Seismology of Magnetic Photospheres

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I. Introduction

Since the advent of local helioseismology, a variety of independently developed diagnostic techniques have converged to suggest the existence of relatively large-scale, near-surface flows associated with active regions. These consistently show large-scale, near-surface inflow into large plages (Gizon, Duvall & Larson 2001; Haber et al. 2004; Zhao & Kosovichev 2004; Lindsey & Braun 1996), which generally have slightly enhanced luminosities with respect to the quiet Sun. For sunspots, which are much smaller and much less luminous than the quiet Sun, the picture is more complicated. A range of independently developed seismic diagnostics focusing on horizontal flows on the outskirts of sunspots show conspicuous, but somewhat more compact, near-surface outflows (Duvall et al. 1996; Lindsey & Braun 1996; Gizon 2003; Braun & Lindsey 2003; Gizon, Duvall & Larsen 2000), roughly consistent with non-seismic diagnostics, such as Harvey & Harvey (1976). Other seismic diagnostics, more heavily including seismic signatures in the magnetic photospheres of the sunspots, suggest significant downflows beneath sunspots (Duvall et al. 1996) and near-surface inflows (Kosovichev 1996; Zhao & Kosovichev 2001,2003).

One of the major developments in local helioseismology of the late 1990s was the discovery by Braun, Duvall and Labonte (1988) that magnetic regions abosrb seismic waves. Another, not obviously related to the first at the time, was the discovery by Duvall et al. (1996) that phase travel times for waves propagating into sunspot photospheres are significantly longer than for waves propagating away from them, a phenomenon to which we refer in this study as "the phase asymmetry" (see also Braun 1997; Lindsey & Braun 2004, 2005c). Duvall et al. (1996) proposed that the phase asymmetry was the signature of rapid downflows beneath sunspots, a thesis developed at length by Kosovichev 1996. Lindsey & Braun (1996) noted concerns respecting mass conservation, recognizing that rapid downdrafts combined with near-surface outflows would quickly evacuate the shallow subphotosphere of the sunspot. Seismic modeling of active regions has advanced considerably in the decade since (Zhao & Kosovichev 2001,2003). However, at this epoch independently developed seismic modeling techniques applied to sunspots do not yet render uniformly consistent results where flows are the issue, particularly when mass conservation is included in the context.

In fact, a major component missing from seismic diagnostics of flows in the neighborhoods of sunspots during the term of *SOHO*/MDI has been a realistic account of the effects of magnetic fields on seismic signatures in active regions. Recent developments in magnetohelioseismology, both theoretical (Cally 2000; Cally, Crouch & Braun 2003; Crouch et al. 2005; Schunker, Cally & Donea 2005; Cally 2005) and observational (Lindsey & Braun 2005a,b; Schunker et al. 2005), suggest that phase perturbations introduced by magnetic forces in active region photospheres are considerable, and that these have major potential implications in active region diagnostics. In our opinion, based on these developments, a credible account of magnetoseismic signatures is essential for further progress in seismic diagnostics of active region subphotospheres. The advent of HMI offers a golden opportunity to develop this aspect of seismic diagnostics.

In this presentation will focus on the specific issue of the contribution of magnetic forces to the phase asymmetry and implications respecting underlying flows. We will briefly introduce a hypothesis that the phase asymmetry is largely the result of phase perturbations induced by magnetic fields in the photospheres or shallow subphotospheres of active regions. We propose that these phase perturbations are predominantly the signature of the mechanism whereby magnetic regions absorb a large fraction of the seismic energy impinging into them from the quiet Sun at large (Braun, Duvall & LaBonte 1988; Braun 1995). Central to the hypothesis is partial conversion of arriving compression waves to Alfvén waves that disappear into the active region subphotosphere.

Helioseismic support for a magnetically induced phase asymmetry has largely emerged from three major developments:

(1) the recognition (see Cally 2000) that inclined magnetic fields are particularly efficient in coupling low-degree p-modes to Alfvén modes. This is an important consideration in our understanding of how magnetic regions absorb p-modes so efficiently in the 2–5 mHz spectrum.

(2) the recognition of a feature in maps of the phase of the "local ingression control correlations" called the "penumbral phase anomaly" (Lindsey & Braun 2005a), referring to conspicuous seismic phase advances that generally mark regions of inclined magnetic field, such as sunspot penumbrae.

