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Magnetoseismic signatures and flow diagnostics beneath magnetic regions

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One of the major, important developments in local helioseismology was the discovery by Duvall et al. (1996) that the travel times of seismic waves into sunspots from the surrounding quiet Sun significantly exceed the same in the reverse direction, a behavior they suggested was the result of rapid downflows directly beneath the sunspot photosphere. This led to the need for rapid near-surface horizontal inflows to replace the mass evacuated from the sunspot subphotosphere by such downflows. The lack of independent evidence for such inflows led to the suggestion that the travel-time asymmetry could be explained by a relative phase delay in the response of the sunspot photosphere to incoming waves with respect to that of the quiet Sun. In the succeeding ten years major progress has been made in our understanding of how magnetic photospheres respond to incoming waves, at the instigation of theoretical work by Spruit, Cally and Bogdan. This has led to the recognition of inclined penumbral magnetic fields as a major avenue for control work on the subject of the travel-time asymmetry and its relation to the absorption of p-modes by magnetic regions. A major recent development has been the discovery by Schunker et al. (2005) that the phase of this response in Doppler observations of penumbral photospheres depends strongly on the vantage of the Doppler measurements projected into the vertical plane of the magnetic field. This discovery heavily reinforces the proposition that *the travel-time asymmetry is largely the signature of the same irreversible damping processes that are responsible for the strong absorption of p-modes in magnetic regions*. We will elaborate on the implications of the foregoing developments respecting the diagnostics of subphotospheric flows based on seismic observations in which magnetic regions cannot be avoided.

1 Introduction

A major development in local helioseismology was the discovery by Braun, Duvall & LaBonte (1988) that magnetic photospheres strongly absorb waves that are efficiently reflected by nonmagnetic photospheres. The importance of this was immediately recognized in terms of the first local demonstration of a strong interaction between magnetic regions and ambient acoustic waves impinging into them. A further major development was the discovery by Duvall et al. (1996) that the travel times of seismic waves into sunspots from the surrounding quiet Sun are consistently greater than the travel times along the same subphotospheric paths in the reverse direction. We generally refer to this behavior either by the term "travel-time asymmetry," or "phase asymmetry." The importance of this was immediately recognized in terms of its potential for flow diagnostics. Indeed, it strongly suggested rapid downflows beneath sunspots.

The first published suggestion that the phase asymmetry was related to absorption of p-modes was by Lindsey & Braun (1996). In the succeeding decade this question has become central to a range of issues that bear on the connection between magnetic fields; local luminosity variations, such as in faculae and sunspots; flows ranging from the scale of the supergranulation to that of the meridional flow, and the solar dynamo. Of central diagnostic concern is the effect of magnetic fields on helioseismic signatures of flows. Surface magnetic fields are almost invariably associated with local anomalies in photospheric luminosity. These appear to be critical to the dynamics of thermal anomalies in the subphotospheres of active regions, capable of driving massive flows (Meyer et al. 1974; Nye, Bruning & LaBonte 1988). We will begin this article with a summary of some of the issues connecting these phenomena.

2 Luminosity-driven flows

When probing into the dynamics of the relationship between magnetic regions and flows, it is tempting to begin by examining the problem in the context of the simplest possible

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dynamics conceivable relative to the observational results that support such a relationship. Any efforts in this direction are certain to confront the likely relevance of local luminosity variations associated with the magnetic fields. It is already clear that local luminosity variations are associated with flows in the non-magnetic solar granulation. The upflowing centers of granules are brighter than the downflowing intergranular lanes simply because they are hotter, and this renders their surfaces more luminous.

