Oscillatory behaviour of chromospheric fine structures in a network and a semi-active region

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ABSTRACT

In this work, we study the periodicities of oscillations in dark fine structures using observations of a network and a semi-active region close to the solar disc centre. We simultaneously obtained spatially high-resolution time series of white light images and narrow-band images in the Hα line using the 2D Göttingen spectrometer, which were based on two Fabry–Perot interferometers and mounted in the Vacuum Tower Telescope/Observatorio del Teide/Tenerife. During the observations, the Hα line was scanned at 18 wavelength positions with steps of 125 mÅ. We computed series of Doppler and intensity images by subtraction and addition of the Hα ± 0.3 Å and ± 0.7 Å pairs, sampling the upper chromosphere and the upper photosphere, respectively. Then, we obtained power, coherence and phase difference spectra by performing a wavelet analysis to the Doppler fluctuations. Here, we present comparative results of oscillatory properties of dark fine structures seen in a network and a semi-active region.

Key words: Sun: chromosphere – Sun: oscillations.

1 INTRODUCTION

When observing the quiet solar chromosphere in the Hα line, dark elongated fine structures can be seen especially in the borders of the supergranular cells (magnetic network). These structures are called mottles on the disc and spicules at the limb and they seem to originate from network bright points. Mottles form into two kind of groups, namely rosettes and chains. They have lengths between 7 and 10 arcsec, widths smaller than 1 arcsec and lifetimes of the order of 10 min (Beckers 1963, 1968; Bray & Loughhead 1974; Suematsu, Wang & Zirin 1995). It has been considered that mottles are the disc counterparts of spicules and that the driving mechanism of these structures has the same origin (Tsiropoula, Alissandrakis & Schmieder 1994; Suematsu et al. 1995; Christopoulou, Georgakilas & Koutchmy 2001; Hansteen et al. 2006; Rouppe van der Voort et al. 2007). These jet-like features act as channels through which energy and mass are supplied from the solar photosphere into the upper solar atmosphere and the solar wind (De Pontieu, Erdélyi & James 2004; De Pontieu & Erdélyi 2006; Morton et al. 2012).

The active solar chromosphere in the Hα line core shows another sort of dark fine features named fibrils. They are mostly classified into two types, traditional fibrils and dynamic fibrils. Dynamic fibrils are jet-like features with higher decelerations, slightly lower velocities, shorter lifetimes and shorter lengths and located mostly in a dense active region plage, while traditional fibrils are low-lying features with lower decelerations, slightly higher velocities, longer lifetimes and longer lengths (for a more detailed description and their properties of these structures see De Pontieu & Erdélyi 2006; Hansteen et al. 2006; Tsiropoula et al. 2012).

The study of oscillations and periodicities of these structures has become more important in recent years as they are believed to be an important source for the heating of the solar chromosphere. Several authors have investigated periodicities and oscillations in these structures. Dominant periods of the order of 5 min are reported in chromospheric mottles (Tziotziou, Tsiropoula & Mein 2004; Tsiropoula et al. 2009; Bostancı 2011). Similarly, the periods for the oscillations in more inclined dynamic fibrils are found to be in the 4–6 min range (De Pontieu et al. 2004; De Pontieu & Erdélyi 2006; Hansteen et al. 2006). These findings support the idea that normally evanescent photospheric 5 min oscillations leak into the higher atmospheric layers along inclined flux tubes (De Pontieu et al. 2004).

Observations performed at photospheric levels show power enhancements at higher frequencies (ν > 5 mHz) in the surrounding active regions (Braun et al. 1992; Brown et al. 1992; Hindman & Brown 1998; Thomas & Stanchfield 2000; Muglach 2003) and in quiet regions around the network magnetic elements (Kriiger et al. 2001; Muglach, Hofmann & Staude 2005). Such power enhancements are called power haloes. On the other hand, chromospheric observations show power suppression called magnetic shadows at higher frequencies especially around magnetic network elements as
well (Judge, Tarbell & Wilhelm 2001; Krijger et al. 2001; Finsterle et al. 2004; Reardon, Uitenbroek & Cauzzi 2009). Kontogiannis, Tsio poula & Tziotziou (2010) observed in a rosette region at photospheric and chromospheric heights power enhancement and suppression for both the 3 and 5 min period bands.

