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On the propagation of p-modes into the solar chromosphere

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Abstract. We employ tomographic observations of a small region of plage to study the propagation of waves from the solar photosphere to the chromosphere using a Fourier phase-difference analysis. Our results show the expected vertical propagation for waves with periods of 3 minutes. Waves with 5-minute periods, i.e., above the acoustic cut-off period, are found to propagate only at the periphery of the plage, and only in the direction in which the field can be reasonably expected to expand. We conclude that field inclination is critically important in the leakage of p-mode oscillations from the photosphere into the chromosphere.

Key words. Waves – Sun: chromosphere – Sun: oscillations – Sun: photosphere

1. Introduction

It has long been known that photospheric 5-minute oscillations propagate upward in and around magnetic flux concentrations (e.g., Giovanelli et al. 1978), yet in the traditional view of the solar atmosphere, propagation is prohibited due to the 3-minute cut-off period. Several mechanisms have been proposed as an explanation, e.g., p-mode leakage along inclined field lines (e.g., Bel & Leroy 1977; Zhugzhda & Dzhalilov 1984), or radiative losses in the photosphere (Roberts 1983).

Recently, the advent of higher resolution observations and modeling has led to renewed interest in this topic, with suggestions that p-mode leakage can lead to formation of spicules (e.g., Suematsu 1990; De Pontieu et al. 2004; Hansteen et al. 2006) and 5-minute oscillations in coronal loops (De Pontieu et al. 2005). This upward propagation may have important consequences for the energetics of the atmosphere (Jefferies et al. 2006) and the damping of p-mode oscillations (de Moortel & Rosner 2007). All this has led to a renewed focus on understanding the propagation of 5-minute oscillations into the atmosphere, with numerical models investigating both proposed mechanisms (e.g., De Pontieu et al. 2004; Heggland et al. 2007; Khomenko et al. 2008). While improvements in these models are important (especially with respect to understanding the role of wave-mode coupling at the $\beta = 1$ surface), new observations with space-based instruments can yield constraints which can guide us towards a resolution of this issue.

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2. Observations and reduction

We employ data sequences taken with the space-borne observatory Hinode (Kosugi et al. 2007). The Solar Optical Telescope (SOT; Tsuneta et al. 2008; Suematsu et al. 2008; Ichimoto et al. 2008; Shimizu et al. 2008) was used to observe a small area of decaying plage close to disk center (μ = 0.89) on 2009 January 30 using both the Spectropolarimeter (SP) and the Narrowband Filter Imager (NFI).

Doppler shifts were derived from the Fe I spectra and Na I D_1 line scans. We employed a Fourier analysis in time to derive phase differences between these Doppler velocities. Propagation along slanted rays is investigated by shifting the Na I D_1 sequence by several pixels in each direction.

It is not obvious which Doppler velocity signal is formed higher. We determine empirically that the Na I D_1 Doppler diagnostic samples lower regions of the atmosphere than the Fe I Doppler diagnostic. Some discussion on this subject can be found in Sect. 4.

3. Results and discussion

3.1. 3-minute oscillations

Figure 1 shows the maps of phase difference at 5.6 mHz, corresponding to a period of 3 minutes. The central panel shows propagation directly upward in the center of the plage region. Acoustic waves with 3-minute periods can propagate in vertical structures in a gravitationally stratified, FAL-like solar atmosphere. Many previous studies of oscillations have shown that this indeed happens in both, network and internetwork areas (e.g., Rutten 1995; Rutten et al. 2004).

We find much larger phase difference inside the plage region than outside it. De Wijn et al. (2005) noticed similarly large values in their phase-difference diagram at 6 mHz and at small spatial scales, and a corresponding peak in their spatially-averaged, phase-difference spectrum of network areas. While those authors conclude that this feature is likely an artifact in their data, the analysis presented here shows the same signature while using wholly different observations. We thus conclude that the large phase difference measured inside the magnetic region must be attributed to the characteristics of the solar 3-minute waves. These waves must be compressible and must propagate at relatively low velocities. Hence, slow-mode magneto-acoustic waves would seem to be good candidates. Further study of 3-minute waves in regions of strong, vertical field through both observations and simulations is warranted.

3.2. 5-minute oscillations

Figure 2 shows the maps of phase difference averaged over a 1-mHz range around 3.3 mHz, corresponding to a period of 5 minutes. In the central panel, only very little propagation is detected. None of the panels show significant propagation in the core of the plage region. Introducing a spatial shift invariably results in phase differences indicative of propagation in those areas of the plage where the field is expected to diverge in the direction of the displacement. Waves with 5-minute periods propagate predominantly in those places where the field is likely inclined in the direction of propagation.

It is possible that the $\beta = 1$ surface plays an important role in p-mode leakage into the chromosphere. The $\beta = 1$ surface is expected to intersect the photosphere at the periphery of a plage region. If MHD mode coupling is important in p-mode leakage into the chromosphere, one would thus expect it to happen preferentially at the edges of plage, consistent with the current results.

Based on observations by Centeno et al. (2006) that show propagation in apparently vertical structures in a plage region, Khomenko et al. (2008) suggest that radiative relaxation allows for the propagation of 5-minute oscillations. In the results presented here very little propagation is found in areas where the field can be reasonably expected to be vertical, suggesting strongly that, for the propagation of 5-minute oscillations in this regiont, field inclination and/or the $\beta = 1$ surface are critically important.

