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LETTER TO THE EDITOR

Three-minute wave enhancement in the solar photosphere

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ABSTRACT

It is a well-known result that the power of five-minute oscillations is progressively reduced by magnetic fields in the solar photosphere. Many authors have pointed out that this could be due to a complex interaction of many processes: opacity effects, MHD mode conversion, and intrinsically weaker acoustic emissivity in strong magnetic fields. While five-minute oscillations predominate in the photosphere, it has been shown that in the chromosphere three-minute oscillations are more common. Two main theories have been proposed to explain the presence of the latter oscillations based upon resonance filtering in the atmospheric cavity and non-linear interactions. In this work, we show, through the analysis of IBIS observations of a solar pore in the photospheric Fe I 617.3 nm line, that three-minute waves are already present at the height of formation of this line, their amplitude depends on the magnetic field strength, and they are strictly confined to the umbral region.

Key words. Sun: oscillations – Sun: helioseismology – Sun: photosphere – sunspots

1. Introduction

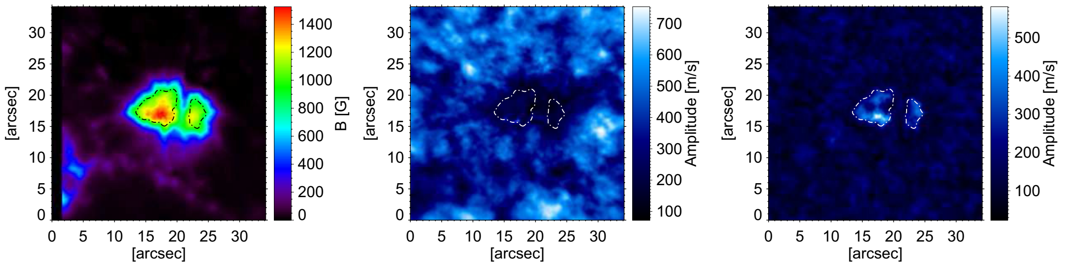
Oscillatory phenomena are ubiquitous in and around magnetically active regions of the Sun. Since their discovery (Beckers & Tallant 1969), waves in sunspots have been detected in many solar magnetic features on all spatial scales and at all heights in the atmosphere as small perturbations in both intensity and velocity (Bogdan & Judge 2006; Centeno et al. 2009). Nevertheless, a clear understanding of their excitation mechanism and interaction with complex magnetic features remains elusive (Kosovichev 2009). Among the many open questions that are unanswered we have for example the role of the residual convection inside the umbra of sunspots and the power reduction of the oscillations in strong magnetic fields. For a detailed treatment of these and many other aspects of waves in sunspots, we refer to Khomenko (2009) and Bogdan & Judge (2006). Simoniello et al. (2010) pointed out that the amplitude reduction may be consistent with the MHD mode conversion theory.

The study of wave generation and propagation in the Sun's atmosphere also provides valuable information about the atmospheric structure itself and its dynamics (Lites 1992; Bogdan & Judge 2006).

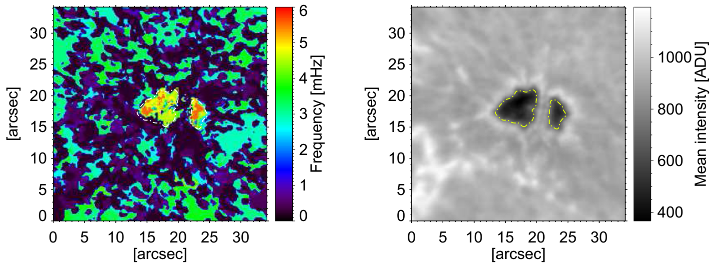
High spectral and high spatial resolution ground-based and space-borne observations have helped to provide improvements in the theoretical interpretation of waves in the solar atmosphere over the past decade. In this context, a very promising observational tool for the investigation of the propagation of waves is multi-line spectroscopy (Berrilli et al. 2002; Jefferies et al. 2006; Centeno et al. 2009; Felipe et al. 2010b), which allows the estimation of the phase lag of the waves between different layers in the solar atmosphere. In particular, Centeno et al. (2009) showed that different magnetic regions have distinct power spectrum features as we move from the photosphere to the chromosphere. They showed that while small magnetic elements are dominated by five-minute oscillations in both the photosphere and the chromosphere, large magnetic structures such as pores and sunspots, in contrast, are still dominated by five-minute oscillations in the photosphere, but in the chromosphere, their power spectrum peak clearly shifts toward higher frequencies (three-minute oscillations or equivalently 5 mHz).