Moreover, the transverse oscillations have also been investigated in spicules (Zaqarashvili & Erdelyi 2009; Okamoto & de Pontieu 2011), in mottles (Rouppe van der Voort et al. 2007; Kuridze et al. 2012, 2013; Morton et al. 2012) and in fibrils (Pietarila et al. 2011; Morton et al. 2014). There are several possible interpretations of these oscillatory phenomena such as kink waves propagating along magnetic flux tubes, volume-filling Alfvén waves propagating in surrounding spicular structures, and transverse pulses excited in the photospheric magnetic flux tube by means of buffeting of granules (see Zaqarashvili & Erdelyi 2009, and references therein).

In this paper, taking advantage of 2D spectroscopic Hα observations, we investigate the oscillations in chromospheric dark fine structures at different levels of height in the solar atmosphere.

2 OBSERVATIONS AND DATA REDUCTION

Observations of a network and a semi-active region were carried out in Hα near the solar disc centre in 2002 May. The data were obtained under good seeing conditions with the ‘Göttingen’ Fabry–Perot spectrometer, which was mounted in the Vacuum Tower Telescope at the Observatorio del Teide/Tenerife (Koschinsky, Kneer & Hirzberger 2001; Bostancı 2011). During the observations, 8 narrow-band images were recorded at 18 wavelength positions by scanning through the Hα line. A spacing of 125 mA between adjoining wavelength positions was selected for the scanned scans. The exposure time was 30 ms and the time interval between the start of two consecutive spectral scans was 49 s. The observed field of view (FOV) of the raw data was 38.4 × 28.6 arcsec² with an image scale of 0.1 arcsec pixel⁻¹. Broad-band images were simultaneously taken with narrow-band images. Total 60 spectral scans per region were acquired with the spectrometer. After the correction for dark current, flat-field and image motion, the broad-band images per each scan were restored by using the spectral ratio (von der Lühe 1984) and the speckle masking technique (Weigelt 1977). The narrow-band images at each wavelength position sampling Hα line were reconstructed by using the Keller & von der Lühe (1992) method.

Since our analysis requires the determination of Doppler and intensity fluctuations at individual height levels of the solar chromosphere, the Hα line profile for each pixel in the FOV was reconstructed from intensity values of narrow-band images belonging to 18 wavelength positions using spline interpolation.

We computed image time series at ± 0.3 and ± 0.7 Å from the Hα centre so as to sample different layers of the solar atmosphere. We then formed intensity and Doppler time series by averaging and subtracting image pairs for each atmospheric layer. After the alignment of data cubes using Fourier cross-correlation techniques, the final FOV sizes of the network and semi-active regions reduced to 28.8 × 16.2 and 30.6 × 16.7 arcsec², respectively.

In order to investigate the temporal properties of both observed regions, we performed the wavelet analysis to the Doppler fluctuations using the WAVELET package (Torrence & Compo 1998) with a Morlet wavelet function as the analysing function. Furthermore, we calculated the global wavelet spectrum for each pixel in the FOV of each observed region to obtain the spatial distribution of power. We then averaged the power over the following frequency bands; 0.73–1.75, 2.46–4.16 and 4.93–8.31 mHz.

We employed a cross-wavelet transform (Torrence & Compo 1998) to derive coherence and phase difference spectra between Doppler fluctuations at Hα ± 0.3 and ± 0.7 Å sampling the upper chromospheric and the upper photospheric heights, respectively. Just as in the same way as the power maps, coherence and phase differences for each pixel in the FOV were calculated and then averaged over the selected frequency bands. Since we took the difference between chromospheric and photospheric signals, positive and negative values in the phase difference maps indicate upward- and downward-propagating waves, respectively.

