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HELIOSEISMOLOGY

Spatial Distribution of Oscillations in Faculae

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Abstract We find that oscillations of the LOS velocity in Hα vary within facula regions. The power spectra show that the contributions of low-frequency modes (1.2 – 2 mHz) increase at the network boundaries. Three- and five-minute periods dominate inside cells. The spectra of photospheric and chromospheric LOS-velocity oscillations differ for most faculae. We detected several cases where oscillations in faculae seem to propagate horizontally with phase velocities of 50 – 70 km s^{-1}. Their location in space and time coincided with the local maximum of the longitudinal magnetic field.

Keywords Faculae, oscillations · Chromosphere, propagating waves

1. Introduction

The heating of the solar corona is a long-standing problem in solar physics. Waves propagating from the photosphere into the chromosphere and further into the corona have been proposed to be responsible for the energy transport. Solar facular structures are quite widespread on the Sun; they are present even in polar areas, which have no sunspots. Usually they are observed in extended patches appearing bright in chromospheric lines. They regularly occupy large regions of the solar surface and can play a significant role in processes of upward energy transport. Photospheric oscillations in faculae have been considered as a source of the five-minute oscillations observed in the upper chromosphere, transition zone, and corona (De Pontieu, Erdélyi, and de Moortel, 2005; Centeno, Collados, and Trujillo Bueno, 2006). The behavior of facular oscillations has been actively studied since the 1960s (Orrall, 1965; Howard, 1967; Sheeley and Bhatnagar, 1971; Deubner, 1974). Investigations were continued by Woods and Cram (1981), Balthasar (1990), Muglach, Solanki, and Livingston (1995), Khomenko *et al.* (2008), and Centeno,

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Collados, and Trujillo Bueno (2009); however, the problem is still far from being solved. It is possible that the facular near active regions and "acoustic moat" (Lindsey and Braun, 1998) are the same things. This paper is a continuation of our previous work (Kobanov and Pulyaev, 2007, hereafter Paper I) to explore the behavior of chromospheric oscillations in various parts of faculae.

