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The nature of running penumbral waves revealed

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Abstract. We seek to clarify the nature of running penumbral (RP) waves: are they chromospheric trans-sunspot waves or a visual pattern of upward-propagating waves? Full Stokes spectropolarimetric time series of the photospheric Si I 10827 Å line and the chromospheric He I 10830 Å multiplet were inverted using a Milne-Eddington code. Spatial pixels were paired between the outer umbral/inner penumbral photosphere and the penumbral chromosphere using inclinations retrieved by the inversion and the dual-height pairings of line-of-sight velocity time series were studied for signatures of wave propagation using a Fourier phase difference analysis. The dispersion relation for radiatively cooling acoustic waves, modified to incorporate an inclined propagation direction, fits well the observed phase differences between the pairs of photospheric and chromospheric pixels. We have thus demonstrated that RP waves are in effect low-β slow-mode waves propagating along the magnetic field.

Keywords. Sun: infrared – Sun: magnetic fields – Sun: sunspots – Techniques: polarimetric – Waves

1. Introduction

The above abstract was taken from the journal paper covering the work presented by the first author at the meeting. The paper has since been published (Bloomfield et al. 2007) and the most important results are summarized here.

Running penumbral (RP) waves are line-of-sight (LOS) velocity wave fronts in the chromosphere above sunspot penumbrae which expand outward from umbrae (Giovanelli 1972; Zirin & Stein 1972). This work concerns Fourier phase difference analysis carried out between i) chromospheric LOS velocities in the umbra and chromospheric LOS velocities at increasing distances into the penumbra, and ii) LOS velocities at photospheric heights in the umbra/penumbra and LOS velocities at chromospheric heights in the penumbra. Investigating these two physically different situations should tell us whether RP waves are i) trans-sunspot waves in the chromosphere, or ii) a signature of field-aligned, upward-propagating waves.

To this end, full-Stokes spectropolarimetry was investigated in the Si I 10827 Å line (upper photosphere) and the He I 10830 Å multiplet (upper chromosphere) from the Tenerife Infrared Polarimeter (TIP; Martínez Pillet et al. 1999) attached to the German Vacuum Tower Telescope on Tenerife, Canary Islands. These data were taken and previously published by Centeno et al. (2006). The magnetic field vector and LOS velocities were retrieved from the Stokes (I, Q, U, V) spectra using the Milne-Eddington inversion code of Lagg et al. (2004). The determination of the magnetic vector in solar coordinates allows for the possibility of pairing pixels between the photosphere and chromosphere based on the measured field inclinations. Such a step has not been possible in previous RP wave analyses (e.g., Christopoulou et al. 2000; Georgakilas et al. 2000; Christopoulou

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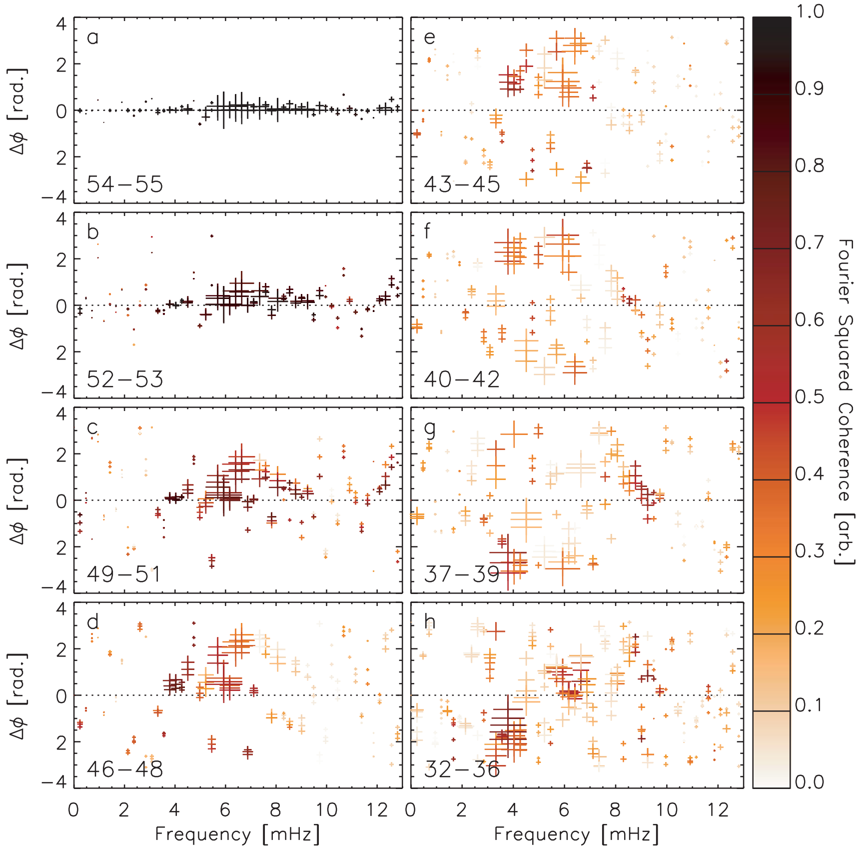

Figure 1. Phase difference spectra between the He I LOS velocity in the umbra and He I LOS velocities at increasing distance into the penumbra. Symbol size and shading denote the cross-spectral power and squared coherence, respectively. Panels show groups of phase difference spectra calculated between umbral pixel 55 and the pixel numbers listed in the lower-left corners (smaller pixel numbers lie further from the umbra), moving from cases concerning the pixels closest to the umbra/penumbra boundary (a) toward those in the middle penumbra (h). The Fourier squared coherence "noise" level has a value of 0.2 for randomly distributed phase differences in these data. From Bloomfield et al. (2007).

et al. 2001; Tziotziou et al. 2006, 2007), yet it is absolutely crucial to accurately study the likelihood of RP waves resulting from field-aligned waves.