3 RESULTS AND DISCUSSIONS

We show in Fig. 1, the temporal averaged intensity and Doppler images corresponding to different depths in the atmosphere for the network (upper two rows) and the semi-active (lower two rows) regions. In the network region, mottles spread out from bright points occupying the network boundary, while in the semi-active region fibrils extend from two groups of bright points located around the lower centre and the upper right of the FOV. Morphologies of mottles and fibrils vary in relevant intensity images belonging to different atmospheric layers. They are highly structured and more elongated in different inclinations and directions at 0.3 Å from Hα centre, corresponding to the chromosphere, but they are less...
Oscillations in chromospheric fine structures

Figure 2. Power maps obtained from Doppler image sequences at two different atmospheric layers for the network region (upper six panels) and the semi-active region (lower six panels). Columns from left to right correspond to frequency ranges of 0.73–1.75, 2.46–4.16 and 4.93–8.31 mHz, respectively. Rows from up to down for each observed region correspond to the wavelengths at 0.3 and 0.7 Å from the line centre, respectively. The intensity scale is logarithmic and brighter patches show strong power areas.

outstanding at 0.7 Å from the line centre, corresponding to the upper photosphere (for details on Hα line formation see e.g. Leenaarts, Carlsson & Rouppe van der Voort 2012). Moreover, the pattern of granules and bright points become visible at the lowest layer. In the temporal averaged Doppler images, darker and lighter shades of grey indicate downflows and upflows, respectively. Brighter and darker elongated structures seen in areas where mottles and fibrils are found in the intensity images, point to the presence of upward and downward motion along these structures. Darker areas close to the bright points indicate that the downflows are significant at the foot point of mottles and fibrils.

We present the averaged Doppler power, coherence and phase difference maps over the three frequency bands for the mottle and fibril regions in Figs 2–4. Brighter patches in the power maps correspond to strong power. Positive (red) and negative (blue) values in phase difference maps indicate upward and downward propagation, respectively.

Low-frequency range, 0.73–1.75 mHz: in the mottle region the power spreads from the network to the structures at the highest atmospheric layer while it is more concentrated on the network at lower layers. In the fibril region, the power seems to cover the whole FOV at the highest layer, but the power occurs primarily on fibrils, especially on the fibril group located around the lower centre part of the FOV. The power also shows granular distribution in the absence of mottles or fibrils at the lower layers.

The network region, outlined with a large number of bright points, is positioned diagonally in the FOV (see the mean intensity image for Hα ± 0.7 Å in Fig. 1). Here, the phase differences are mostly positive (a mean value of about 20°) with higher coherence, showing the existence of upward-propagating waves. In the inter-network regions covered by inclined mottles, phase differences have both positive and negative values with a mean value of about −3°, indicating the presence of both upward and downward-propagating waves. Similarly, Gupta et al. (2013) observed pronounced upward...
Figure 3. Coherence (left) and phase difference maps (right) between Doppler fluctuations at 0.3 and 0.7 Å from the Hα centre for the network region. Rows from up to down are the maps averaged over the selected frequency bands: 0.73–1.75, 2.46–4.16 and 4.93–8.31 mHz, respectively. Positive (red) and negative (blue) phase differences correspond to upward and downward propagation, respectively. The darkest areas in coherence maps correspond to pixels, where coherence does not lie within $2\sigma$. The same areas are marked in a green colour in phase maps, and have been ignored for further analysis.

Propagation at magnetic network regions and a mixture of upward and downward propagation at other locations. Furthermore, Vecchio et al. (2007) showed that chromospheric acoustic power at lower frequencies below the acoustic cut-off, directly propagates upward from the photosphere in the proximity of the magnetic network elements.