Under the assumption that field inclination is the critical factor in allowing propagation,

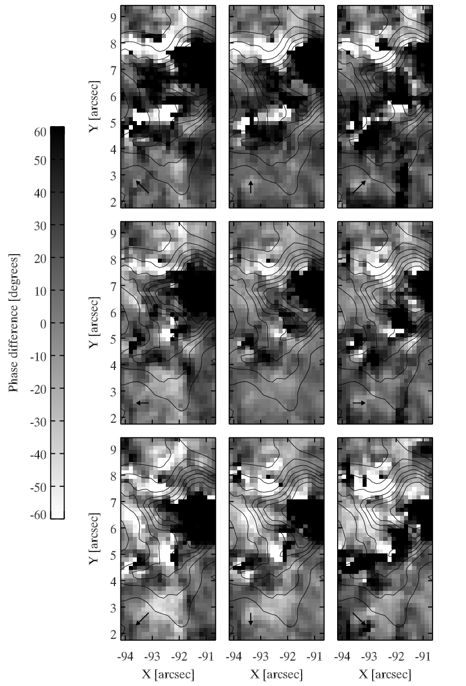

Fig. 1. Phase difference between Doppler shift in Fe I and Na I D_1 at 5.6 mHz. Black and white, respectively, indicate positive and negative phase difference, i.e., upward and downward propagation. Contours indicate the average Stokes *V* signal in Fe I at 2.5% intervals. Arrows in the bottom left corner of each panel indicate the shift between Na I D_1 and Fe I using Na I D_1 as reference. Rows are shifted in north by 3, 0, and −3 NFI pixels of 0.″16, respectively from top to bottom. Columns are shifted east by 3, 0, and −3 NFI pixels, respectively from left to right.

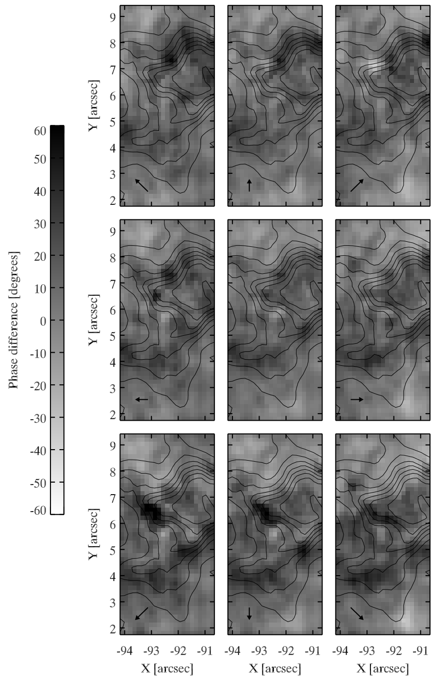

Fig. 2. Phase difference between Doppler shift in Fe I and Na I D_1 at 3.3 mHz in the same format as Fig. 1.

apparently vertical propagation is in principle possible provided the field is sufficiently twisted, because the twist causes the field to be everywhere inclined from the vertical. Since we do not accurately know the difference in the formation heights of the diagnostics used here, we cannot estimate the angle ϕ of propagation from these data. However, in order to adequately lower the acoustic cut-off of a typical FAL-like atmosphere, $\phi \geq 30°$ is needed (De Pontieu et al. 2004). Assuming a constant radius of 50 km, we find that the fluxtube must be twisted once over a height range of less than 180 km. As the fluxtube expands with height, inclination is enhanced naturally, so that the height may be significantly increased (e.g., Parker 1974). Measuring twist in such a small structure is difficult, and so it is not immediately clear that this limiting value for the height is reasonable. However, since we do not see significant propagation inside the plage region, it seems that at least in this case, there is insufficient twist to allow for apparently vertical propagation of *p*-mode oscillations.

4. Sampling heights of the Na I D_1 Doppler diagnostic

We found empirically that the Na I D_1 Doppler diagnostic samples lower heights than the Fe I one. This is somewhat unexpected, because at least the core of the Na I D_1 line is expected to originate from higher layers than the core of the Fe I line. Experiments using synthesized observations from numerical simulations suggest that the determination of the Doppler velocity from the Na I D_1 line by a parabolic fit to our 5-point line scan is to blame, and that some other methods may provide a more chromospheric measurement (B. Fleck, private communication). However, both a "relative intensity difference" of the two inner wing positions as well as a quadratic fit to the profile gave essentially identical results. In any case, comparison between the synthesized and real observations shows major discrepancies. Granulation remains visible in the Na I D_1 line core observations, most likely due to the imperfect suppression of NFI passband sidelobes. Hence, we must conclude that instrumental effects do not allow us to sample Doppler velocities in the chromosphere with our NFI dataset, and possibly with the Hinode Na I D_1 filter in general.

5. Conclusions

We have studied the propagation of waves in a small region of plage using a Fourier phase-difference analysis. We find the expected behavior for the 3-minute oscillations. These oscillations are observed to propagate vertically. We find unexplained, large phase difference inside the plage region. Our results show that propagation of 5-minute oscillations happens only along field that is most likely inclined, and at the periphery of the plage region. We find very little propagation of 5-minute oscillations in the core of the plage, where the field is expected to be mostly vertical. We conclude that at least in this region, inclination of the field and/or the location of the $\beta = 1$ surface are the critical factors in the leakage of p-modes into the chromosphere.

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