FULL TITLE
ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**
NAMES OF EDITORS

Behaviour of Acoustic Waves in Sunspots

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Abstract. Because helioseismology uses surface signals to calculate subsurface characteristics the behaviour of surface acoustic oscillations in sunspots is important in interpreting helioseismic results. SOHO-MDI Doppler velocity analysis of AR9026 and AR9033 at 3, 4 and 5 mHz, using helioseismic holography, show that the amplitude and the phase in the correlation of the acoustic ingression with the observed surface velocity are found to be sensitive to the relative line-of-sight angle in the penumbra of both sunspots. This is consistent with a conversion of vertically propagating acoustic waves into magneto-acoustic waves with motion described by ellipses.

1. Introduction

Local helioseismic techniques have been used to infer sound speed anomalies and flows beneath sunspots (e.g. Fan et al. (1995); Kosovichev et al. (2000)) which sometimes differ substantially in describing the depth of the anomalies. Lindsey & Braun (2005a,b) have discussed the possible contribution of surface magnetic fields to the phase of observed helioseismic signals. An acoustic wave is observed to lose up to half its energy in traversing a sunspot (Braun et al. 1987). A possible explanation is offered by Crouch & Cally (2003): the extent of absorption is determined by mode-conversion occurring where the sound speed (c_s) and the Alfvén speed (a) are comparable and is dependent on the magnetic field orientation. This is based on a model employing modal analysis with a uniform inclined magnetic field. Cally (2006) describes a model based on ray theory which can determine how much energy is mode converted (the 'transmission coefficient'). The slow acoustic wave is guided by the magnetic field lines in regions where $c_s \ll a$ - close to the surface. It may be this slow mode that is inherently determining the phase shifts of surface oscillation signals.

Using the Solar and Heliospheric Observatory's Michelson Doppler Imager (SOHO-MDI ; Scherrer et al. (1995)) Dopplergrams, as input for helioseismic holography, and the Imaging Vector Magnetograph (IVM; Mickey et al. (1996)) magnetograms Schunker et al. (2005) found variations of phase shifts of the Doppler signal with the line-of-sight angle in the penumbrae of sunspots. This paper presents work that builds upon and updates the analysis of Schunker et al. (2005) adding support to the claims that the acoustic oscillations are affected by the presence of the surface magnetic field.

Section 2 outlines the additional analysis and results of the data presented in Schunker et al. (2005) The modelling has further been developed by Cally and will be briefly discussed in relation to the observations in Section 3. Section 4 offers a discussion of the results and possible implications for helioseismology.

2. Results

Two sunspots were selected for study: the primary sunspots in AR9026 and AR9033. These were observed over 10 days (3rd -12th June 2000) and 6 days (7th - 12th June 2000) respectively. We first calculate the holographic ingression H_{-}, and correlation, C, between the H_{-} with direct surface signal, Ψ, for waves with a temporal frequency between 4.5 and 5.5 mHz within the penumbrae of the sunspots for each day (see Schunker et al. (2005)). The angle, θ_p (Fig. 1), is the angle between the radial vector normal to the surface and the line-of-sight vector projected onto the plane containing the magnetic field and radial vectors.

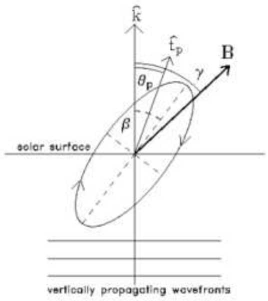

Figure 1. The definition of θ_p. A plane containing the magnetic field, $\mathbf{B}$, of inclination, γ, and the radial vector, $\mathbf{k}$, is constructed. The line-of-sight vector, $\hat{\mathbf{t}}$, is not necessarily in the same plane, and so it is projected onto the plane, $\mathbf{t}_p$. The angle between $\hat{\mathbf{t}_p}$ and $\mathbf{k}$, is θ_p. A hypothetical velocity ellipse of β inclination is superimposed, which is expected if the surface velocity is indeed being guided by the magnetic field direction.

