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# Sunspot seismology: accounting for magneto-hydrodynamic wave processes using imaging spectropolarimetry

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**Abstract.** Effects of acoustic wave absorption, mode conversion and transmission by a sunspot on the helioseismic inferences are widely discussed, yet accounting for them has proved difficult for lack of a consistent framework within helioseismic modelling. Here, following a discussion of problems and issues that the near-surface magnetohydrodynamics hosts through a complex interplay of radiative transfer, measurement issues, and MHD wave processes, I present some possibilities entirely from observational analyses based on imaging spectropolarimetry. In particular, I present some results on wave evolution as a function of observation height and inclination of magnetic field to the vertical, derived from a high-cadence imaging spectropolarimetric observation of a sunspot and its surroundings using the instrument IBIS (NSO/Sac Peak, USA). These observations were made in magnetically sensitive (Fe I 6173 Å) and insensitive (Fe I 7090 Å) upper photospheric absorption lines. Wave travel time contributions from within the photospheric layers of a sunspot estimated here would then need to be removed from the inversion modelling procedure, that does not have the provision to account for them.

*Keywords* : sunspots – Sun: helioseismology – MHD

## 1. Introduction

Developments in sunspot seismology trace back to the original suggestion by Thomas, Cram & Nye (1982) that interactions between sunspots and helioseismic p modes could be used to probe the sub-surface structure of sunspots. The analyses that followed Thomas et al. (1982) focussed mainly on changes in the frequency - wavenumber spectrum ($\nu$ - k) and in the modal power distribution. These studies led to the discovery of 'absorption' of p modes by sunspots (Braun, Duvall & Labonte 1987):

about 50% of the flux of acoustic wave energy impinging on a sunspot is not observed to return to the quiet Sun. Development of several local helioseismic techniques, viz. the ring diagram analysis (Hill 1988), helioseismic holography (Lindsey & Braun 1990) and time-distance helioseismology (Duvall et al. 1993), has since brought in new ways of probing the subsurface structure and dynamics of sunspots. However, the question, viz. is a sunspot formed, in the sub-surface layers, of a monolithic flux tube or a cluster of flux tubes?, still remains to be answered. An answer to this question would also address the dynamics of heat and material flow in and around sunspots, and hence would have far reaching implications for the magnetohydrodynamics of solar and stellar magnetism.

Applications of time-distance helioseismology appeared as a promising avenue with its 3-dimensional tomographic images of flow and sound speed structures beneath sunspots (Kosovichev, Duvall & Scherrer 2000; Zhao, Kosovichev & Duvall 2001). These early results showed an increased sound speed region extending from about 4 Mm down to about 18 Mm with a maximum change of about 1 - 2 %, while the near surface layers in the 1 - 3 Mm depth range show a decrease in sound speed of similar magnitude. The flow pattern (Zhao et al. 2001) consists of a shallow (1.5 - 3.0 Mm) converging flow that feeds a strong downflow beneath the sunspot (Duvall et al. 1996) up to depths of about 5 Mm. Though these results have features indicative of the cluster model (Parker 1979), new developments and improvements in several different fronts in local helioseismology have served to emphasise the inadequacy of such analyses (Gizon et al. 2010). In contrast to results from time-distance helioseismology, studies based on phase sensitive holography (Braun & Lindsey 2000) have shown phase shifts of waves consistent with a faster propagation in the near surface layers, in direct correlation with the surface magnetic proxies (e.g. LOS magnetogram signals), and which decrease monotonically with depth becoming undetectable at layers deeper than about 5 Mm. Recent new ways of travel time measurements and inversions (Moradi et al. 2010; Svanda et al. 2011) show that the moat outflows around sunspots extend much deeper (up to about 4 - 5 Mm). These new developments have brought to the fore the dominant direct interactions between acoustic waves and magnetic fields, which leave too large a signal in measurements to be treated with the conventional methods of seismic inversions that club such effects into thermal perurbations.

The early contentions that p mode absorption of sunspots could be used to probe them, thus, have come around a full circle to the realization, through theoretical attempts at explaining the above surface effects (Cally, Crouch & Braun 2003; Crouch & Cally 2005; Schunker et al. 2006), that they are the very processes that need to be accounted for before we proceed further in the application of the later developed local helioseismic techniques.