2. Results & Conclusions

To investigate the possibility of RP waves being a chromospheric wave propagating radially out from the sunspot umbra, Fourier phase differences were calculated between the He I LOS velocity signal within the umbra and those He I LOS velocity signals in the penumbra. The phase difference spectra are plotted in Figure 1, where panels a to h depict groups of phase difference spectra between the LOS velocity signals from the umbra and LOS velocity signals at increasing distances into the penumbra. The usual form of an upward-propagating acoustic wave dispersion relation (i.e., increasing phase difference with increasing oscillation frequency) is not observed and the coherence values depicted by the symbol shading (white for 0; black for 1) rapidly approach the "noise" level of 0.2 for these data.

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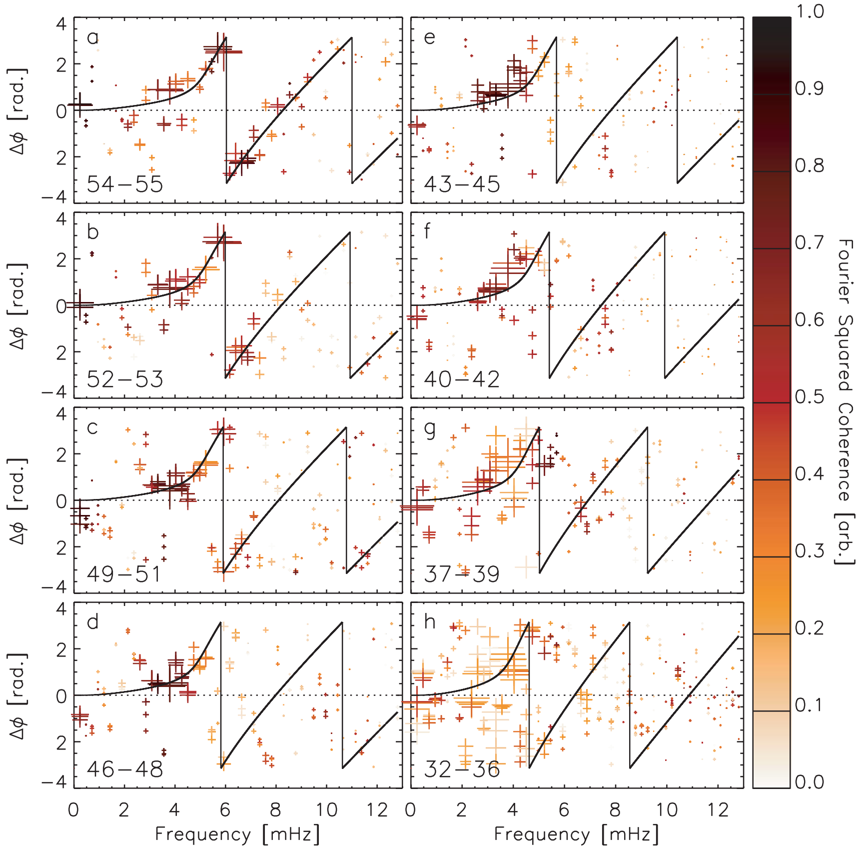

Figure 2. Same as Fig. 1, but for the spatially-offset, field-linked dual-height pairs of photospheric and chromospheric pixels. Curves show the acoustic dispersion curves expected from the equations of Centeno et al. (2006) after being modified from the vertical case using the measured Si I field inclinations. From Bloomfield et al. (2007).

To investigate the other possibility of RP waves being a "visual pattern" of upward-propagating waves, spatial pixels were paired between the photosphere and chromosphere using the retrieved field inclinations and an assumed vertical separation between the Si I and He I velocity response heights (taken as 1000 km from the work of Centeno et al. 2006 on this sunspot umbra). Fourier phase differences were again calculated, this time between the LOS velocity signals from the field-linked photospheric and chromospheric spatial pixels. These spectra are plotted in Figure 2, where panels *a* to *h* again show groups of spectra which cover increasing distances into the penumbra. There is a stark contrast with Figure 1, where the existence of increasing values of phase difference with frequency indicates upward-propagating waves.

Figure 2 also shows the dispersion relations for vertical acoustic waves with radiative cooling provided by the equations in Centeno et al. (2006), modified for propagation along inclined field lines – i.e., effective gravity decreased and propagation distance increased by the cosine of the inclination angle. The similarity between these modified dispersion relations and our measured data points indicates that RP waves are upward-propagating, field-aligned, low-β acoustic-like (i.e., slow magnetoacoustic) waves. The existence of such waves in the penumbrae of sunspots is not unexpected as similar waves have been observed propagating both in the lower atmosphere of sunspot umbrae (Centeno et al.

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2006) and in the transition region above sunspots (e.g., Brynildsen et al. 2002; Marsh & Walsh 2006). However, this is the first study that has been able to actually discriminate between the two possible physical scenarios leading to the existence of RP waves.

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