THE PENUMBRAL ACOUSTIC ANOMALY

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ABSTRACT

The magnetic photosphere can introduce large phase shifts to waves arriving into it from below, significantly impairing their coherence. This is the function of a shower glass in electromagnetic radiation. An important aspect of the acoustic showerglass is the dependence of the surface signature of upcoming acoustic waves on inclined magnetic fields, such as are characteristic of the penumbrae of sunspots. Holographic control correlations focused on magnetic regions show a conspicuously enhanced phase shift in sunspot penumbrae, which we call the penumbral acoustic anomaly. 3-D Numerical simulations of magneto-acoustic noise waves from the solar interior impinging into magnetic photospheres can greatly facilitate realistic thermal modeling of magnetic subphotospheres.

Key words: local helioseismology, sunspots, magnetic fields.

1. INTRODUCTION

A major obstacle that encumbers local seismic diagnostics of the shallow subphotospheres of strong active regions is relatively large phase shifts introduced by overlying surface magnetic fields. These phase shifts function as a sort of "acoustic showerglass" that impairs the coherence of acoustic waves impinging into the solar surface from below, degrading phase-coherent diagnostics such as time-distance correlation measurements and phase-coherrent seismic imaging of subsurface anomalies. Computational seismic holography makes it possible to measure phase and amplitude perturbations introduced in magnetic photospheres to the signatures of upcoming waves. A large part of the perturbation is understood to be due to the physics of magnetic forces on motion driven by the wave (Cally & Bogdan, 1993; Cally, 2000; Schunker et al., 2004). Another significant contributor is likely to be the different thermal structure of the upper few hundred km of the magnetic subphotosphere, particularly in the case of sunspot umbrae and penumbrae. A clear understanding of the physics of the former together with state-of-the-art helioseismic diagnostics could facilitate realistic modeling of the latter.

The clear understanding of the physics is a major undertaking, including the application of powerful computing facilities to simulate magneto-acoustic wave mechanics in the shallow subphotosphere (Cally & Bogdan, 1993; Cally, 2000; Werne, 2004; Manseur, 2004). In this study we address the problem of what helioseismic diagnostics can tell us.

2. PROCEDURE

We compute maps of the local holographic control correlations focused in active region subphotospheres to assess the acoustic perturbations that characterize the photospheric acoustic signatures of magnetic regions. The basic procedure is described in greater detail by Lindsey & Braun (2004b). The emphasis of that study was relatively high frequencies, 4.5–5.5 mHz. Since then we have examined the 2.5–3.5 mHz spectrum in somewhat more detail.

We compute holographic projections, $H_\pm^{\mathcal{P}}$, of the acoustic field, ψ, from regions, $\mathcal{P}$, in the quiet Sun to focal points in magnetic regions to determine the effects of magnetic fields on waves arriving into the magnetic photosphere (see Lindsey & Braun, 2000). The "coherent acoustic *in*gression," $H_-^{\mathcal{P}}(\mathbf{R},\ \nu)$, represents the forward progression in time of the acoustic field, ψ, in a surrounding annular pupil, $\mathcal{P}$, to a focal point $\mathbf{R}$ at the solar surface in the center of the annulus (Lindsey & Braun, 2004a). $H_+^{\mathcal{P}}$ similarly represents the "coherent acoustic *e*gression," as the *re*gression of ψ from $\mathcal{P}$ back in time to the focus, $\mathbf{R}$. Statistics of the "local control correlations,"

$$C_{LC-}(\mathbf{R}) \;=\; \langle \psi(\mathbf{R},\ \nu)\, H_-^{\mathcal{P}*}(\mathbf{R},\ \nu)\rangle_{\Delta\nu}, \qquad (1)$$

and

$$C_{LC+}(\mathbf{R}) \;=\; \langle H_+^{\mathcal{P}}(\mathbf{R},\ \nu)\, \psi^*(\mathbf{R},\ \nu)\rangle_{\Delta\nu}, \qquad (2)$$

allow us to relate showerglass phase shifts to surface magnetic fields at $\mathbf{R}$. The angular brackets in equations (1) and (2) signify the average of their contents over a positive frequency range, represented by $\Delta\nu$.