## 2. New developments: unreliability of old results

The physical setting and nature of changes in the global structure and dynamics of the Sun is consistent with a conventional helioseismic analysis procedure, viz. a linear first order perturbation to the equilibrium structure of the Sun that the p mode frequencies effectively sense. However, such a treatment is much less adequate to probe the influence of sunspots in the near surface layers. The major sources of inadequacy in the local helioseismic analyses of sunspots, as have been gleaned from recent research, can be identified to arise from two basic causes: (i) inadequate understanding and modelling of the interactions between the acoustic waves and the sunspots, where magnetohydrodynamic effects dominate, and (ii) inadequate identification of the helioseismic observables due to complexities in the observation and measurement procedures themselves. However, much of what are known as 'surface magnetic effects' contain subtle inter-mixture of physical, measurement and analysis issues and hence have contributions from both the above causes.

## 2.1 Surface magnetic effects

The neglect of direct magnetic effects due to the pressure and tension forces of the magnetic field on the wave speed, while inverting either the travel times or frequency shifts, is the foremost of issues arising from the cause (i) above. Interesting, but not yet fully understood, revelations on the seismic disguises of the dominantly near-surface interactions between the magnetic field and acoustic waves came forth from analyses based on phase-sensitive holography (Braun & Lindsey 2000): the 'showerglass effect' of Lindsey & Braun (2005a) and the 'inclined magnetic field effect' of Schunker et al. (2005). The former effect refers to strong surface phase perturbations that the upcoming acoustic waves in active regions undergo resulting in impairment of their coherence, similar to the blurring of images seen through a commercial showerglass. These are measured as phases of the so called 'local control correlations' of *ingressing* (ingoing) and *egressing* (outgoing) waves with wavefield observed at a particular point in active region (or sunspot) and are found to increase almost exponentially with magnetic field strength $B$. The 'inclined magnetic field effect' pertains to the penumbral regions, where there are anomalous changes that depend on the inclination angle of the magnetic field and the line of sight angle of observations (Schunker et al. 2005). To correct for the showerglass effect Lindsey & Braun (2005b) devised a magnetic proxy, which is a complex amplitude that depends on $B^2$ and is nothing but the reciprocal of the appropriate local control correlation. 'Corrected measurements' follow upon multiplying local surface signal with the above proxy. Such corrections (Lindsey & Braun 2005b) show that the sub-surface acoustic anomalies disappear below a depth of $\approx$ 5 Mm, in contrast to the time-distance helioseismic inferences (Duvall et al. 1996; Kosovichev et al. 2000).

It is also likely that additional effects such as changes in the path length of the waves due to thermal expansion or contraction make significant contributions of either sign, and hence incorrect estimates of changes in sound speed from those in travel times. In particular, the path length changes associated with the Wilson depression and the propagating nature of (magneto-)acoustic waves (due to reduced cut-off frequency) would add contributions of opposite signs in the wave travel times. Clearly, neither thermal nor magnetic perturbations alone can explain the inferences.

### 2.2 Observational issues: radiative transfer effects

The altered thermal conditions in sunspots mean that the transfer of spectral line radiation is different from that in quiet Sun, and in the case of Zeeman sensitive lines the polarization and shape of the line interfere with the Doppler measurement procedure. With the added situation that the character of waves also are changed due to the magnetic field, radiative transfer effects manifest in Doppler velocity signals through subtle interaction of the above changes: the second basic cause [case (ii)] described earlier, viz. inadequate identification of the helioseismic observables due to complexities in the observation and measurement procedures themselves. Here the helioseismic observable is the phase or travel time of a wave observed within a sunspot. Because the magnetic field lowers the acoustic cut-off frequency, and because it converts some of the incident acoustic waves into upward propagating ones confined to follow the field lines, the phases of waves measured within sunspots depend sensitively on the height within the line forming layers. Any line of sight angle dependent changes in (line) optical depth would then manifest as changes in the wave phases, i.e. different locations within a sunspot located at an off-disk center position would yield different phases for waves. This radiative transfer effect has been brought out clearly in an observational study of a sunspot in Ni I line (6768 A) using the Advanced Stokes Polarimeter (ASP) at the Dunn Solar Telescope of the National Solar Observatory at Sac Peak, Sunspot, New Mexico (Rajaguru et al. 2007).