(3) a strong dependence of Doppler seismic signatures on the vantage of the observations with respect to the relative azimuth of the magnetic field when both the magnetic field and the vantage are oblique. We refer to this vantage dependence, discovered by Schunker et al. 2005 (see also Schunker, Braun & Lindsey 2005) by the term "inclined magnetic phase parallax," or simply "phase parallax" when the magnetic context is clearly established.

II. Mode Coupling and Absorption of p-Modes by Photospheric Magnetic Fields

A great deal of modern agnetohelioseismology of active regions has been motivated by theoretical efforts (Spruit & Bogdan, 1992; Cally & Bogdan 1992, 1997; Cally, Crouch & Braun 2003; Crouch et al. 2005; Cally 2005 and others) to explain the absoption of acoustic waves by magnetic regions. A major breakthrough in those efforts was the recognition by Cally (2000) of the importance of inclined magnetic fields. Discrimination of magnetically induced phase shifts from those introduced by thermal perturbations and flows has similarly benefitted from attention to the peculiarities of seismic signatures of waves arriving into photospheres permeated by inclined magnetic fields.

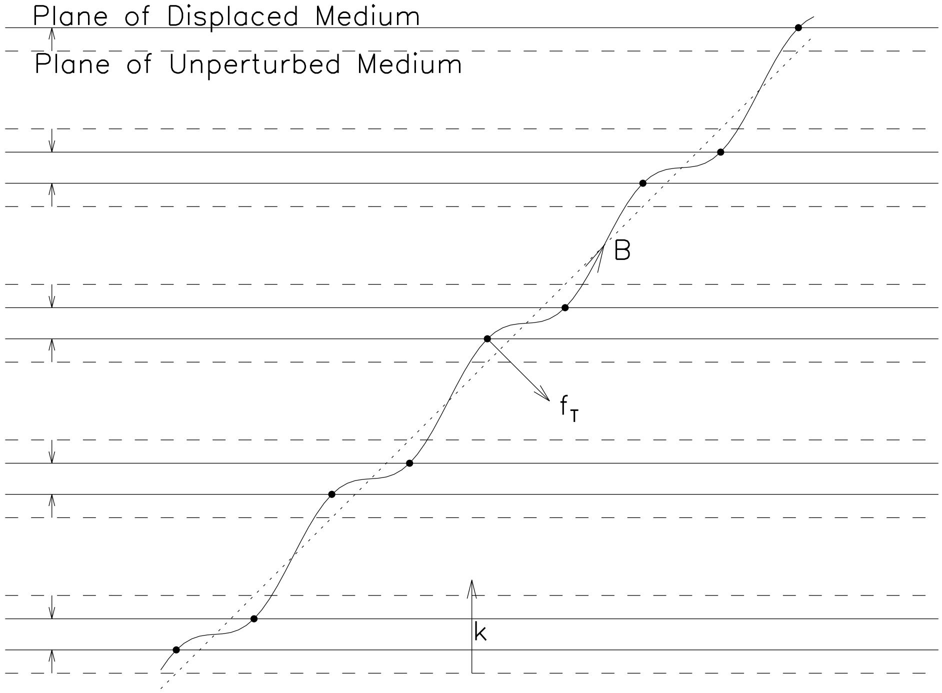

Figure 1. Inclined magnetic tension forces introduced vertical compressional displacement in the simple case of a uniform medium.

The basic coupling force between compression waves and Alfvén waves, and also the restoring force for the Alfvén waves themselves, is magnetic tension:

$$\mathbf{f}_T = \frac{1}{4\pi}(\mathbf{B}\cdot\nabla)\mathbf{B}, \tag{1}$$

where $\mathbf{B}$ is the magnetic field vector. In the case of waves arriving into a magnetic photosphere from directly below, propagating vertically into a region of inclined magnetic field, $\mathbf{f}_T$ has a substantial horizontal component, as illustrated by the diagram in Figure 1.

These forces introduce a substantial horizontal perturbation into photospheric motion that without a magnetic field would be purely vertical. Where the function of the coupling force is to transfer energy from a vertical compression wave into an Alfvén wave, the horizontal motion for any given frequency is substantially phase shifted with respect to the vertical, resulting in motion following an elliptical trajectory, as illustrated by Figure 2.