Schunker et al. (2005) discusses the dependence of the $\delta\phi = \arg(C)$ with the line-of-sight angle in more detail, but relevant details are highlighted here. The penumbra is divided into three regions of magnetic field vector inclination, γ, and the strength of the field is found to generally have a strong linear relationship with the inclination. There is a clear dependency, in fig. 5 of Schunker et al. (2005), of the correlation phase on the angle from which the magnetic surface is viewed from. It is worth noting the geometrical implications of the value of θ_p. Larger projected inclinations are achievable when the sunspot is towards either limb. If $\mathbf{t}_p$ points towards $\mathbf{B}$ (like fig. 1) θ_p is positive. A negative value of θ_p indicates lines-of-sight which tilt away from $\mathbf{B}$. Here we present further results from AR9026 exploring the surface velocity signals within the penumbra.

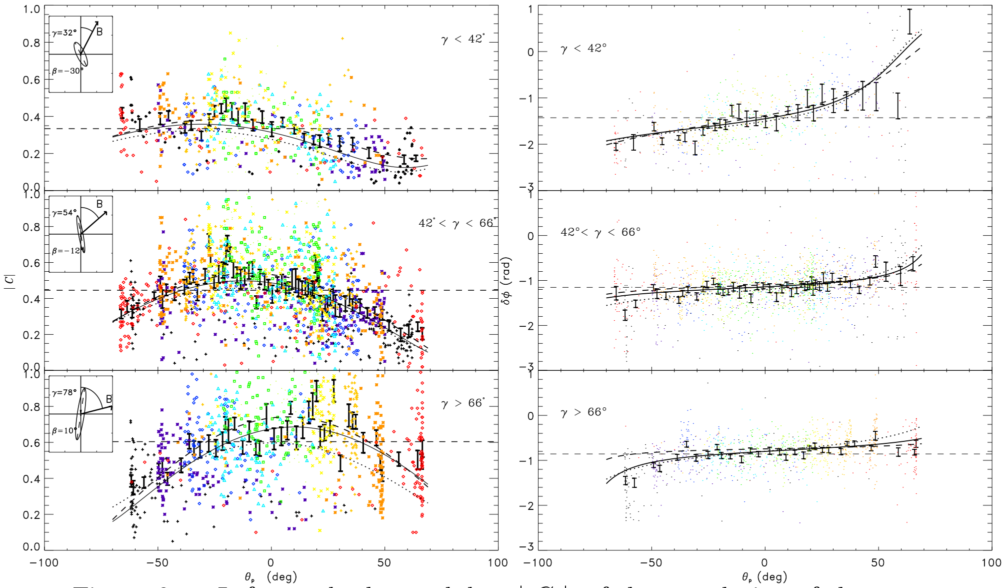

Figure 2. Left panel: the modulus, $\mid C \mid$, of the correlation of the sunspot in AR9026. For clarity, the velocity ellipse, normalised to the quiet-Sun ingression amplitude, determined by a least-squares fits to the data is shown in the top-left corner of each panel. The magnetic field vector is drawn at an angle of the *average* γ for the corresponding data. β is the inclination of the ellipse. Right panel: the argument, $\delta\phi$, of the correlation. They are both divided into segments based on γ. The horizontal dashed line is the mean of $\mid C \mid$ and $\delta\phi$. The solid curve is the best fit for all of the days observed. The dotted curve represents the fit for 3rd - 7th June 2000. The dashed curve represents the fit for 8th - 12th June 2000.

The left panel of fig. 2 plots the dependence of the modulus of the correlation, $\mid C \mid$ of AR9026 upon θ_p. The right panel is the same as fig. 5 of Schunker et al. (2005), with the addition of least-squares fits to elliptical motion. The IVM magnetogram was observed on 5 July, and the sunspot did not evolve significantly over the days. The trends are similar for two halves of the time series (dotted and dashed lines). The left panels also show the relevant surface ellipses derived from $\mid C \mid$ and $\delta\phi$ for that particular range of γ. The average inclination angle of the magnetic field is also shown. For $\gamma < 42°$ the velocity ellipse is inclined by $\beta = -30°$ with a relatively small amplitude of $\mid C \mid \sim 0.34$. The amplitude increases and β decreases with larger γ which agrees with observations that stronger magnetic fields are more inhibiting to p-modes. The tilt, β, is actually inclined *toward* the magnetic field for $\gamma > 66°$, although not by much. Due to the evolution of the magnetic field over the course of the 6 days, a similar analysis of AR9033 reveals similar but less reliable results.