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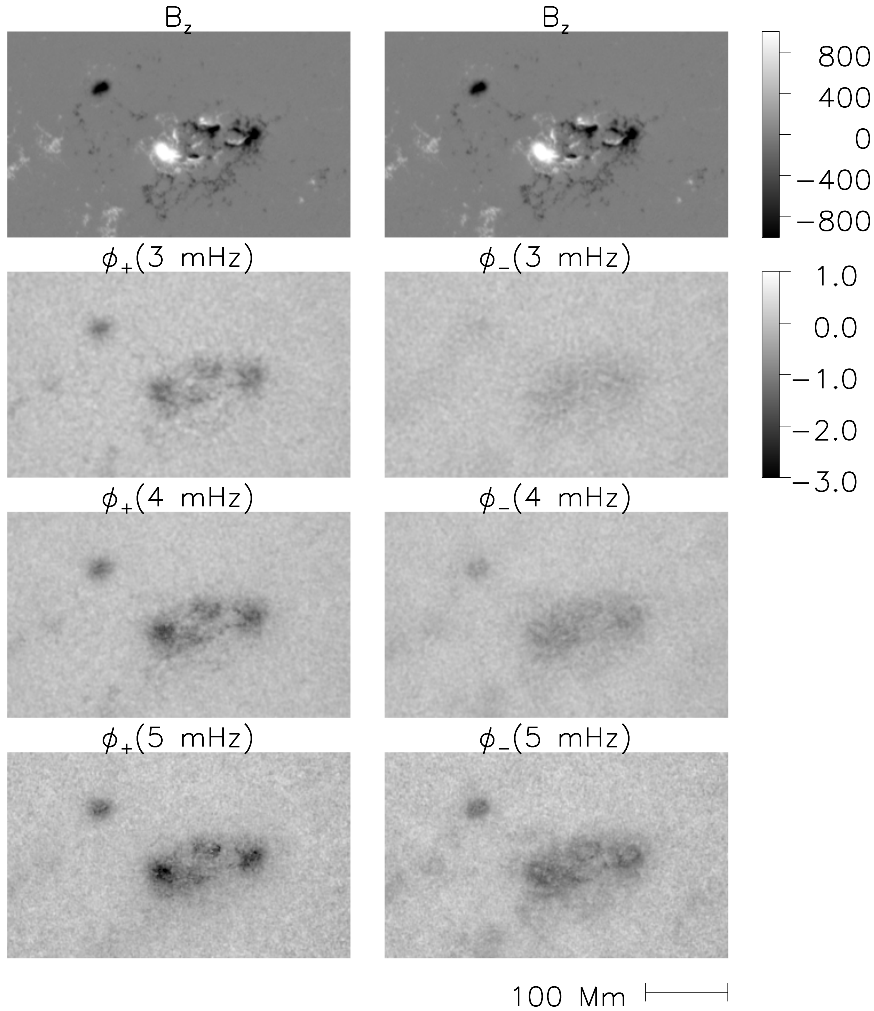

Figure 1. The phase asymmetry. The phase, ϕ_+, of the local egression control correlation, $C_+ = \langle H_+ \, \psi^* \rangle_{\Delta\nu}$, departs significantly from, ϕ_-, the phase of the local ingression control correlation, $C_- = \langle \psi \, H_-^* \rangle_{\Delta\nu}$, in a strong magnetic region (NOAA AR 8179, 1998 March 15 11:00–35:00 UT). This, effect, discovered by Duvall et al. (1999) (see also Braun, 1997), and sometimes attributed to flows, must be the result of an interaction between compression waves and magnetic regions that discriminates between temporal directions (past and future). It is possible that the phase asymmetry in the 2.5–4.5 mHz spectrum is largely the signature of a strong absorbing interaction between compression waves and magnetic fields in the shallow subphotosphere (Cally & Bogdan, 1993; Cally, 2000).

3. RESULTS

Fig 1 shows maps of the phases of the local control correlations of an active region, NOAA AR 8179, in 1 mHz bandpasses centered at 3, 4, and 5 mHz, integrated over a 24 hr period beginning at 11:00 UT on 1998 March 15:

$$\phi_{\pm} \;=\; \arg C_{LC\pm}. \qquad (3)$$

The local control correlations show a strong phase asymmetry between waves traveling into a magnetic photosphere, represented by ϕ_-, as compared with waves emanating from the magnetic region, represented by ϕ_+.

The local control correlations also exhibit a phenomenon we call the "penumbral acoustic anomaly," characterized by a conspicuous advance of $\phi_\pm$ in regions of inclined magnetic field. This is most pronounced in the ingression control phase, ϕ_-, at 5 mHz, where a more acute diffraction limit renders finer spatial resolution and greater statistics. The 5 mHz egression control correlation does not show this enhancement. At 3 mHz the enhancement is more apparent in the egression control correlation, although the statistics are weaker.

Figs 2–5 show diagnostic plots of the local control correlations for the 3 mHz and 5 mHz acoustic spectra, measured over NOAA AR 8185 integrated over the 24-hr period beginning 1998 March 27.0. The locus of the phase (lower right panel of each Fig) tends to encounter a gradient reversal or inflection at fields approaching 1 kGauss. This appears to be a signature significantly inclined penumbral fields.