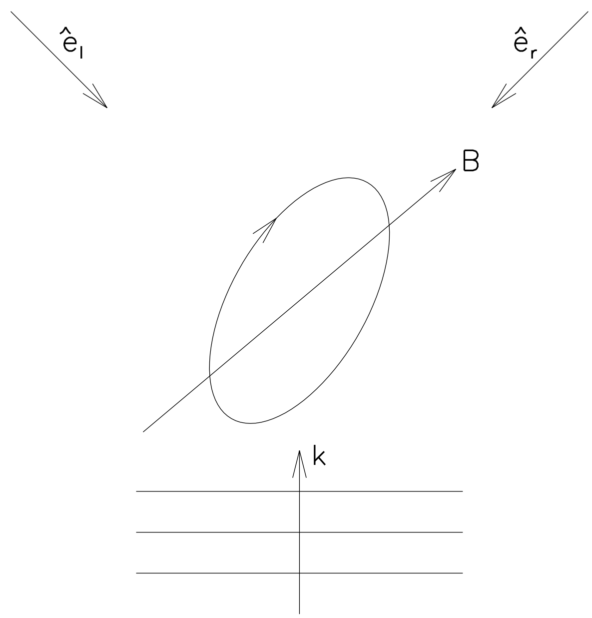

Figure 2. Diagram illustrating the elliptical motion of a medium in an inclined magnetic field, represented by vector $\mathbf{B}$, in response to vertically propagating compression waves, represented by vertical wave vector $\mathbf{k}$.

Where the seismic signature is determined by a line-of-sight Doppler measurement this elliptical motion results in a signature whose phase is strongly dependent on the direction (see vectors $\hat{\mathbf{e}}_l$ and $\hat{\mathbf{e}}_r$ in Fig 2) from which the motion is observed with respect to the inclination of the the magnetic field, $\mathbf{B}$. Because the tension force for an inclined magnetic field has a vertical component, it introduces a similar phase shift into the vertical component of the motion with respect to that of the displacement an incoming compression wave would exert in a photospheric medium containing a weak or null magnetic field.

III. The Penumbral Phase Anomaly

The penumbral phase anomaly (Lindsey & Braun 2005a,b) refers to a conspicuous advance that invariably characterizes the phase, ϕ_-, of the seismic signature of waves arriving into a photosphere permeated by a substantially inclined magnetic field. An example is shown in Fig 4 for a complex active region crossing the meridian near disk center. A second example similar to that of Fig 3 is shown for a small isolated sunspot in Fig 4. The isolated sunspot, while it offers not nearly the statistical weight of the complex region shown in Fig 3, has the advantage of cleanliness, in that the pupil (annulus drawn in lower left corner of Fig 3a) of the holographic projection is securely free of strong magnetic regions when the focus is in a strong magnetic region. As before, the region of relatively strong $B_\perp^2$ (Fig 4c) manifests a conspicuous signature in ϕ_- (Fig 4d).

