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 cutoff 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: Sun: chromosphere – Sun: magnetic fields – Sun: oscillations

1. INTRODUCTION

The chromosphere appears as a dynamic, thin, barbed red ring around the moon about the time of total solar eclipse. Early detailed observations by, e.g., Secchi (1877) have puzzled solar astronomers ever since. We know now that the magnetized chromosphere is dominated by “spicules” at the limb and their on-disk counterparts (“mottles” and “fibrils”; Beckers 1968). Over 90% of the non-radiative energy going into the outer atmosphere is deposited in the chromosphere (Withbroe 1983).

The chromosphere requires nearly one hundred times the mass and energy flux of the corona for sustenance (Withbroe & Noyes 1977) and remains the most poorly understood region of the outer atmosphere. The complex dynamic appearance of the chromosphere, at the interface of photospheric and coronal plasmas where (on average) the magnetic and hydrodynamic forces balance, is incredibly difficult to interpret unambiguously and is largely responsible for the paucity of our knowledge.

Recent analyses of observations of the chromosphere at high spatial and temporal resolution made at multiple heights, guided by state-of-the-art numerical simulations, have begun to unlock the mysteries of the dynamic chromosphere (De Pontieu et al. 2004; Hansteen et al. 2006; McIntosh & Jeffries 2006; Jeffries et al. 2006; De Pontieu et al. 2007a; Rouppe van der Voort et al. 2007; Heggland et al. 2007; Khomenko et al. 2008). Several mechanisms have been proposed to explain the upward propagation of oscillations that have frequencies below the canonical values for the cutoff frequency in the photosphere (e.g., Giovanelli et al. 1978). Several mechanisms have been proposed to explain this upward propagation of oscillations that have frequencies below the canonical values for the cutoff frequency in the photosphere, e.g., leakage along inclined field lines (e.g., Bel & Leroy 1977; Zhugzhda & Dzhaliilov 1984), or radiative losses in the photosphere (Roberts 1983). Because of a lack of high-resolution observations and modeling, this issue has not been resolved yet.

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, 2007a; Hansteen et al. 2006; Rouppe van der Voort et al. 2007; Heggland et al. 2007) and 5 minute oscillations in coronal loops (De Pontieu et al. 2005), and that it has important consequences for the energetics of the chromosphere (Jeffries et al. 2006) and the damping of p-mode oscillations (de Moortel & Rosner 2007).

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 = 0.11) on 2009 January 30 using both the Spectropolarimeter (SP) and the Narrowband Filter Imager (NFI). A context image is shown in Figure 1. SP was programmed to make repeating raster scans of 4′8 × 61′4, with a resolution of 0′16 and an integration time of 1.6 s per slit. NFI was concurrently used to observe five positions in the Na I D1 line, at ±168, ±80, and 0 mÅ from the center of the line (see Figure 2). The cadences of the SP rasters and NFI line scans are about 55 s and 32 s, respectively.

The data were carefully aligned using Fourier cross-correlation techniques. First, the Na I D1 far and inner wings were aligned for each time step separately on the basis of their absolute Stokes V signal, using the far blue wing image as reference. Then, using the intensity image, the core of the line was aligned to the far blue wing. The sequence was then aligned using the Stokes V signal in the far blue wing. The NFI wing data
were then resampled using cubic spline interpolation to match the observing time of the core images. Doppler velocities were calculated by fitting parabolas to each Na\textsc{i} D\textsc{1} 5 point line scan.

For the SP data, a linear minus Gaussian function was fitted to each spectrum of the Fe\textsc{i} 630.25 nm line. The Doppler velocities derived from the repeating SP scans were interpolated in time to match the Na\textsc{i} D\textsc{1} core images. Finally, the SP data were mapped onto a grid matching the square NFI pixels of $0.16''$. This entails scaling and warping of the SP data to correct for slit rotation and other distortions as well as the application of a fixed offset between the SP and NFI sequences plus the displacements computed for the Na\textsc{i} D\textsc{1} core sequence in order to correct for image motion. The fixed offset was computed by optimizing the correlation between the SP Stokes $V$ amplitude and the Stokes $V$ signal in the Na\textsc{i} D\textsc{1} far blue wing. The final sequence contains 211 frames. A manual check shows an excellent alignment between the SP and NFI sequences.

We employ a Fourier analysis to derive phase differences between the Doppler velocities derived from the SP data and those from the NFI data. The cadence of the SP observations limits the Nyquist frequency to 9 mHz. A cos$^2$ apodization window is applied to 10\% of the sequence. In order to reduce noise, we average the phase difference by summation of crosspower weighted by a Gaussian with a FWHM of 1 mHz centered on the frequency of interest. Propagation along slanted rays is sampled by shifting the Na\textsc{i} D\textsc{1} sequence by several pixels in each direction.