For flows with a much greater horizontal scale, the relationship with luminosity would have to be different, at least in certain respects. The effective cooling time of the granular photosphere is comparable to the characteristic flow time across a granule and hence also to the lifetime of the granule. Thus, the substantial cooling that results in the downflow can take place in a significantly different location than that of the downflow itself. For supergranular scales the characteristic times are much greater. We suppose that this may be closely related to intersupergranular lanes being *more* luminous than the centers of the supergranules (Foukal & Fowler 1984; Lin & Kuhn 1992); the excess cooling apparently taking place in the photosphere directly overlying the downflow. [1]

In fact, the basic concept of local downflows motivated by luminosity enhancements directly overlying the downflows on relatively large horizontal scales is supported by a number of conspicuous examples to which helioseismology now contributes significantly. In all of these examples the luminosity enhancements of concern are conspicuously related to the presence of magnetic fields. The excess radiation found emanating from supergranular lanes, for example, appears to be largely the result of radiation from magnetic regions swept into the supergranular lanes. Rast (2003) finds that intersupergranular lanes are not significantly more luminous than the cell interiors when radiation from the magnetic elements are excluded from the statistics.

Stein (private communication) has recently run non-magnetic simulations of convection on horizontal scales sufficient to accommodate supergranules. While his simulations realistically represent the solar granulation, including acoustic emission by granular turbulence, he finds a general reluctance of the photosphere to convect on supergranular scales without the inclusion of magnetic fields. This opens the question whether some property of magnetic fields determines the horizontal scale of the supergranulation. This question could be answered by simulations Stein is planning that incorporate magnetic fields characteristic of the quiet Sun.

If magnetic fields turn out to be a key element of supergranular dynamics, a significant factor will almost certainly have to be the local luminosity variations magnetic elements appear to instigate. Spruit (1976) explained enhanced radiation from a photosphere infused with thin magnetic flux tubes by a mechanism that simply facilitates the escape of thermal energy from a subphotosphere that has no greater a momentary supply of thermal energy than a non-magnetic subphotosphere. In this "hot wall" model, the enhanced radiative efficiency is the result of a magnetically reduced opacity in the flux tube, directly exposing the hot non-magnetic subphotosphere at the boundary separating it from the magnetic flux tube to cold space. In Spruit's models, the excess radiative loss due to this direct exposure manifests a significant thermal depletion some distance into the non-magnetic subphotosphere surrounding the flux tube, in which energy transport in the non-magnetic medium is accomplished by normal radiative and convective diffusion, assuming no anomalous, flows.

On the horizontal scale of a large magnetic region, such a thermal depletion suggests a mechanism to drive horizontal inflows on a scale comparable to that of the magnetic region itself. In the absence of a large-scale flow, the thermal depletion would manifest a local "hydrostatic" imbalance in bouyancy with respect to the subphotosphere surrounding that of the magnetic region. The cooled subphotosphere underlying the magnetic region would then supposedly sink, drawing a substantial horizontal inflow from the surrounding medium. The energy flux carried by such an inflow would be critical to the replacement of the energy lost at the surface by the local excess in the radiative flux.

Something like the foregoing mechanics may explain the dynamics of flows that appear to be associated with all of the luminosity anomalies we know of with horizontal scales ranging from those of the supergranulation to the meridional flow. Helioseismic flow maps, for example, generally show strong inflows into plage-intensive active regions (see Haber et al. 2001). These inflows are comparable in scale and magnitude to those of the meridional flow, which now appears to play an integral role in the operation of the solar dynamo (Dikpati, de Toma & Gilman 2006).

The luminosity anomalies we have considered thus far have been local enhancements. The other side of this coin would have to be the case of sunspots, with their heavily diminished local luminosities, for which a similar line of argument would suggest outflows in place of inflows (Meyer et al. 1974; Nye, Bruning & LaBonte 1988). Evidence for surface outflows in sunspot penumbrae (Evershed 1909) is now nearly a century old. Evidence for deeper, more extensive outflows has been found by others (Harvey & Harvey 1976; Brickhouse & LaBonte 1988). Helioseismic diagnostics to probe subsurface flows directly have given us strong evidence of outflows, but this is ambiguous. Horizontal flow signatures (Lindsey & Braun 1996; Duvall et al. 1996; Braun & Lindsey 2000; Gizon, Duvall & Larsen 2000; Braun, Birch & Lindsey 2004 and others) have almost invariably shown indications of outflows of order 1 km/s in the upper $\sim$3 Mm of the subphotospheres immediately surrounding sunspots. At the same time, studies attributing the phase asymmetry to vertical flows suggest downflows of several hundred m/s 2–3 Mm directly beneath sunspots