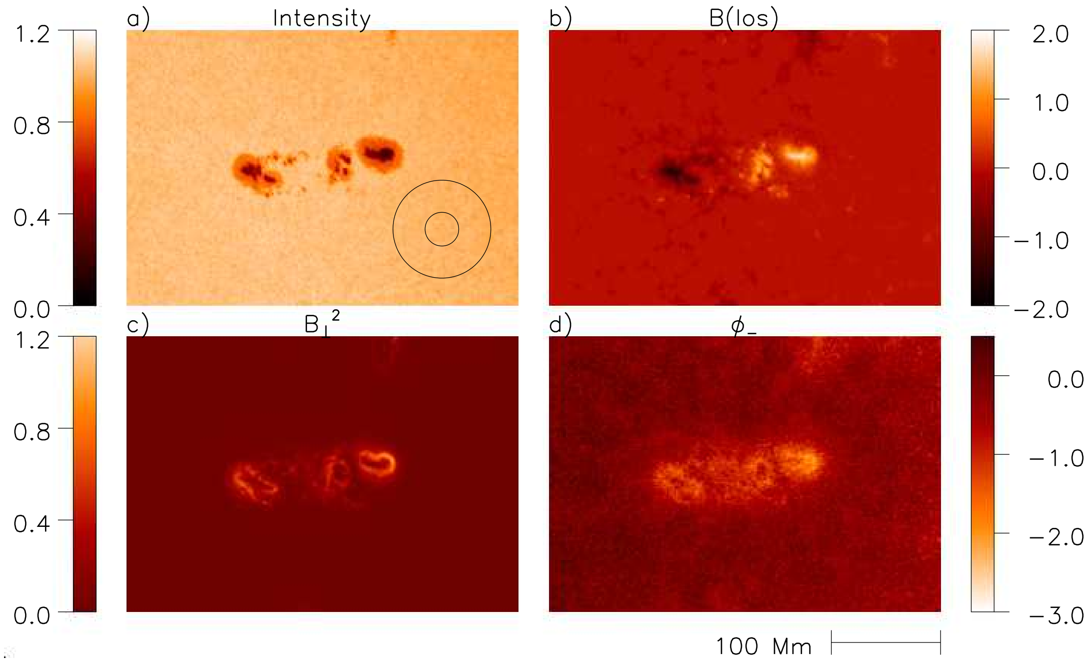

Figure 3. The penumbral phase anomaly in NOAA AR9887 observed on 2003 April 4–5. Frame a: MDI continuum intensity. Frame b: MDI line-of-sight magnetogram, in units of kG. Frame c: square of the horizontal magnetic field derived from the line-of-sight magnetogram assuming that the magnetic field is the gradient of a potential, in units of (kG)^2. Frame d: 4.5–5.5 mHz ingression control correlation phase over a 27 hr 44 min period, in radians. Annulus drawn into lower right corner of upper left frame shows dimensions of the pupil the holographic projection of arriving waves.

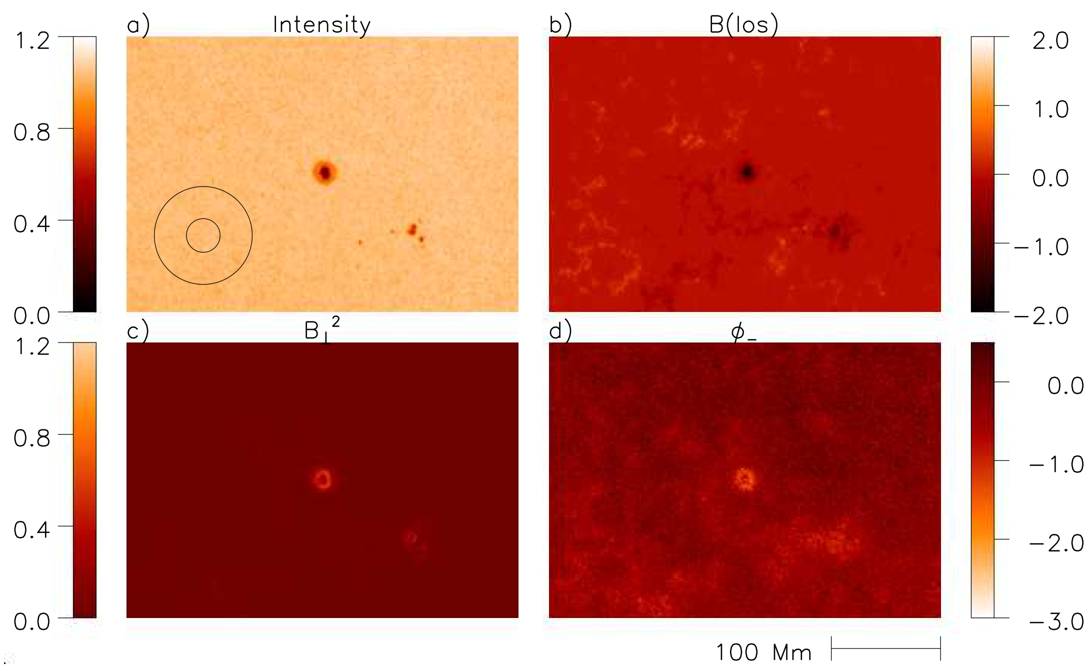

Figure 4. The penumbral phase anomaly in NOAA AR9896 observed on 2003 April 11. See caption of Fig 3 for details.

