Trapped Eigenoscillations in the Lower Solar Atmosphere: Is there a Resonant Coupling?

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Abstract. Magnetic coupling through MHD waves and oscillations at the solar interior - lower corona interface is studied here. First, the effect of a magnetic solar atmosphere on solar global oscillations is investigated. Frequency shifts of acoustic eigenmodes are found due to the presence of the chromospheric and coronal magnetic fields. Potential application to local magneto-seismology is highlighted.

Next, the propagation and leakage of global acoustic waves is studied in a multi-dimensional realistic model of the lower solar magnetized atmosphere with temperature, pressure and density profiles based on the VAL IIIc model. The higher atmosphere, on the other hand, is the McWhirter atmospheric model. Acoustic waves, mainly identified by solar global oscillations, manifest at photospheric heights. Their leakage into the lower atmosphere is approximated by a harmonic point velocity driver at a range of realistic driver periods measured at photospheric heights, positioned just above the temperature minimum in the photosphere. Convective instability may thus be ignored.

The excited high-frequency waves are seen to propagate through the lower atmosphere to the transition region, and, dependant on the wave period, are transmitted into the lower corona. It was found that for periods close to the lower atmospheric resonant cavity period, reflection from the transition region and trapping in the cavity formed right below the transition region is manifested in the form of chromospheric standing waves. We urge observers to justify these standing waves in the region between the photosphere and transition region by carrying out space or ground-based high-resolution and high-cadence observations.

Further, it is observed in the simulations that waves driven below the cut-off period propagate through into the higher atmosphere with only a slight reflected component. Waves driven at a higher period, in contrast, are largely trapped in the lower atmosphere, with some leakage through the transition region. For specific drivers of around 5 minutes, clear evidence of standing waves being set up in the lower atmospheric cavity is found, and the formation of surface waves travelling outwards along the transition region is demonstrated.

When the lower atmospheric magnetic canopy is also considered, global oscillations can resonantly interact at a much wider range of frequencies as opposed to quiet Sun regions. The properties of this interaction allow us to carry out local magneto-seismology, i.e. to derive diagnostic information about the chromospheric magnetic field. This technique can be further used to improve the missing details of wave leakage, spicule and chromospheric jet formation.
1. Introduction

There is now plenty of evidence that the solar photosphere, chromosphere, transition zone and the corona are magnetically coupled. If one would make a hypothetic vertical journey from the visible surface of the Sun to the corona, and at various consecutive heights (where each height roughly corresponds to a given temperature from about 5,000 K at photospheric levels to 4-6 MK X-ray corona) in the solar atmosphere one would take a horizontal snapshot, the obtained images would contain numerous bright and very inhomogeneous patches. Overlaying these images above a magnetogram taken at the visible photosphere would indicate that the loci of these bright patches correspond well to the loci of magnetic field concentrations of the magnetogram. The manifestation of this magnetic coupling has at least two exciting aspects:

- What is the influence of the magnetic solar atmosphere on solar global coherent motions (i.e. on the acoustic $p/f$ or possibly even $g$ mode oscillations)?
- What is the role -if any- of the solar global oscillations in the dynamics of the solar atmosphere?

In the present paper we briefly address these two complementary questions by highlighting some key points of the magnetic coupling. We shall use a working toy-model of the solar atmosphere (see Fig. 1) and will demonstrate how magnetic coupling is manifested. Some observational predictions will be made, in order to encourage the closure of gap between modeling (analytical and numerical) and observational efforts. The methodology implemented here will be magneto-seismology, i.e. using MHD waves and oscillations in order to obtain information about the physical conditions (geometry, shape, temperature, density, magnetic field diagnostics, transport coefficients, etc.) of the wave guides these periodic motions take place.
2. Magnetic Coupling

Coupling between the solar interior and magnetic atmosphere can occur at various scales (local or random vs. global or coherent) and can involve various coupling elements (flow fields or magnetic fields). The transitional layer between the solar interior and the corona (also called as solar boundary layer), that includes the photosphere, chromosphere and TR, is around 2-3 Mm thick and contains both coherent and random magnetic and velocity fields making it a very difficult task to describe wave perturbations even in approximate terms. Random flows (e.g., turbulent granular motion), coherent flows (meridional flows or the near-surface component of the differential rotation), random magnetic fields (e.g., the continuously emerging tiny magnetic fluxes or magnetic carpet) and coherent fields (large loops and their magnetic canopy region) each have their own effect on wave perturbations. Some of these effects may be more important than the others. The magnitude of these corrections has to be estimated one by one and it is suspected that, unfortunately, they all may contribute to line widths or frequency shifts of the global acoustic oscillations on a rather equal basis (for a review, see Erdélyi 2006). In helioseismology, corrections from this boundary layer are called the surface term (Basu 2002), and in many helioseismologic modelings the surface term is taken in some ad-hoc functional form.