[1] Indeed, Rast (2003) points out that even for the granulation the most luminous component of the photosphere is substantially displaced from the center of the convective cell toward its down-flowing edge.

(Duvall et al. 1996; Kosovichev 1996; Zhao & Kosovichev 2001; Zhao & Kosovichev 2003).

These two interpretations of helioseismic signatures, downflows directly beneath sunspots and near-surface outflows from their peripheries, confront the basic requirements of mass conservation with a significant challenge. Models of flows beneath sunspots have evolved considerably since Duvall et al. (1996). However, in our opinion this problem remains unsolved. A more detailed elaboration of our assessment of the downflow/outflow conflict is given by Lindsey (2006). A rapid near-surface downflow directly beneath the sunspot requires a near-surface inflow to replace the mass evacuated by the downflow. We do not see how both the massive downflow and rapid outflow interpretations can be integrated into a physically realistic model of sunspot subphotospheres. Indeed, we doubt whether this problem can be solved in any context that attributes the entirety of the phase asymmetry to flows.

The foregoing dilemma has been one of the major considerations in our formulation of the proposition that the phase asymmetry discovered by Duvall et al. (1996) is largely a manifestation of irreversible processes in the wave mechanics of magnetic regions that is related to the strong absorption of p-modes by magnetic regions, itself a conspicuously irreversible process. This proposition is the subject of this article. For the discussion that follows we draw heavily from work recently summarized by Schunker (2006), Schunker & Cally (2006), and Lindsey (2006).

3 The penumbral acoustic anomaly

The attention Cally (2000) drew to the importance of inclined magnetic fields in p-mode absorption was reinforced by conspicuous anomalies Lindsey & Braun (2005a) subsequently found in seismic signatures in sunspot penumbrae. They referred to the collective phenomenon by the term "penumbral acoustic anomaly." Of particular interest was a conspicuous phase perturbation, ϕ_-, seen in the "local ingression control correlation," $C_{\mathrm{LC}-}$, representing the signatures of waves arriving into sunspot penumbrae from below. This was based on phase comparisons between penumbral seismic signatures and those of holographic projections of waves arriving therein from appropriately extended pupils. The local ingression control correlation phases showed a significant lead in the penumbral photosphere relative to those of the surrounding quiet Sun. Lindsey & Braun (2005a) referred to this aspect of the penumbral acoustic anomaly as the "penumbral phase anomaly".

The penumbral phase anomaly is actually hard to miss in holographic maps of ϕ_- covering nearly any active region that contains sunspots based on holographic reconstructions computed in the 5 mHz spectrum, where the relatively high frequency affords proportionately high spatial resolution and accordingly enhanced statistics in any given area. An example is shown in Fig. 1. Figures 1a and b respectively show continuum intensity and line-of-sight magnetic field maps of AR9887 near disk center on 2002 April 03. Figure 1c shows a map of the square horizontal magnetic field, $B_\perp^2$, derived from the line-of-sight magnetic field under the assumption that the vector field, $\boldsymbol{B}$, is the gradient of a potential (i.e. that the field above the photosphere is free of currents). Figure 1d shows a map of ϕ_-, the phase of the local ingression control correlation, $C_{\mathrm{LC}-}$ (see Lindsey & Braun 2000; Lindsey & Braun 2005a), with the acoustic ingression computed in the annular pupil drawn in Fig. 1a. The penumbral phase anomaly refers to the ring-like enhancements of ϕ_- that predominate regions of inclined magnetic field as mapped in Fig. 1c.