Many competing theories have been proposed to explain the presence of three-minute waves in sunspots. Zhugzhda & Locans (1981) and Zhugzhda (2008) proposed a resonant atmospheric cavity to explain the multiple peaks in the power spectra. Cally & Bogdan (1993) proposed in turn a theory based on eigenoscillations of sunspots, while Fleck & Schmitz (1991) demonstrated that the presence of a cutoff frequency in a stratified atmosphere may easily provide a basic physical mechanism for the onset of the three-minute regime in the chromosphere.

Felipe et al. (2010a) showed, by using a three-dimensional (3D) simulation of wave propagation in a sunspot atmosphere, that in such a magnetic structure the three-minute amplification in the chromosphere is related to the acoustic cutoff frequency. Waves below the cutoff frequency ($\nu_c = 5.2$ mHz) are not allowed to upward propagate and are evanescent. On the other hand, higher frequency waves are free to propagate toward the chromosphere. During the propagation, they increase their amplitude in response to the rapid drop in the density and, therefore, they are amplified, dominating the power spectrum. In small magnetic elements, the cutoff frequency is much smaller owing to the radiative losses (Khomenko et al. 2008), allowing the propagation of five-minute waves toward the chromosphere. The cutoff frequency can also be lowered by the so-called ramp effect, allowing the propagation of low frequency waves in an inclined magnetic field environment (Jefferies et al. 2006). Stangalini et al. (2011) found, using the same IBIS data investigated in this work, that the amount of energy transferred toward the upper layers of the Sun depends strongly on the complexity of the magnetic field geometry, through a combination of ramp effect and MHD mode conversion.



(a) Magnetogram (b) Amplitude @ 3 mHz (c) Amplitute @ 5 mHz



(d) Frequency peak (e) Intensity core Fe 617⊳3 nm

Fig. 1. a) Centre-of-gravity magnetogram Fe 617.3 nm (absolute value). **b)** Amplitude of 3 mHz oscillations (Fe 617.3 nm). **c)** Amplitude of 5 mHz oscillations (Fe 617.3 nm). **d)** Position in frequency of the power spectrum peak (Fe 617.3 nm). The contour indicates the position of the umbra as seen in intensity images.

In addition to this, many authors have reported suspicious high-frequency power enhancements in rings surrounding active regions, both in the photosphere (Brown et al. 1992) and the chromosphere (Braun et al. 1992). Later Khomenko & Collados (2009) suggested that these "acoustic halos" are probably generated by fast MHD mode refraction in the vicinity of the conversion layer (i.e. the layer where the sound speed equals the Alfven speed). Schunker & Braun (2011) pointed out that the halos of high frequency acoustic power are strongest at intermediate magnetic field strength (150–250 G), in agreement with Jain & Haber (2002) and Hindman & Brown (1998), and they also discovered a clear association with horizontal magnetic fields. In addition, they also found that the frequency peak of the acoustic enhancement also slightly increases with the magnetic field strength.

In this work, we report on the presence of the three-minute waves also in the umbral photosphere of a pore. In more detail, we study the three-minute power enhancement and its relation to the magnetic field strength. By using a wavelet analysis, we also found that enhanced three-minute signal is non-stationary. The three-minute enhancement, moreover, interests only the umbra of the pore, as seen in intensity images, and inside this region the oscillations are in phase.