Here we shall only demonstrate one particular aspect of the effect of the transitional layer on global oscillations. No background flow fields will be considered (for that see e.g. Erdélyi & Taroyan 2001a; Erdélyi & Taroyan 2001b), neither random magnetic fields are allowed (see e.g. Erdélyi et al. 2005). We solve the eigenvalue problem of the model atmosphere (Fig. 1) subject to boundary conditions that at ±∞ the energy density drops to zero. In this plain-parallel model, −∞ represents the solar center and +∞ is the outer corona. The spatial eigensolutions indicate that global oscillations penetrate into the magnetized solar atmosphere and interact resonantly with local Alfvénic and/or slow MHD oscillations (see Fig. 2a). The result of this resonant interaction is that the eigenfrequencies of global oscillations will be shifted of the order of μHz when compared to their non-magnetic counterparts, and, the eigenfrequencies will also
have an imaginary part referring to dissipation. Dissipation will occur at the resonant layer and will result in damping of global oscillations. Changing e.g., the strength of the equilibrium magnetic field (that may for instance mimic the global solar cycle variations) or the direction of propagation of the global $p/f$ modes will influence the derived frequency shifts and/or line widths (the latter is directly linked to the complex part of the global acoustic eigenfrequency, $\Im(\omega)$). Figure 2b shows how, for example, the direction of propagation vector will influence the frequencies of the resonant coupling of the global modes to the magnetized atmosphere. The example shows the frequency shift for the $p_4$ mode. Note, that there is a maximum shift when global oscillations propagate perpendicular to the coherent atmospheric magnetic field. We strongly suggest that, this feature can be fully exploited when carrying out local seismology, e.g., ring analysis, and the method will provide an additional information about the direction of the magnetic field!

3. Dynamical Coupling

Next, we try to briefly investigate the answer to the second question raised above in the Introduction. (Un)fortunately, the solar atmosphere is not a time-independent static environment. Dynamical phenomena occur at almost all time scales (from very short lived surges, explosive events to dynamical jets, spicules and variations in solar wind). Here we shall demonstrate only one particular aspect: the consequence of leakage of global oscillations into the magnetized solar atmosphere.

A great deal of work has been carried out on examining the propagation of photospheric signals in regions of strong magnetic fields where waves are to some extent guided by field lines (Bogdan et al. 2003; De Pontieu et al. 2004; Hasan et al. 2005). Photospheric motions (e.g., $p$ modes or granular buffeting) perturb the flux tubes and these motions can, depending on the relation of their periods to the acoustic cut-off frequency, propagate along the field lines up in
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Figure 4. (a) Snapshot of low-frequency standing waves trapped between the photosphere and transition region of the solar atmosphere. (b) Zoom in of a snapshot of the transition region, showing the propagation of surface gravity waves along the thin transition zone. Local velocity vectors are over-plotted.

the stratified atmosphere. For a schematic view of thin flux tubes supporting wave leakage (harmonic and solitary) see Fig. 3a. High frequency foot-point perturbations leak rather easily into the upper atmosphere, as it is shown on a snapshot for a photospheric velocity driver with a period of 30 s in Fig. 3b. However, acoustic waves with periods of around 300 s will resonantly interact with the photosphere - transition region cavity. These low-frequency perturbations are reflected from the strong temperature gradient at the transition region and are trapped in the lower solar atmosphere. A typical snapshot of the vertical velocity component of such trapped perturbations is shown in Fig. 4a. These low-frequency trapped (standing or resonant) oscillations also perturb the transition region and disturbances in form of surface gravity waves will propagate along the thin transition zone (see a zoomed in snapshot in Fig. 4b).

Of course, the real advancement in numerical modeling of leakage of global acoustic motions, and, in understanding the dynamical role of photospheric - coronal coupling would be if studies were carried out in the framework of full 3-dimensional radiative MHD. Initial steps in the direction of 3D modeling have very recently taken. Numerical simulations of a vertical magnetic flux tube embedded in VAL IIIc model (Vernazza et al. 1981) combined with a McWhirter higher atmosphere (McWhirter et al. 1975) confirm the one- and two-dimensional findings presented above. In Fig. 5a, the visualization of such 3D equilibrium state is shown, while Fig. 5b is a snapshot of photospheric $p$-mode leakage into the 3-D solar VAL IIIc atmosphere. The horizontal plane indicates the transition region. Observe the extensive surface wave propagation along the transition region.

This paper is a short progress report of where we are now with the numerical and analytical modeling of MHD wave coupling of the solar interior - atmosphere. Reasonable advancement is already made in one- and two-dimensional modeling. Simulations show fine scale structures (spicules) that can be observationally tested and with impetus from space and ground-based data modeling efforts can be refined. Various photospheric drivers have been investigated (point source, harmonic 2-D driver with fundamental, 1st harmonic and broad-band spectra,
etc.). Advanced 3-D MHD simulations, however, are still in their infancy state and it is anticipated that major progress will be achieved in the near future.

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