What Schunker et al. (2005) realized about the penumbral phase anomaly was that the vector displacement of the magnetic photosphere in response to waves impinging into them from below is of major diagnostic interest in the dynamics of p-mode absorption. The development of the theory of these dynamics opens a tool shed of powerful control diagnostics that can take advantage of line-of-sight Doppler seismic signatures of active regions from various vantages. What follows is an attempt to abstract in intuitive terms certain aspects of concepts developed rigorously by Cally (2005) and Schunker & Cally (2006) that have led to this perspective.

4 Seismic signatures of mode coupling

Consider two harmonic oscillators, O_{f} and O_{s}, of the same natural frequency, ω_0. Let q_{f} and q_{s} represent the respective generalized coordinates that express the amplitudes of oscillations in O_{f} and O_{s}. Now consider the application of a linear coupling between O_{f} and O_{s} whose Lagrangian can be expressed as a function, $V(q_{\mathrm{f}}, q_{\mathrm{s}})$, of q_{f} and q_{s}. Suppose further that the action of V during some significant epoch of the coupling is such as to consistently transfer energy from one to the other, e.g. from O_{f} to O_{s}. It is a relatively elementary exercise in Lagrangian mechanics to show that there must be a consistent phase shift between q_{f} and q_{s} over such an epoch. If the direction of the transfer of energy is reversed, the sign of the phase shift between q_{f} and q_{s} is similarly reversed.

In the present context, O_{f} and O_{s} respectively represent the fast and slow magneto-acoustic modes in a conducting medium infused with a magnetic field, where "fast" and "slow" refer to characteristic wave-propagation speeds deep beneath the photosphere where the Alfvén speed, $a = B/\sqrt{8\pi\rho}$, is decidedly less than the sound speed, c. The basic restoring force for fast magneto-acoustic modes is that expressed by the compression modulus, which includes perturbations in gas pressure and magnetic pressure if the magnetic field has a significant component transverse to the direction of propagation. For slow magneto-acoustic modes the basic restoring force is the reaction force due to distension of the magnetic field. This can also be regarded as the