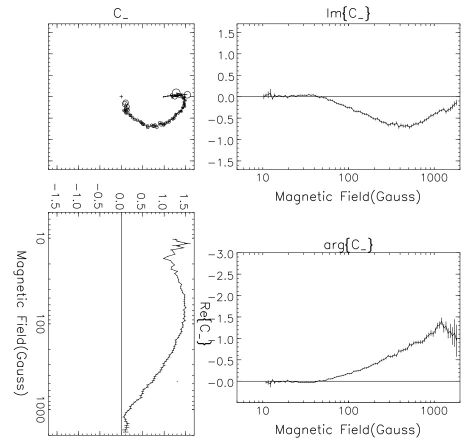

Figure 2. Diagnostic plots of the local ingression control correlations at 5 mHz as a function of the magnitude, B, of the magnetic field at the focal point. Top left panel shows the locus of C_- in the complex plane over magnetic fields, B, ranging from 5 G–2 kG. Bottom left panel shows the real part of C_- plotted as a function of B. Top right and lower right panels show the imaginary part of C_- and the argument of C_- (in radians), respectively, plotted as functions of B.

4. DISCUSSION AND CONCLUSIONS

It should be evident that a realistic representation of the acoustics of inclined magnetic fields should contain an account of field inclination. The penumbral acoustic anomaly appears to be consistent with a strong interaction between acoustic waves and magnetic fields in the photosphere and shallow-subphotosphere that involves mode conversion and acoustic absorption (Cally & Bogdan, 1993; Cally, 2000). Maps of the egression-ingression correlation over a range of focus depths (see Lindsey & Braun 2000b) show signatures consistent with an active region acoustic anomaly that is predominantly superficial. There are good reasons to expect magnetic effects to be quite weak only a few Mm beneath the surface (Lindsey & Braun, 1996). However, it is becoming quite evident that a careful account of magnetic forces in acoustics is needed in the upper few hundred km of the subphotosphere. The application of powerful computational resources to simulations of showerglass acoustics will lead to greatly improved seismic diagnostics of active region subphotospheres. Similar computations of magneto-acoustic gravity waves propagating through models of active region subphotospheres are also needed to facilitate the interpretation of holographic signatures that have been corrected for the acoustic showerglass.

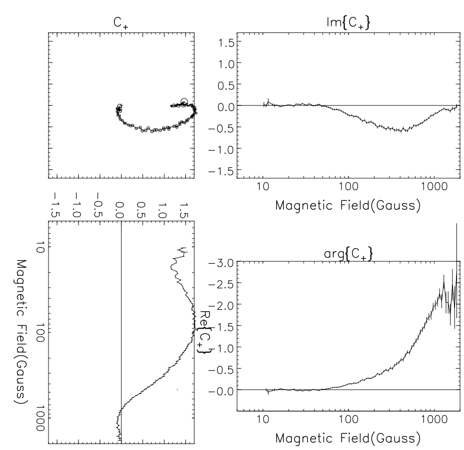

Figure 3. Diagnostic plots of the local egression control correlations at 5 mHz as a function of the magnitude, B, of the magnetic field at the focal point. For details see Fig 2.

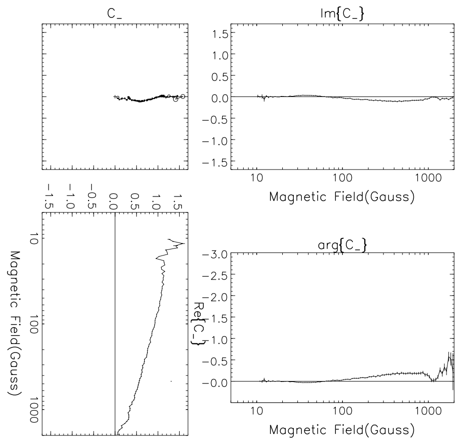

Figure 4. Diagnostic plots of the local ingression control correlations at 3 mHz as a function of the magnitude, B, of the magnetic field at the focal point. For details see Fig 2.

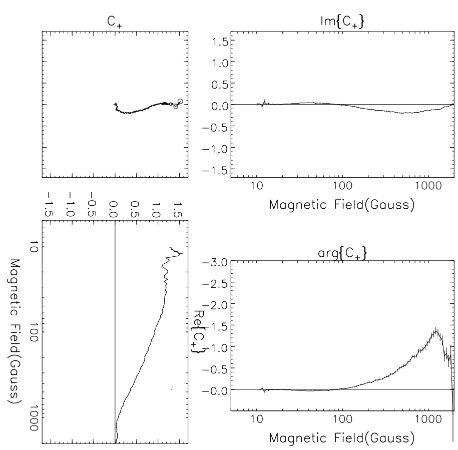

Figure 5. Diagnostic plots of the local egression control correlations at 3 mHz as a function of the magnitude, B, of the magnetic field at the focal point. For details see Fig 2.

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