for mid-values of γ (Fig. 6, middle panel) where the total variation is on the order of 2 radians (120°), and perhaps slightly larger in stronger, more vertical, fields (top panel). There is more scatter in the top panel, which is likely due to the significant decrease in the acoustic amplitude with increasing magnetic field strength. It is difficult to assess whether a variation with θ_p exists in the weaker fields in the outer penumbra (bottom panel) given the current observations. We interpret the variation of the phase in Fig. 6 as evidence that the phase shift introduced by magnetic fields depends on the line-of-sight angle with respect to the magnetic field inclination, consistent with the concept that the wave velocity does in fact have a significant component along the direction of the magnetic field vector at the surface. The previous discussion of the variations of $\Delta\Phi$ with ξ shown in Figs. 2 and 3 is consistent with this interpretation. For the points plotted in the middle panel of Fig. 6, the inclination of the magnetic field is around 60°. Thus, as θ_p varies from $-60°$ to $+60°$, we are observing at an angle with respect to the field ranging from $+120°$ to $0°$ as we move around the sunspot penumbra.

4. CONCLUSIONS

The results from simple models predict that the upcoming acoustic wave interacts with the magnetic field so that at the surface the velocity vector is somewhat aligned with the magnetic field direction. The correlation phase, which expresses the effect that the magnetic field has had

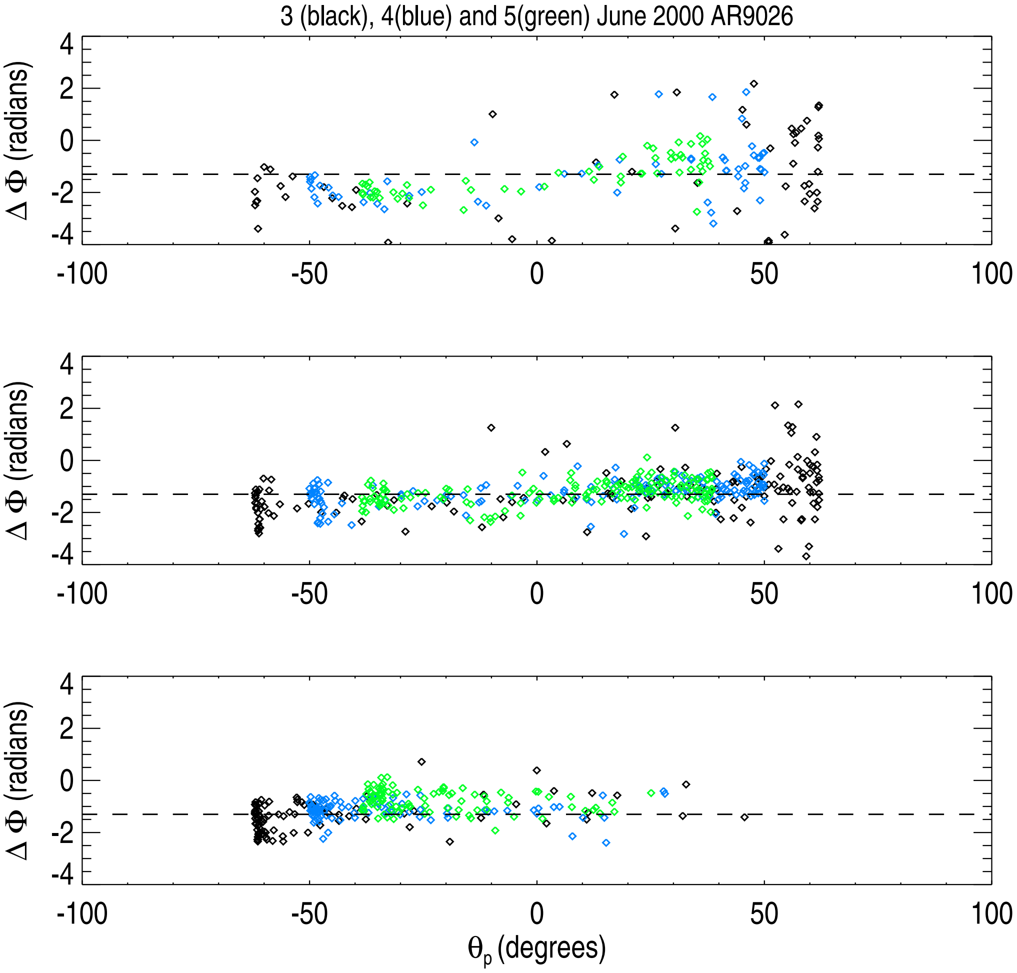

Figure 6. AR9026: the correlation phase ($\Delta\Phi$) against projected angle, θ_p. Three consecutive days are represented, 3 June 2000 is black, 4 June 2000 is green and 5 June 2000 is blue. The narrowing of the range for θ_p is synonymous with the changing viewing angle as the sunspot crosses the solar disk. The three different panels represent different portions of the penumbra, as shown in Fig. 4. The top panel shows $\gamma < 42^\circ$, $\langle \boldsymbol{B} \rangle = 1900$ Gauss, the middle panel shows $42^\circ < \gamma < 66^\circ$, $\langle \boldsymbol{B} \rangle = 1400$ Gauss and the bottom panel shows $\gamma > 66^\circ$, $\langle \boldsymbol{B} \rangle = 600$ Gauss.

on the incoming wave clearly varies with ξ, with an amplitude that depends on the heliocentric distance of the sunspot from disk centre. The sense is that there is a significantly smaller phase-shift when one is observing along the direction of the magnetic field, compared to when the field is perpendicular to the line-of-sight. Using vector magnetograph observations, the effect is confirmed by plotting the correlation phase against projected line-of-sight angle. The strength of the effect is dependent on the magnitude (and/or inclination) of the magnetic field, there being apparently less variation with θ_p for weaker (more inclined) fields. The next step is to determine the velocity ellipse of the wave motion from this data, and to compare the results with simple models.

These findings have obvious and important implications for understanding and modelling the showerglass effect, and for interpretation of local helioseismic measurements around and beneath sunspots. It is significant that within sunspot penumbrae, the variation of the phase shifts at 5 mHz with viewing angle about the mean phase shift is comparable to the mean itself. As it is difficult to conceive of any subsurface perturbation that could produce this variation, these findings argue that a significant, perhaps dominant, component of the phase shift must have a superficial origin. At the very least, we hope our results can encourage local helioseismologists exploring the subsurface structure of active regions to consider details of the magnetic field, including the geometry.

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