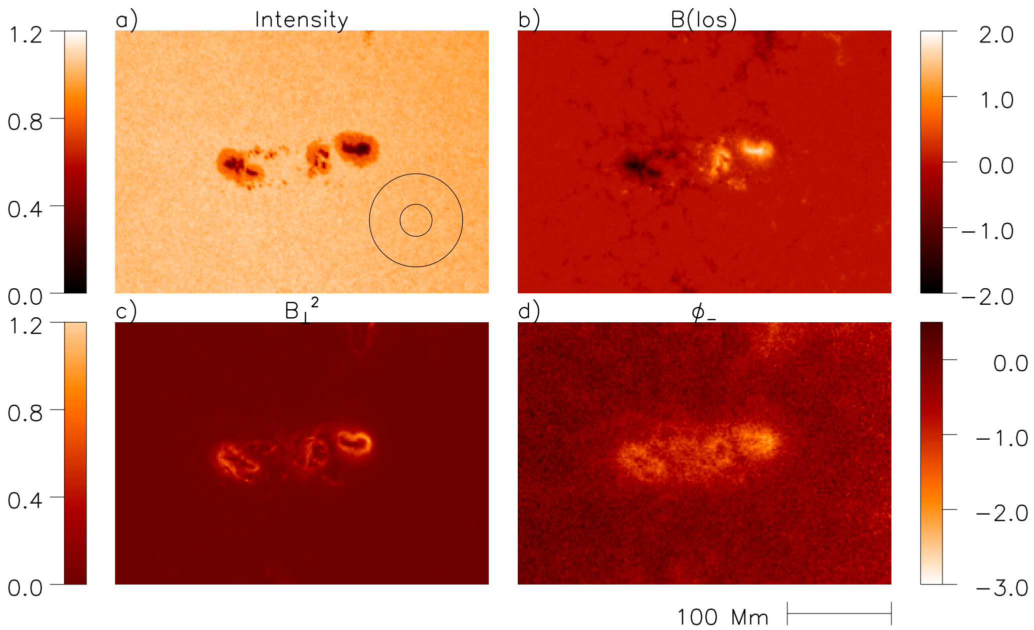

Fig. 1 The penumbral phase anomaly, characterized by a strong perturbation in the phase of the seismic response of photospheric motion to upcoming waves arriving into sunspot penumbrae, where the magnetic field is significantly inclined. Panels (a) and (b) respectively show continuum intensity and line-of-sight magnetic field maps of AR9887 as it passes the meridian 6–10° north of disk center on 2002 April 03. Panel (c) shows a map of the square horizontal magnetic field, $B_\perp^2$, computed under the assumption of a current free corona. Panel (d) shows a map of the phase, ϕ_-, of the local ingression control correlation, with the ingression extrapolated from an annular pupil, drawn in panel (a), centered on the focus of the computation (see Lindsey & Braun 2000). The penumbral phase anomaly refers to the conspicuous ring-like enhancement of ϕ_- in regions of inclined magnetic field as mapped in panel (c).

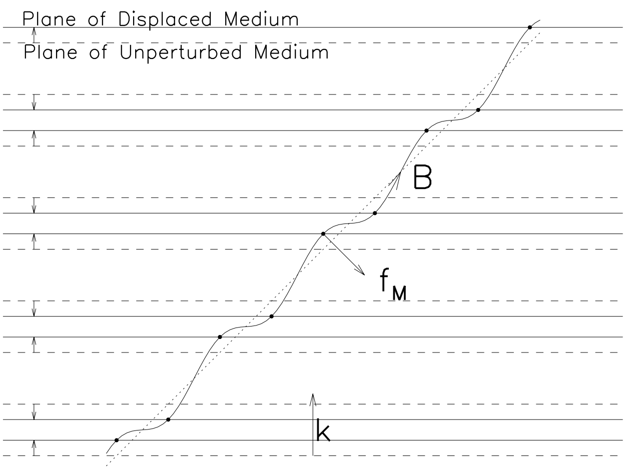

Fig. 2 Diagram showing the distension of an inclined magnetic field line due to of a vertically propagating wave and the resulting magnetic restoring force, $\boldsymbol{f}_{\rm M}$.

primary coupling force connecting slow and fast magneto-acoustic modes in the region where a is comparable to c.

Figure 2 illustrates a particular aspect of this coupling in how the presence of an inclined magnetic field perturbs the motion of a medium into which we have injected a vertically propagating wave, nominally characterized by vertical wave vector $\boldsymbol{k}$ and frequency $\omega = kc$. For simplicity we assume that gravitational forces can be neglected and that the unperturbed medium is uniform.

We first consider the case of a medium that is infused by a magnetic field that is freely advected by the fluid but exerts no significant reaction forces in response, either because it is too weak or simply because this is the postulate however unphysical. In this case, the motion induced into the medium remains purely vertical, alternately upward and downward, as it would be in the absence of a magnetic field. These planar displacements are represented in Fig. 2 by the solid vertical lines above or below dashed reference lines that record the initial positions from which the fluid has been displaced. The effect of such a motion on an inclined magnetic field line, initially straight, as represented by the dashed diagonal line in Fig. 2, is the sinuous distension of the dashed line, expressed by the solid curve labeled $\boldsymbol{B}$.