## 3. Helioseismic signatures of wave evolution in the observable layers: an example

As an example of the near-surface effects discussed in the previous Section, I present here results of a study using a high cadence imaging spectropolarimetric observation of a sunspot and its surroundings in magnetically sensitive (Fe I 6173 Å ) and insensitive (Fe I 7090 Å ) upper photospheric absorption lines. The results of this study have already been published (Rajaguru et al. 2010) and we refer the readers to this original paper for a detailed account. We restrict ourselves here to a brief account of the observations and major physical implications of the results. The observations were made using the Interferometric BI-dimensional Spectrometer (IBIS) installed at the Dunn Solar Telescope of the National Solar Observatory, Sac Peak, New Mexico, USA. We observed a medium sized sunspot (NOAA AR10960, diameter $\approx$ 18 Mm) located close to the disk center (S07W17) on 2007 June 8. Our observations involved scanning and imaging in all the Stokes profiles ($I, Q, U, V$) of magnetic Fe I 6173.34 Å and in Stokes $I$ of non-magnetic Fe I 7090.4 Å , with a cadence of 47.5 s. A 7 hr continuous observation was chosen for our analysis

Line-of-sight (LOS) velocities of plasma motions within the line forming layers are derived from the Doppler shifts of line bisectors. We use 10 bisector levels with equal spacing in line intensity, ordered from the line core (level 0) to the wings (level 9), and derive 10 velocity data cubes, $v_i(x, y, t)(i = 0, ..., 9)$, for each line. For the magnetic line, we use the average of bisector velocities from the left $(I + V)$ and right $(I - V)$ circular polarization (CP) profiles (Sankarasubramanian & Rimmele 2002; del Toro Iniesta 2003) and those from the $I$ profile for the non-magnetic line. The 10 bisector levels span the height range within the line formation region in an unique one-to-one way.

### 3.1 Instantaneous wave phases and helioseismic travel times

Instantaneous wave phases in the form of phase shifts $\delta\phi_{i,0}(\nu)$=Phase$[\mathbf{V}_i(\nu)\mathbf{V}_0^*(\nu)]$, where $\nu$ is the cyclic frequency of a wave and $\mathbf{V}$ is the Fourier transform of $v$, due to wave progression between two heights corresponding to any one of the bisector levels $i = 1, 2, ..., 9$ and level 0 (the top most layer) are calculated (Rajaguru et al. 2007). The 10 different data cubes from each line are run through a standard $p$-mode time-distance analysis procedure in center-annulus geometry (Rajaguru et al. 2004). Here, travel times for $\Delta = 16.95$ Mm are analysed, because, given the sizes of observed region (radius $\approx$ 29 Mm) and the spot (radius $\approx$ 9 Mm), this is the optimum $\Delta$ that facilitates distinguishing clearly the ingoing and outgoing waves in the sense of their interactions with the spot. Height dependent contributions to out- and ingoing phase travel times $\tau^+$ and $\tau^-$ from within the line forming layers are determined using $\delta\tau^{\pm}_{i,0} = \tau^{\pm}_0 - \tau^{\pm}_i$ $(i = 1, ..., 9)$.

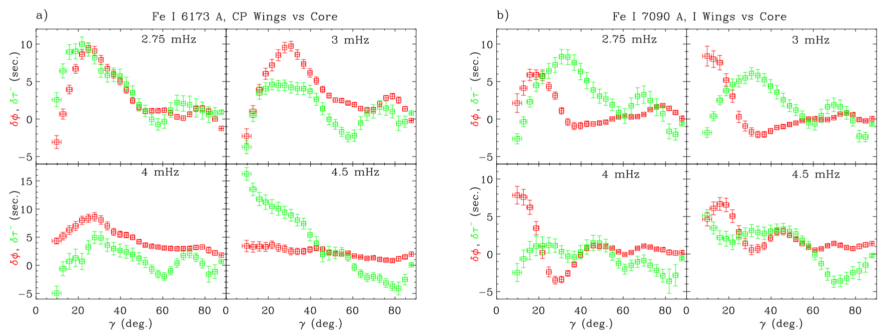


**Figure 1.** Instantaneous phase shifts, $\delta\phi_{8,0}(\nu)$, and changes in ingoing wave travel times, $\delta\tau^-_{8,0}$, due to wave propagation between the formation heights of wings (20 km) and core (270 km) of Fe I 6173 Å (panel a), and of Fe I 7090 Å (panel b) against $\gamma$ of B.

We show in Fig.1 $\delta\phi_{8,0}$ and $\delta\tau^-_{8,0}$, due to wave evolution within the region bounded by the wing (level 8) and core (level 0) formation heights, against $\gamma$. The $\nu$ values marked in the panels of Figure 1 are the central frequencies of 1 mHz band filters used. Keeping in mind that $\delta\phi_{8,0}$ have contributions from a larger set of waves (as discussed above), results in Fig. 1(a) for the magnetic line show a surprising amount of correlation between the two measurements, and moreover exhibit a strikingly similar $\gamma$ dependence. These results immediately reveal several interesting aspects of magnetic field - acoustic wave interactions: (1) first of all they confirm that helioseismic waves incident on the sunspot see themselves through to higher layers of its atmosphere with a striking dependence on $\gamma$: a coherent let through of incident waves happen, peaking around $\gamma \approx 30°$, maintaining a smooth evolution of time-distance correlations; (2) remembering that CP profiles of the magnetic line have maximum sensitivities for velocities within vertical magnetic field, it is seen that a large fraction of waves propagating upward within such field are due to helioseismic waves originating at distant locations; and, (3) provide direct evidences that ingoing wave travel times would cause observing height dependent signals in flow inferences from travel time differences.