The consistent negative signatures that invariably mark ϕ_- in inclined magnetic photospheres strongly suggest, but do not prove, that the penumbral phase anomaly is directly caused by magnetic forces themselves. Given our limited understanding of the physics of magnetic subphotospheres, it is entirely possible that inclined magnetic regions tend to be attached to sound-speed anomalies or flows a few Mm beneath that cause the observed phase shifts instead of the photospheric magnetic fields themselves. However magnetic forces have seismic properties that distinguish them from those we understand to characterize sound-speed anomalies and flows more than a few hundred km beneath the surface, and helioseismic diagnostics can be fashioned to capitalize on these.

IV. Phase Parallax

We apply the term "inclined magnetic phase parallax" to describe a strong apparent dependence of the phase of line-of-sight Doppler signatures of waves arriving in a photosphere permeated by an inclined magnetic field. This effect was first reported by Schunker et al. (2005a,b) and recently confirmed by Zhao & Kosovichev 2005. The impetus that motivated Schunker et al. was their expectation of the elliptical motion conceptually illustrated in Fig 2 as a response to magnetic tension forces in regions of inclined magnetic fields. As explained above, this would render the line-of-sight Doppler signature of photospheric motion in response to waves of a particular frequency arriving from the outlying quiet Sun significantly dependent on the angle from which it is viewed.

The ideal diagnostic whereby to verify such a phase relation would be stereo Doppler helioseimology of inclined magnetic fields, and this should be recognized as a major potential of an HMI on a the European Space Agency's *Solar Orbiter*, presently planned for launch in 2015. Pending the possibility of a direct stereo phase comparison, Schunker et al. applied ingression control correlation phase statistics to a controlled selection of active regions at various distances and directions from disk center to secure the vantage dependence indirectly. They found a clear, consistent accentuation of the negative signature in ϕ_- towards the limbward penumbra. This effect is unmistakable in correlations based on relatively high-frequency holographic projections. Figure 5, above, shows the effect for the small active region whose ingression control correlation phase is mapped in Fig 4. When the sunspot is near disk center, the penumbral phase anomaly appears as a roughly symmetrical annulus of enhanced negative ϕ_- in the penumbra (Fig 5d). When the active region is near the limb, this signature is heavily accentuated towards the limb (Fig 5c), hence the term "parallax," to characterize the apparent motion of the centroid of the signature as a response to the shift in vantage.

The effect shown in Fig 5 could conceivably be a result of statistical fluctuation, either acoustic or magnetic, in any single case. However, Schunker et al. (2005) examined control correlation phase maps for a substantial selection of active regions, including some for which Stokes magnetic observations were available, and the statistics of phase parallax in their study was overwhelming.

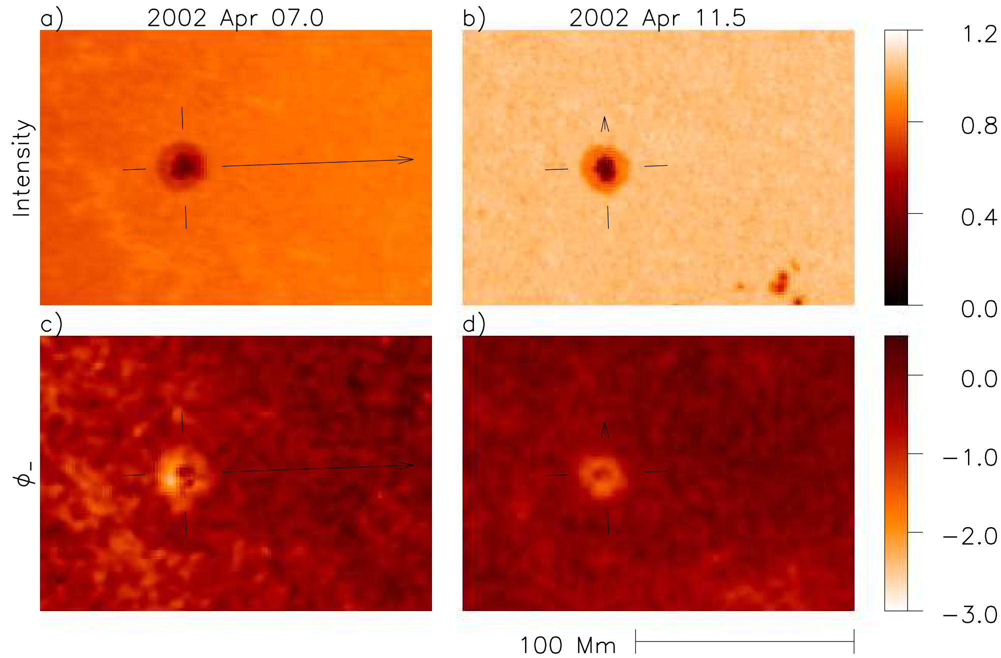

Figure 5. Phase parallax in AR9896 (see Fig 4). Top row: continuum intensity. Bottom row: control correlation phase, ϕ_-. Left column: sunspot 65° from disk center, toward east limb, 4.5 days before meridian passage. Right column: sunspot crossing the meridian 2° south of disk center. Arrows show the 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.