We now consider how the motion of the fluid would evolve if at some point we suddenly "turn on" the magnetic reaction forces that result from the distension of the field:

$$\boldsymbol{f}_{\rm M} = -\frac{1}{4\pi}\boldsymbol{B} \times (\nabla \times \boldsymbol{B}), \qquad (1)$$

which, being essentially perpendicular to $\boldsymbol{B}$, proceed to induce a perturbation into the displacement of the fluid that includes both horizontal and vertical components. This transverse perturbation represents the beginning of a transfer of energy from the fast magneto-acoustic mode, $O_{\rm f}$, to the slow magneto-acoustic mode, $O_{\rm s}$, at the significant eventual expense of the energy initially invested into $O_{\rm f}$. When the Alfvén speed, a, is close to the sound speed, c, over something like a wavelength or more, the coupling is strong,

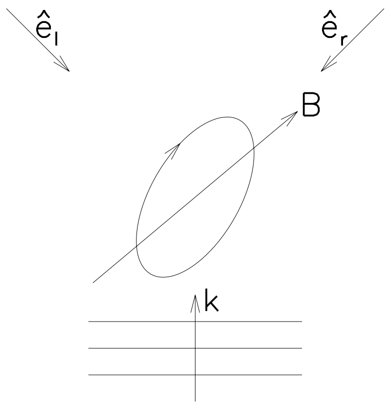

Fig. 3 The local displacement trajectory for the medium of a magnetic photosphere in response to vertically incident monochromatic seismic radiation, represented by wavenumber $\boldsymbol{k}$, generally describes an inclined ellipse in the vertical plane containing the magnetic field, $\boldsymbol{B}$, characterizing the preferential transfer of energy from an incident fast magneto-wave into a slow magneto-acoustic wave.

and the resulting apparent absorption of fast-mode energy is highly efficient, in terms of rapid transfer of energy from $O_{\rm f}$ into $O_{\rm s}$ (Cally 2005; Schunker & Cally 2006).

In general, the phase of the perturbed motion introduced by $\boldsymbol{f}_{\rm M}$ will be shifted with respect to that of the motion representing the incident wave. Since $O_{\rm s}$ is characterized by a significant horizontal component of motion, as opposed to the purely vertical motion of the nominal, the resultant displacement of the medium, for a given frequency, will generally be inclined. Moreover, since the phase between $O_{\rm f}$ and $O_{\rm s}$ will be shifted in accordance with the preferential transfer of energy from $O_{\rm f}$ to $O_{\rm s}$, the trajectory of the motion will be elliptical, i.e. that of an inclined ellipse such as shown in Fig. 3. An immediate consequence of this elliptical trajectory is that the relative phase of line-of-sight Doppler observations of the magnetic photosphere will depend continuously on the vantage from which the photosphere is viewed with respect to the inclination of the ellipse.

5 Diagnostic techniques and results

We refer to Schunker (2006) and Schunker, Cally & Braun (2006) for a detailed discussion of the diagnostic techniques Schunker et al. (2005) developed to determine the characteristic ellipses of penumbral seismic signatures over the acoustic spectrum. An obvious, greatly desired resource for the study of the acoustics of inclined magnetic photospheres will be stereo observations from the Helioseismic Magnetic Image (HMI) aboard the *Solar Dynamics Observatory (SDO)* and hopefully a helioseismometer on ESA's *Solar Orbiter*, planned for launch in 2015. The techniques Schunker et al. (2005) developed for the considerable interim rely on statistics of penumbral control correlation measurements determined from Doppler observations of sunspots at various distances from disk center. These statistics are subject to errors introduced by unknowable variations in other attributes of penumbrae besides the magnetic field strength and inclination[2] that effect the response of the magnetic photosphere to upcoming waves. These uncertainties could be essentially eliminated if the same magnetic photosphere could be observed simultaneously from two different vantages. Nevertheless, the statistical errors resulting from these in an unbiased sample of sunspot penumbrae distributed over the solar disk are random and easily assessed. Indeed, the general variation Schunker et al. (2005) found in the control correlation phase with vantage was unmistakable.