While the core of the Na\textsc{i} D\textsc{1} line is expected to sample higher layers than the core of the Fe\textsc{i} line, it is not immediately obvious which Doppler velocity signal is formed higher. In order to deduce empirically which is higher, we examine the phase difference of oscillations with $2\frac{1}{2}$ minute periods. Upward propagation is expected in the non-magnetic internetwork (e.g., Lites et al. 1993). In the majority these areas, we find a positive phase difference (i.e., upward propagation) if we assume the Na\textsc{i} D\textsc{1} Doppler velocity signal is formed lower than the Fe\textsc{i} signal. We thus take the Na\textsc{i} D\textsc{1} Doppler velocity signal as the reference. The Fe\textsc{i} line is sampled with high spectral resolution, which allows for very accurate determination of the line core position. Conversely, the relatively wide NFI passband, imperfect suppression of sidelobes, and the contribution of the Na\textsc{i} D\textsc{1} wings in the determination of the Doppler velocity cause this diagnostic to sample deeper layers.

3. RESULTS AND DISCUSSION

3.1. 3 Minute Oscillations

Figure 3 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. The general pattern remains the same under northward shifts, though upward propagation becomes more pronounced over a larger area. There is less propagation in the core of the plage when sampling in the southwest direction. By introducing a sufficiently large shift, patches of downward propagation appear.

While the specifics of these results depend on the magnetic configuration of the plage, they are not unexpected. Acoustic waves with 3 minute periods can propagate in vertical structures in the traditional treatment of wave propagation in the 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). Oscillation power is reduced inside the network compared to the internetwork, but enhanced in the area immediately surrounding the network (e.g., Krieger et al. 2001). No obvious phase-difference signal that would correspond to these “power aureoles” is present.

We find much larger phase difference inside the plage region than outside it. De Wijn et al. (2005) analyzed TRACE UV continua (Handy et al. 1999), and noticed a peak in their phase-difference $(k_\parallel, f)$ diagram at 6 mHz and at small spatial scales reaching $110''$, and also a corresponding peak in their spatially averaged phase-difference spectrum of network areas at the same temporal frequency. While those authors conclude that these features are likely an artifact in their data, the analysis presented here shows a conspicuously similar signature while using wholly different observations. We thus conclude that the large phase difference measured inside the magnetic region here and also by De Wijn et al. (2005) is not an artifact of the data or processing, but must be attributed to solar 3 minute waves in magnetic regions. These waves must be compressible, since
they would not show up as an intensity-modulation the TRACE UV continua otherwise. Due to the large phase difference, slow mode magneto-acoustic waves are a good candidate. 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 4 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 shift invariably results in phase difference indicative of propagation in those areas of the plage region where the field is expected to diverge in the direction of the displacement. As an example, the left upper panel shows enhanced phase difference in the northeast corner of the plage region. Conversely, the bottom row shows increased phase difference on the southern edge. Waves with 5 minute periods propagate predominantly in those places where the field is 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 plage. If 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. Only weak indications of downward propagation are detected, mostly at large shifts, e.g., at $(-92.5, 7)$ in the upper right panel. Potentially, signals of downward propagation are not detected because they are overwhelmed by signals of upward propagating waves. If a weaker signal of propagation in the opposite direction is present, the phase difference will be underestimated. In the case where both signals are of equal amplitude, they can be considered as a standing wave with zero phase difference. Because of the uncertainty in the sampling heights of the two diagnostics used, we should consider that in areas with strong magnetic field the heights could be reversed as compared to in internetwork. However, in such a case, the phase difference would be negative, indicative of downward propagation, which conflicts with other studies (e.g., De Wijn et al. 2007). While we cannot deduce a propagation velocity from the phase differences measured, we are confident that we indeed detect upward propagation.
Studies by Centeno et al. (2006, 2009) show propagation in apparently vertical structures in a plage region. Based on these observations, Khomenko et al. (2008) suggest that radiative relaxation is key to the propagation of 5 minute oscillations. Our analysis is based on observations with much higher spatial resolution. Conceivably, Centeno et al. (2006) observed slanted propagation inside their resolution element; however, inversions of their spectropolarimetric measurements indicated that the field was truly vertical. In the results presented here no propagation is found in areas where the field can be reasonably expected to be vertical, suggesting strongly that inclination is critically important for the propagation of 5 minute oscillations, at least in this plage region.

Given the results presented in this Letter, one may theorize that apparently vertical propagation is possible provided the field is sufficiently twisted. The field is then inclined with respect to the gravity vector, and oscillations may travel upward along this field. A structure with radius \( r \) reaches an inclination of \( \phi \) at its periphery if it makes at least one complete twist over a height of \( h = 2\pi r \tan(\phi) \). Since we do not accurately know the difference in the formation height of the observations used here, we cannot estimate the angle of propagation from these data. However, in order to adequately lower the acoustic cutoff, \( \phi \geq 30^\circ \) is needed (De Pontieu et al. 2004). Assuming a constant \( r = 50 \) km, we find \( h \leq 180 \) km. As the fluxtube expands with height, twist and hence inclination are enhanced naturally, so that \( h \) 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 \( h \) 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. CONCLUSIONS

We have studied the propagation of waves in a small region of plage using a Fourier phase-difference analysis. We find expected behavior of 3 minute oscillations. These oscillations are seen to propagate vertically, as is expected in the traditional view of the propagation of acoustic waves in the solar atmosphere. We find a much larger phase difference for these oscillations inside the plage region than outside it. Our results show that propagation of 5 minute \( p \)-mode oscillations happens only along inclined field at the periphery of the plage region. We find no propagation of \( p \)-modes in the core of the plage, where the field is expected to be mostly vertical.

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