2. Observations

The data used in the work have been also used in Stangalini et al. (2011) and were acquired on October 15th 2008 in full Stokes mode with IBIS at DST. IBIS is the Interferometric BIdimensional Spectrometer based on a dual Fabry-Perot system combining high-spectral resolution and large FoV (field of view), as well as the ability to measure the polarization (Cavallini 2006).

The region observed was the AR11005 which consists of a small pore with a light bridge in the northern hemisphere [25.2° N, 10.0° W]. The data set consists of 80 sequences, containing a full Stokes 21 points scan of the Fe 617.3 nm line. The temporal sampling is 52 s and the pixel scale of these 512 × 512 pixel images was set at 0.167 arcsec.

For further details of the data set and the calibration pipeline, we refer to Stangalini et al. (2011) and Viticchié et al. (2009) respectively.

3. Results

3.1. Three-minute enhancement

We studied the amplitude enhancement of three-minute waves and the five-minute wave absorption as a function of the magnetic field strength. To limit the distortions of the FFT power spectrum estimation caused by the limited duration of the time series (Edge & Liu 1970), we used the Blackman-Tukey method with a Barlett windowing function (Blackman & Tukey 1958) to estimate the amplitude spectrum.

We produced maps of the amplitude of the oscillations in two spectral bands, namely 3 mHz and 5 mHz, corresponding to periods of three and five minutes, by integrating over a 1 mHz frequency interval (panels c and b of Fig. 1). In the following, we use the periods to refer to the respective oscillations.

We then studied the behaviour of the amplitude of the waves as a function of the magnetic field, estimated by means of the center of gravity (COG, see Uitenbroek 2003, for details) method (panel (a) of Fig. 1). Our power maps (panel (c) of Fig. 1) reveal a power enhancement of the three-minute waves for magnetic field strengths higher than 1000 G. No acoustic halo is apparent in our maps. In Fig. 2, we show the behaviour of the amplitude of the oscillations in both spectral bands versus the magnetic field strength. The five-minute waves (upper panel) are absorbed as expected, and their amplitude is lower by roughly a factor of two. Conversely, the three-minute oscillations (bottom panel) strengthen as the magnetic field strength increases. The amplitudes of the three-minute waves are almost constant up to 700−1000 G and then suddenly increase for higher field strengths.

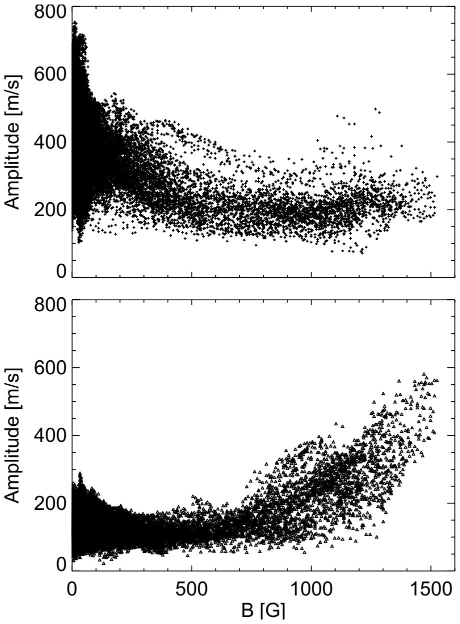


Fig. 2. (*Top*) Amplitude of the five- (*upper panel*) and three-minute (*bottom panel*) waves as a function of magnetic field strength. In this scatter plot, each dot represents the amplitude of the wave and the magnetic field in one pixel in the spatial map shown in Fig. 1.