3. Mode Conversion

? has recently developed a simple 2D model of mode conversion within the near subsurface of a sunspot (Fig. 3). Using a uniform, inclined typical sunspot field strength of several thousand Gauss, a ray is propagated through the atmosphere,

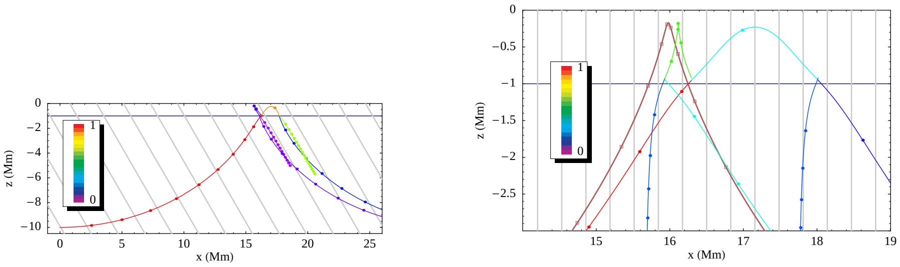

Figure 3. The 2D propagation of an acoustic fast mode in a polytrope in the presence of an inclined magnetic field (left) and a vertical field (right). The incoming ray (darkest), splits in the $a \sim c_s$ region (horizontal line) into a slow and fast wave. It is clear that the slow wave follows the direction of the magnetic field (slanting lines). The vertical axis is the depth (Mm) into the solar interior, where $z = 0$ is the surface. The horizontal axis is the spatial distance (Mm) in the x-direction. Each 'dot' along the ray path represents a one minute time interval.

and when it reaches the $a \sim c_s$ (set at $z = -1$ Mm in the figures) layer mode conversion occurs. The amount of conversion is dependent upon the sharpness of the $a \sim c_s$ layer as seen along the ray path s of wavenumber k, the frequency of the wave, and the 'attack angle' α (angle at which the ray approaches the field). This is expressed by the *transmission coefficient*,

$$T = \exp\left[-\frac{\pi k \sin^2 \alpha}{\left|\frac{d}{ds}\frac{{c_s}^2}{a^2}\right|}\right]_{a=c_s}, \tag{1}$$

which is the proportion of energy transmitted to the opposite branch (slow or fast). The grey-scale of Fig. 3 is indicative of T, the transmission energy. Fig. 3 (right) shows a clear depiction of the conversion in a uniform vertical magnetic field. Each time any part of the ray encounters the $a \sim c_s$ layer it undergoes ray splitting. From the minute interval ticks, it is clear to see which is the slow or fast wave. In the absence of magnetic field the surface acoustic velocity would be purely real and nearly vertical. The magnetic field adjusts the phase and also guides the direction of the wavevector, shown most clearly in fig. 3 (left).

4. Discussion

The phase variations are dependent on the line-of-sight angle suggesting a photospheric magnetic origin for much of the wave perturbation, which is supported by mode conversion theory. From these models (3) we expect the tilt of the ellipse, β, to be inclined towards the magnetic field vector, however from fig. 2 this does not *not* seem to be the case. It is curious to see that unlike what we expected, the velocity is *not* strongly aligned with the magnetic field direction.

We are in the process of analysing a third sunspot in AR9057, which is static during it's passage across the solar disk. The results will (hopefully) help clarify the nature of the surface velocities in the presence of magnetic fields.

It is uncertain whether we are observing the slow wave or the fast wave when observing surface acoustic waves within AR's. If we are observing the slow wave we should see these as field guided velocities but a fast wave would normally display no such alignment. We intend to take up the issue of the theoretical interpretation of these results in a future paper. However, we note that the behavior of the phase-shifts observed are consistent with elliptical oscillatory motion in the photosphere, in support of surface phase perturbations of the sort discussed by Lindsey & Braun (2005a,b). Zhao & Kosovichev (2005) have also observed qualitatively similar line-of-sight variations in the raw time-distance correlations themselves and infer only minor changes in the inferred sound-speed anomalies on different days. The issue of why different models infer qualitative and quantitatively different results beneath sunspots remains an interesting mystery in local helioseismology.

Acknowledgments. Thanks go to KD Leka for her time and generosity in providing the IVM magnetograms, as well as the Astronomical Society of Australia for partially funding the first author's ability to participate in the workshop.

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