In the fibril region, higher coherence is specially seen in the fibril group located on the lower centre part of the FOV, whereas fibrils located on the right part of the FOV have slightly lower coherence. In phase difference maps, fibrils on lower centre of FOV have both positive and negative values while on the right of FOV positive phase differences are more significant in the form of fibrils. Similarly, the contrast in these fibril groups was also observed on power maps; on fibrils at the lower centre part, power is getting dimmer through the higher atmospheric layers, whereas power is getting more significant on fibrils at the right part. This increase in the power can be interpreted as leakage of p modes along inclined magnetic fields into the chromosphere (De Pontieu et al. 2004; Jeffries et al. 2006; Vecchio et al. 2007). This reveals differences in magnetic topologies of two fibril groups in the FOV as well.

Intermediate-frequency range, 2.46–4.16 mHz: this is centred at 5 min. At the highest atmospheric height, for both observed regions, the power appears to occur somewhat diffused over the whole FOV with a small tendency to be less suppressed in areas where the power in low-frequency range is significant. However, at lower atmospheric heights the power distribution is more pronounced on magnetic fields in the shape of mottles or fibrils. This is more obvious in the semi-active region.

Phase differences are negative with a mean value of about $-25^\circ$ in the surrounding network, where the coherence has higher value. This area corresponds to the foot parts of mottles and seems quite dense as a result of overlapping of these parts. The negative phase differences here indicate downward-reflected waves by the inclined magnetic fields. However, in areas far from the network, where distances between neighbouring mottles get larger (the upper-left or the lower-right corner parts of FOV), the phase differences are mostly positive. This may point to waves which propagate upwards and are not impeded by the inclined magnetic fields (Kontogiannis et al. 2010). The downward propagation shows itself in power maps as well. The power in areas around the magnetic network is suppressed at chromospheric heights, but it is significant at photospheric heights. Lawrence & Cadavid (2010) found power suppression in the presence of magnetic fields for both G-band and Ca ii H-line oscillations in the frequency range $5.5 < f < 8.0$ mHz. Kontogiannis et al. (2010) observed similar power suppression in 3 and 5 min ranges at chromospheric heights but they found it more significant in the 3 min range. Morton et al. (2014) reported that the velocity power appears to decrease significantly from the chromosphere to the corona, with the power of the high-frequency waves decreasing to a much greater degree. In our observation, we found that the power suppression exists in mottles in the 3 and 5 min ranges although more noticeable at 3 min. This phenomenon is known as ‘magnetic shadow’ described in the introduction.
2D simulations Rosenthal et al. (2007) showed that in regions called magnetic canopy, where the magnetic field is significantly inclined to the vertical, waves could be reflected at a surface whose altitude is highly variable having consequences on the oscillatory processes.

In the 5 min band, the phase differences have mostly negative values in fibrils on lower centre part of the FOV, whereas fibrils on the right part of the FOV show both positive and negative phase differences. In the corresponding power maps, while the power concentrates in fibrils at photospheric heights, it gets weaker and shows almost uniform distribution with a tendency to be some significant on areas where a large number of magnetic features are closely packed at chromospheric heights.

High-frequency range, 4.93–8.31 mHz: this is the 3 min range. It can be noticed that both observed regions show similar behaviour. The power distribution shows suppression in locations of mottles or fibrils at the highest atmospheric layer. However, in contrast with this view, the power becomes significant on magnetic fields (i.e. in mottles or fibrils) at the lower atmospheric heights.

Coherence maps reveal fibrillar structures clearly in the 3 min range as well as in the 5 min range. There seems to be an increase of the coherence in the lower-right area of the mottle FOV. This area corresponds to the region of less dense structures. Both positive and negative phase values are seen over the FOV. Considering the power maps, one can conclude that the wave reflection for this frequency range is stronger than that for the 5 min range (Vecchio et al. 2007). As a result, the power suppression in the 3 min range seems to be stronger than the suppression in the 5 min range. However, the phase values do not reflect this situation. This finding might indicate that waves of downward propagation are overwhelmed by waves of upward propagation. De Wijn, McIntosh & De Pontieu (2009) reported a similar behaviour for the 5 min range.