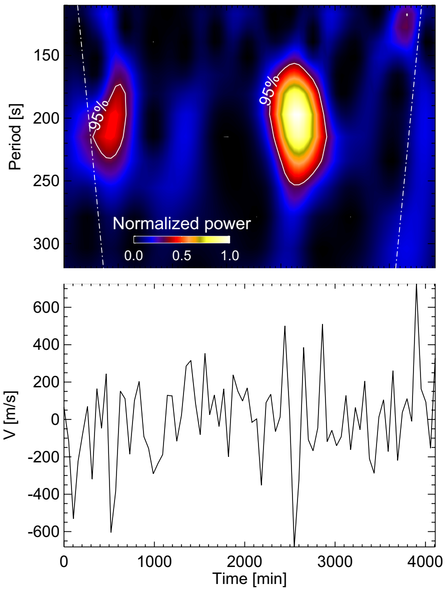


Fig. 3. Wavelet spectrum (*top panel*) of the velocity signal averaged over the entire umbra (*bottom panel*). Positive values indicate redshifts. The continuous contours indicate the 95% confidence level, and dot-dashed contours indicate the cone of influence.

To further investigate this scenario, we study the frequency shift of the power spectrum peak throughout the FoV. This analysis is reported in panel (d) of Fig. 1. In this map, it is evident that in the quiet Sun, but also in the diffuse magnetic field surrounding the pore, the power spectrum peaks around 3 mHz. Three-minute waves (5 mHz) are in turn the dominant component inside the umbra of the pore. For comparison, panel (e) of Fig. 1 shows the intensity map in the core of the Fe 617.3 nm spectral line.

We note that the frequency shift occurs abruptly at the boundaries of the umbra without any smooth transition from the low values observed outside (3 mHz), to the higher frequencies observed inside the pore (5 mHz).

3.2. Wavelet analysis and spatial coherence

To analyse the nature of the three-minute signal in the umbra of the pore, we used a wavelet analysis with a Morlet mother function. We studied the spatially averaged signal in the umbra delineated by the contours in Fig. 1. In Fig. 3, we show the wavelet spectrum (upper panel) and the spatially averaged signal (bottom panel). The spectrum shows at least two main features located in time at 10 min and 43 min, where the signal manifests three-minute oscillations (over 95% confidence level). The time interval between these two wave trains is around 30 min, even though the short duration of our data does not allow us to provide a statistically relevant estimate. Interestingly, these non-stationary oscillations are spatially coherent throughout the umbra of the structure. This is apparent in Fig. 4, where we show the temporal evolution of the velocity field during the onset of the second power peak shown in the wavelet spectrum (38 min $< t <$ 45 min). All the spatial positions within the umbra oscillate in phase, as is clearly evident in panels (d) and (g) of Fig. 4. We note that another interesting feature is clearly visible in panels (d, e). After the rapid increase in the velocity (redshift) inside the umbra, the surrounding region around the umbra itself appears to be influenced by a velocity perturbation, which resembles an expanding wave.

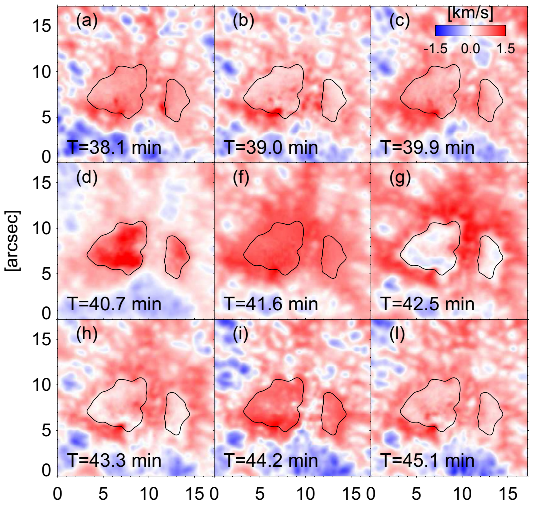


Fig. 4. Temporal evolution of the velocity field in the Fe 617.3 nm. Positive values are redshifts.