V. Magnetohelioseismology in the Advent of HMI

V.1 Implications respecting subphotospheric thermal anomalies and flows.

Magnetohelioseismology has already given us what we clearly perceive as major insight into the long standing problem of how magnetic regions absorb seismic waves. However, what is now quite imposing is the broader implications, which include the need for a realistic account of magnetoseismic signatures in diagnostics of thermal anomalies and flows beneath magnetic photospheres. Magnetic forces themselves are thought to be significant only in the upper few hundred km of the subphotosphere (Lindsey & Braun 1996). However, the phase shifts that characterize phase parallax, if we understand them correctly, introduce a vantage-dependent phase asymmetry of the same order as the entirety of that discovered by Duvall et al. (1996). It should be borne in mind that the magnetic forces that introduce the horizontal motion to which we propose to attribute the phase parallax have a vertical component as well as a horizontal one (Fig 1). Phase parallax should therefore be regarded as only a single manifestation, i.e. just the vantage dependence, of the magneticseismic signature at large. A careful study of the effects of magnetic fields on helioseismic waves is therefore needed to address the formidable problem of separating magnetoseismic signatures from those introduced by flows.

V.2 Luminosity Driven Flows?

At this point we regard evidence of significant magnetoseismic signatures to be unavoidable. This includes both symmetric and antisymmetric phase shifts, the latter of which are particularly pertinent to the question of rapid downflows beneath sunspots. At this point the proposition that something like the *entirety* of the phase asymmetry can be attributed to magnetically-induced phase shifts remains hypothetical and a major object of both theoretical and observational interest for the advent of HMI. If this hypothesis is borne out by careful physical modeling and observational analysis, evidence for significant near-surface outflows from sunspots will very likely become regarded as both considerable and consistent. This would support a general theory of flows in the convection zone driven by magnetically imposed luminosity variations at the overlying solar surface. A clear understanding of the dynamics of flows in magnetic subphotospheres is therefore crucial to our understanding of the function of luminosity perturbations instigated by active regions in driving massive flows in the convection zone.

V.3 What is needed from HMI

The foregoing developments could hardly come at a more opportune time to qualify magnetoseismology of active regions as a major issue for the advent of the HMI. HMI will be a major improvement over the *SOHO*-borne MDI (Scherrer 1995), which that revolutionized local helioseismology in Solar Activity Cycle 23. What is particularly needed for this undertaking is *high-quality Doppler and magnetic observations of sunspots*, and the resources for *detailed theoretical modeling of the physics of magnetic forces* over a realistic range of photospheric and subphotospheric conditions. The former includes as realistic an account of scattered light in the instrument as is practical and an understanding the effects of contamination of the sunspot spectrum by molecular lines. With these accommodations, the HMI will greatly facilitate the development of magnetohelioseismology and related helioseismic and other solar research, such as modeling active region subphotospheres with a credible account for the effects of photospheric magnetic fields on helioseismic signatures.

To date, no model of flows in active region subphotospheres explicitly includes the possible influence of magnetic fields in producing trave-time asymmetries by any of the several mechanisms that have been proposed and discussed over the years. The inclusion of expliciti magnetic effects in forward modeling efforts, the rapidly growing maturity of theories of MAG waves and absorption, and the availabiltiy of high-performance computes make this a great opportunity th face this challenging problem head-on. A careful re-examination of seismic flow diagnostics with a practical account of magnetoseismic signatures should therefore be a major part of the HMI scientific program. The stakes include a realistic grasp of the structure and dynamics of magnetic subphotopsheres as well as a credible perspective into the function of surface-instigated flows, extrapolated deep into the convection zone, in the maintenance of the variation in solar irradiance over the solar activity cycle.

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