A single example is shown in Fig. 4 in the subject of AR9896, a single, isolated monopolar sunspot that crossed the solar meridian on 2002 April 11 4° south of disk center. When the active region is near the east limb (left column) the perturbation shown by its signature in ϕ_- (bottom panel) is substantially skewed toward the limbward side of the penumbra. This is the side on which the vantage would normally be more nearly perpendicular to the outwardly inclined magnetic field, as opposed to the earthward side of the penumbra, on which the magnetic field would tend to be more nearly parallel to the line of sight of the helioseismometer. When the experiment is repeated as the active region crosses the meridian very close to disk center (right column), the perturbation in ϕ_- is significantly more evenly distributed around the penumbra. While a skewed penumbral profile is known to occur accidentally in some complex active regions even near disk center, this would be untypical of single isolated sunspots such as AR9896.

The vantage dependence of ϕ_- has been confirmed by Zhao & Kosovichev (2006). In fact, Zhao & Kosovichev (2006) also ran the control experiment on seismic intensity variations, showing that the vantage dependence was null to within statistical errors if the phase correlation measurements Schunker et al. (2005) applied to Doppler observations were applied to intensity observations instead. We refer to Fig. 4 to emphasize that this important control result is entirely consistent with expectations if our understanding of the vantage dependence of the control correlations is correct. The *line-of-sight Doppler* signature depends strongly on vantage; the *continuum intensity* signature does not. It should be evident, for example, that if the photospheric medium is moving directly toward a *Doppler* helioseismometer whose vantage is indicated by the vector $\hat{\boldsymbol{e}}_r$ in Fig. 3, then it will register a blue shift accordingly, while a Doppler helioseismometer whose vantage, $\hat{\boldsymbol{e}}_l$, is at an angle of 90° from $\hat{\boldsymbol{e}}_r$ will register a null signature. The continuum brightness of the same photosphere, on the other hand, will remain essentially the same for both vantages, and brightness variations in response to vertically-propagating seismic waves are accordingly equal and concurrent as measured from both vantages.[3]

[2] An example would be the thermal structure of the penumbral subphotosphere.

[3] As a matter of technicality, the continuum brightness of the photosphere is in fact weakly dependent on the line-of-sight velocity. The varia-