In the phase difference maps of the fibril region, both positive and negative values are seen in two fibril groups in the FOV, while negative phase values are noticeable in the fibril-free region. However, in the power maps from photosphere to chromosphere, fibrils show a power suppression while the fibril-free region shows a power increase. It can be said that positive phase difference may indicate waves which are not obstructed by the inclined magnetic fields and travel upwards, while downward-directed waves may be the result of the reflection of acoustic oscillations at the inclined magnetic fields (Kontogiannis et al. 2010). On the other hand, this view does not explain the negative phase values, which occurs in the fibril-free region. On the contrary, there is also a power increase in this region upwards to the chromosphere. This could indicate downward-directed and damped oscillations. The same area shows positive phase values and a diffuse power increase in the chromospheric heights in the 5 min band. It is questionable if this is a result of wave refraction.

Following dark elongated fine structures such as mottles and fibrils during their lifetime in Hα is a complex task since their shape and length change continuously and their contrast is not sufficient to outline these structures. For the definition of their areas in the FOV, we used the time averaged intensity image at 0.3 Å from the line centre and masked the pixels, where values lie under the mean value of the image. We show in Fig. 5 the distributions of phase differences in the three frequency bands for both structures (mottles and fibrils) selected by masks. In the low-frequency range, the phase values for the mottles have a Gaussian distribution, while in the intermediate-frequency range, the phase values for the mottles have a relatively symmetrically distribution around zero confirming...
the results derived from the phase maps. The phase values for the fibrils in the 3 and 5 min ranges are also symmetrically distributed around zero, showing a slightly higher number of negative values, but there is no obvious dominance.

4 CONCLUSION

De Wijn et al. (2009) investigated the oscillations in a plage and expressed that the 5 min oscillations can only propagate along inclined magnetic field lines and not in the central region of the plage, where the magnetic field is expected to be vertical. However, in the present study, a power increase is seen in the chromospheric heights on network bright points in the 5 min band. Roberts (1983) proposed that radiative losses in thin flux tubes can lead to a significant reduction of the cut-off frequency. This mechanism enables propagation of the 5 min oscillations to the chromosphere in the vertical magnetic structures. Afterwards, Centeno, Collados & Trujillo Bueno (2006, 2009) and Khomenko et al. (2008) stated that if the radiative relaxation time is short enough, then the acoustic cut-off frequency would decrease to lower values and this would allow the vertical propagation of 5 min waves to the chromosphere. Heggland et al. (2011) found in their simulations 5 min long-period oscillations to be dominant in strong and inclined magnetic field, while the 3 min oscillations to be dominant in areas with weak or vertical magnetic fields. Nutto, Steiner & Roth (2012) connected the slow acoustic mode power observed on magnetic network elements to mode conversion. In the present study, the power of the 3 min oscillations gets stronger with increasing atmospheric heights in regions where the magnetic field is weak. But it is difficult to say that the 5 min waves propagate along inclined magnetic fields. On the contrary to this, we found for both regions in areas of inclined magnetic fields a power suppression, which is stronger in the 3 min band, confirming the results of Kontogiannis et al. (2010). A power increase in inclined magnetic fields through higher atmospheric heights is seen for the low-frequency range, which may be a signature of leakage of \( p \) modes (De Pontieu et al. 2004; Jefferies et al. 2006; Vecchio et al. 2007). In the same frequency range, our investigations revealed the presence of propagating waves in the magnetic network, which was also reported by Gupta et al. (2013). In relation with the intermediate-frequency range, a weak power suppression was found in regions of inclined magnetic fields for both FOVs showing negative phase differences and indicating downward-reflected waves. A stronger suppression was observed for the high-frequency range, while the phase values did not reflect this case. This may be due to an overwhelming of downward-propagating signals by upward-propagating signals. One of the interesting results of this study is the negative phase values in the 3 min band and the positive phase values in the 5 min band, which occurs for the same area in a fibril-free region. A possible explanation for the negative phase values could be downward-directed and damped oscillations since the power decreases towards lower heights.

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Oscillations in chromospheric fine structures

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