4. Discussion

Our presented results provide information about the three-minute wave generation in active regions by finding a clear three-minute enhancement in a photospheric magnetic region. Three-minute waves are generally expected to predominate at chromospheric heights in large magnetic elements (Centeno et al. 2009). In this work, we have shown that the three-minute wave enhancement is confined to the region within the umbra of the pore, as seen in intensity images. This boundary does not coincide with the boundaries of the magnetic signal, which extends a few arcseconds beyond the umbra. As a consequence, the three-minute enhancement appears to be related to a different regime of the magneto-convection. As we go into the umbra boundaries, we observe an abrupt increase in power as we can see in the frequency map (panel (d) of Fig. 1). The frequency shift exactly coincides with the umbra boundary, which indicates the onset of a different regime for the oscillation field.

Regardless of the origins of the three-minute oscillations, it appears that they depend strongly on the magneto-convection regime, and our results firmly point to this.

The p-mode absorption in magnetic structures has been investigated in detail by many authors. Among the many mechanisms proposed so far to explain this power suppression, at least two of them are worthy of consideration in light of our results: the opacity effect and the local suppression due to reduced emissivity. The first one is a well-known result that the magnetic field, exerting its own pressure, empties the plasma environment (Wilson depression). This means that the spectral line used originates well below the height of formation in the quiet Sun, allowing us to observe deeper and deeper into the solar atmosphere as the magnetic field increases. In addition to this, we have to keep in mind that owing to the rapid drop in the density with height, the amplitude of the waves is subject to a rapid increase during their upward propagation. These two findings together mean that, in magnetic environments, we expect to see a suppression of the wave amplitude due to the Wilson depression. The latter mechanism also goes in the same direction producing a power suppression within magnetic regions. Both mechanisms should work independently for the five-minute and three-minute waves. Our results suggest in turn that this cannot be the case and the three-minute waves, contrarily to what happens with the five-minute waves, are enhanced in the umbra of the pore.

Moreover, Fleck & Schmitz (1991) and Felipe et al. (2010a) argued that the three-minute waves may originate from a very basic physical effect related to the cutoff frequency. All the waves with frequencies above the cutoff value are free to upward propagate, increasing their amplitude, as we already said. On the other hand, waves with lower frequencies are not free to propagate. This means that in the higher layers the three-minute waves dominate the spectrum of oscillations.

Involving the cutoff frequency is appealing but the altitude of formation of the Fe 617.3 nm spectral line used in this work (300 km in the quiet Sun (Norton et al. 2006) and even below within the magnetic region) is insufficient to explain the observed amplification. In addition, we should also see this effect in other regions of the FoV (for example in the diffuse magnetic field).

By using a wavelet analysis, we also noted that the three-minute waves found in the umbra are not stationary and present wave-trains lasting for a few minutes (less than ten minutes). More interestingly, the umbral oscillations show a clear spatial coherence involving the entire umbra. In addition, the two umbral regions divided by a light bridge also produce oscillations in phase, which probably implies that the generation mechanism responsible for the three-minute waves involves the structure as a whole.

5. Conclusions

We have reported on a three-minute wave enhancement in the magnetic umbra of a pore at photospheric heights. Making use of IBIS observations, we have shown that the three-minute enhancement is strictly confined in the umbral region. This means that it does not depend on the magnetic field alone but on the magneto-convection regime. This seems to be in contrast with the behaviour of the five-minute waves, which are in turn suppressed as expected. In addition, we have shown that the three-minute oscillations are strictly in phase throughout the umbra even if the umbra is divided into two by a light bridge.

The inspection of the velocity fields, during the appearance of the three-minute wave-train, suggests that there is expanding wavefront produced by the perturbations within the umbra. This wavefront appears to be the echo of the three-minute oscillations enhanced inside the umbra.

These observational results, as far as we know, have never been reported so far, and we believe that further multi-height observations are required to provide a fairly consistent picture explaining this interesting three-minute enhancing mechanisms.

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