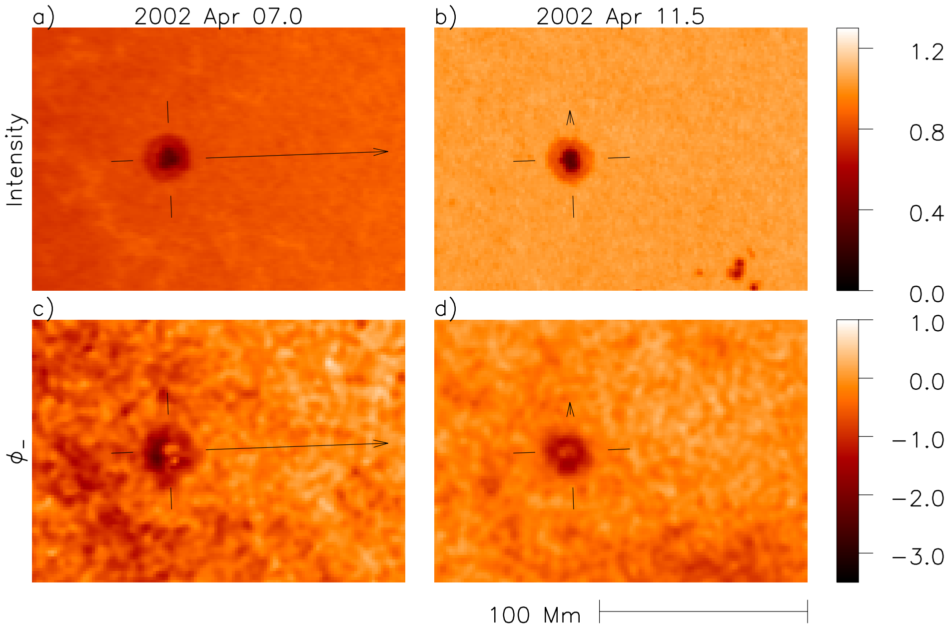

Fig. 4 Illustration of the limbward accentuation of the phase perturbation in the Doppler response of a penumbral photosphere to upcoming waves. Top row shows MDI continuum intensity images of AR9896 4.5 days before (left column) and during (right column) passage across central solar meridian. Bottom row shows concurrent maps of the phase, ϕ_-, of the ingression control correlation, $C_{\rm LC-}$. Arrows show the direction toward disk center. The length of each arrow is a tenth of the distance along the great circle from the center of the active region to disk center.

6 Discussion

Two of the most important developments in local helioseismology in the last two decades have been (1) the discovery that magnetic regions absorb p-modes that are efficiently reflected by the quiet Sun (Braun, Duvall & LaBonte 1988; Braun 1995) and (2) the discovery of the travel-time asymmetry in magnetic regions. It might have seemed a remarkable accident ten years ago that these two phenomena would transpire to be closely related. In fact, it now appears highly probable to some of us that they are. and this is indeed a remarkable development. What is fundamentally needed to explain the travel-time asymmetry is a physical process that looks substantially different if time is reversed, since the travel-time asymmetry is clearly reversed if we analyze helioseismic observations backwards in time. Thus, the travel-time asymmetry cannot be explained by elastic scattering of any kind, at least not the familiar kind that obeys time-reversal invariance. Advection of seismic waves by flows *is* reversed under time reversal, since the directions of the flows themselves are reversed, and there is, accordingly, general agreement that flows fully qualify as a means of introducing a travel-time asymmetry.

However, it should be similarly evident that any number of damping mechanisms also qualify to introduce travel-time asymmetries, as the operation of any of these invariably discriminates the future from the past, always depleting the mode to be damped as time progresses forward rather than backward. Where wave mechanics is concerned, the site of the dissipation that gives rise to a time-discriminant phase shift can be completely hidden from view. For example, in the context of the discussion in Sect. 4 the signs of the phase shifts that characterize the vantage dependence discovered by Schunker et al. (2005) depend on energy being pumped consistently from the fast magneto-acoustic mode to the slow. This depends on the latter generally having less energy to send back into the other direction, which, in turn, depends on the energy received by the slow mode eventually being dissipated somewhere. If this dissipation were not eventually accomplished, the energy would evidently have to accumulate in the slow mode until statistical accident brought it back to the magnetic photosphere to undergo something like the time reverse of the process discussed in Sect. 4. The consistent transfer of energy from $O_{\rm s}$ back to $O_{\rm f}$ by the coupling Lagrangian would have to be characterized by a reversal of the phase shift describing the motion of the photosphere around the characteristic ellipse illustrated in Fig. 3, a commensurate reversal of the travel-time asymmetry, and a general lack of any substantial depletion of waves emanating from magnetic regions. Thus, the travel-time asymmetry, if it is the signature of mode coupling in the way some of us understand it, must also be a signature of eventual slow magneto-acoustic dissipation at some location that could be completely hidden from view.

In summary, then, the vantage dependence of the penumbral phase anomaly adds considerably to evidence that the phase asymmetry is largely the signature of wave

tion in specific intensity as a result of the blue-shifted continuum spectrum gives rise to a relative signature less than 10^{-4} times that of the Doppler signature.

absorption in magnetic photospheres and shallow subphotospheres. A careful account of the magnetic effects in seismic flow diagnostics is thus crucial to credible modeling of flows in magnetic subphotospheres. This will likely have a bearing on our understanding of issues that include the effects of magnetic fields on flow diagnostics in active region subphotospheres, the function of luminosity variations in driving subphotospheric flows, the role of subphotospheric flows in active region dynamics, the role of flows in the operation of the solar dynamo, and the possible application of large-scale flow diagnostics in forecasting of the solar activity cycle.

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