Outgoing waves at a given measurement location, in general, would consist of those locally generated and those generated elsewhere undergoing reflection at the photosphere directly below it. These latter components would be seen in neither $\delta\phi_{i,0}$ nor $\delta\tau^{\pm}_{i,0}$, as they are evanescent at the observing height. For locally generated waves, circular wavefronts form a source, while their upward propagating parts see themselves up through the magnetic field, would cause outgoing wave correlations yielding distinct signatures in $\delta\tau^{+}_{i,0}$ (see Fig.2(b)). Results in Fig.2(a), for $\delta\tau^{+}_{8,0}$ from both the magnetic and non-magnetic lines, do indeed provide such a diagnostic: outgoing waves starting at higher height (line core) within the sunspot atmosphere and reaching the quiet-Sun at the chosen $\Delta$ have shorter travel times than those starting at a lower height (line wings) and reaching the same quiet-Sun location; since this is simply not possible, the only explanation for this observation is the one contained in our previous sentence and illustrated in Fig.2(b), viz., outgoing wave time-distance correlations are predominantly due to waves directly from sources just beneath the sunspot photosphere when oscillations observed within it are used.

## 4. Discussions and conclusion

Almost all time-distance helioseismic analyses proceed under the working assumption that wave signals at observation heights are evanescent and hence oppositely directed wave paths involving photospheric reflections at two separated points are of identical path length. This assumption is basic to the inferences on flows and wave speed from travel time differences and mean, respectively. In an early theoretical study, accompanied by attempts to model the helioseismic observations of Braun (1997), Bogdan, Braun, Lites & Thomas (1998) showed the influences of both the $p$-mode forcing of, and spontaneous emissions by, sunspots on acoustic wave travel times. Our analyses here have yielded transparent observational proofs for both effects, for the first time, with important new perspectives: (1) the process of transformation of incident acoustic waves into propagating (magneto)-acoustic waves up through the magnetic field hap-

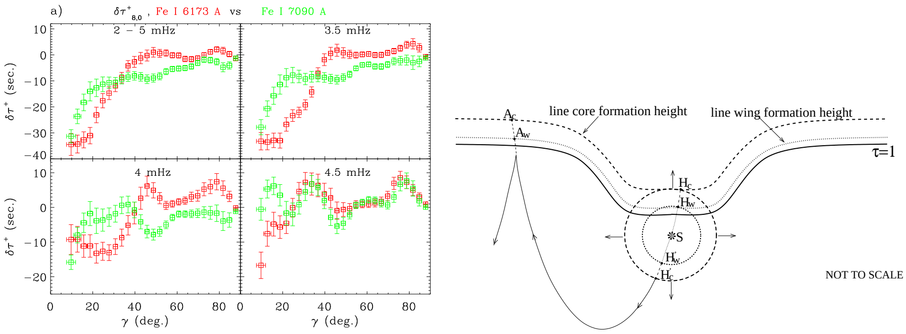


**Figure 2.** Changes in outgoing wave travel times, $\delta\tau^{+}_{8,0}$, due to wave propagation between the formation heights of the wings (20 km) and the core (270 km) of Fe ɪ 6173 Å (in red) and 7090 Å (in green) lines as a function of $\gamma$ of B. (Panel b), a cartoon depicting wavefronts from acoustic sources beneath the umbra, wave paths and line formation heights (see text for details).

pen in a coherent manner allowing a smooth evolution of time-distance correlations and, in agreement with several recent theoretical and numerical studies (Cally 2005; Crouch & Cally 2005; Schunker & Cally 2006), this process depends on the inclination angle ($\gamma$) of magnetic field to the vertical, and (2) outgoing waves from acoustic sources located just beneath the sunspot photosphere add important additional contributions for both mean travel times and differences. Our results have also shown observational prospects for consistently accounting for the above effects in sunspot seismology, viz. the indispensability of imaging spectroscopy to extract wave fields so as to be able to correctly account for the wave evolution within the directly observable layers of sunspot atmosphere.

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