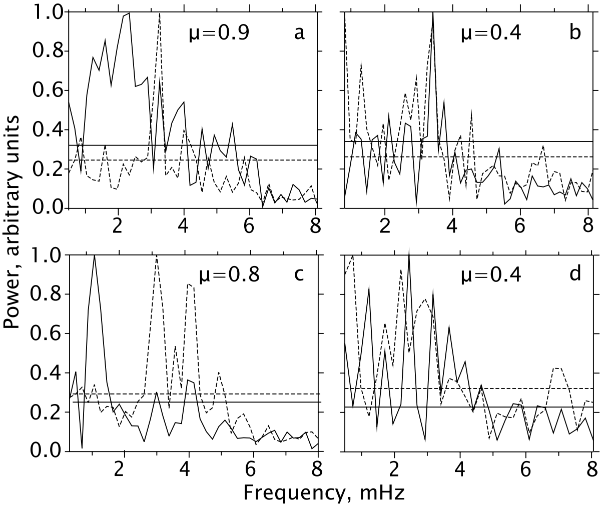
2. Instrument and Method

Observational material was obtained over several years at the horizontal solar telescope of the Sayan Solar Observatory, located at an altitude of 2000 meters on a mountain peak. The telescope is six meters above the terrain and equipped with a wind-screen system. The diameter of the coelostat mirrors is 800 mm, and the focal length of the main mirror is 21 meters. A photoelectric guiding system provides image tracking with an accuracy of about one arcsecond, with compensation for solar rotation. The observer can change the orientation of the solar image relative to the spectrograph entrance slit using a Dove prism. A Princeton Instrument CCD camera (256 × 1024) was used. One pixel along the entrance slit corresponds to $0.24''$ and along the spectrograph dispersion to 6 – 8 mÅ. In most cases, the width of the entrance spectrograph slit was taken to be between 100 and 200 μ, which corresponds to $1 - 2''$ on the image and is in satisfactory agreement with the actual attainable spatial resolution, which is limited by the influence of the Earth's atmosphere. Because of seeing, the average spatial resolution was about $1.5 - 2''$. We made observations in the Hα 6562.8 Å, Fe I 6569.2 Å, Ca II 8542 Å, and Fe I 8538 Å spectral lines. Sometimes we used polarization optics to measure the strength of the longitudinal magnetic field simultaneously with the line-of-sight velocity (Kobanov, 2001). In order to reduce the influence of temporal aliasing, the measurement process was organized such that the time interval between the end of one exposure and the start of the next exposure was shorter than the exposure time. We applied corrections for tilt of the spectra, the influence of dust on the CCD, and the flat field. The velocity was calculated using the center-of-gravity method over a range of ±0.03 Å from the spectral line center for photospheric lines, ±0.15 Å for Hα, ±0.1 Å for Ca II. A shift of the center-of-gravity wavelength position corresponds to the line-of-sight (LOS) velocity. For more details, see Kobanov *et al.* (2009). The longitudinal magnetic field was calculated from the observed Zeeman splitting, determined as the distance between the centers of gravity of the polarized components. We then obtained gray-scale spatial-temporal diagrams of the LOS velocity, intensity, and magnetic-field strength (for observations with the polarization optics).

3. Results and Discussion

In our observations, the locations of facular areas near the limb were determined using white-light images (D = 175 mm) from the guide system. Sometimes (for faculae far from the limb) we used Hα or Ca II K slit-jaw images. To obtain more accurate locations with fine-structure facular elements, we used bright intervals of the spectrum. The coincidence of power spectra of photospheric and chromospheric oscillations may be considered as evidence of the fact that five-minute photosphere oscillations penetrate into the chromosphere. We have analyzed 32 time series for 32 faculae. The average duration of the time series is about an hour. The cadence varied from one to ten seconds. However, comparison of oscillation spectra obtained in the Hα 6562.8 Å, Fe I 6569.2 Å, Ca II 8542 Å, and Fe I 8538 Å

Figure 1 Examples of LOS-velocity power spectra for several faculae, averaged over two arcseconds. Solid line: chromosphere, dashed: photosphere. (a) In spectral lines: Ca II 8542 Å, Fe I 8538 Å. (b, c, d) In spectral lines: Hα 6563 Å, Fe I 6569 Å. Solid and dashed horizontal lines indicate the 95% confidence levels, $\mu = \cos\theta$.



spectral lines frequently reveals differences rather than similarities (Figure 1). One can assume that the projection is the source of the apparent discrepancy. It is known that the contribution of low-frequency oscillations can increase towards the limb (Stix and Wöhl, 1974). Interestingly, the two faculae located near disk center show significant differences between the photosphere and chromosphere spectra (Figure 1a, c).

We conclude that the differences are not a consequence of instrumental effects. Our result is in contradiction to that obtained by Centeno, Collados, and Trujillo Bueno (2006, 2009) and Khomenko *et al.* (2008). They made observations (in He I 10830 Å and Si I 10827 Å) of a facular area located near the disk center on 14 June 2004. The illustration given in these papers shows spectra of photospheric and chromospheric oscillations averaged over 40 arcseconds. The coincidence of the spectra is impressive. Currently we have no idea of the origin of the above-mentioned contradictions. The reason may possibly lie in the use of different spectral lines and accordingly different ranges of heights observed in the solar atmosphere. Previously Livshits *et al.* (1976) established that the formation height of the He I 10830 Å line is significantly reduced over a facular area. Taking into account that the height of formation for the Si I 10827 Å line is estimated to be 540 km (Bard and Carlsson, 2008), one can assume convergence of the observed levels above faculae. The latter is no more than a speculation to be tested by more observations in He I and Si I.

Even if the same frequencies are present in the spatially averaged photosphere and chromosphere spectra, considerable differences are noticed in gray-scale diagrams showing the spatial position of the power of these oscillations (Figure 2). It can be seen that the different frequency modes belong to spatial elements of a facula remote from each other.

The reason for the differences could be the local topology of magnetic fields in different parts of a facula. It is known that the chromosphere network is not suppressed in facular areas. We identify the network boundaries as facular parts where a quasi-steady downflow is observed. For that, the LOS-velocity signal is averaged over the whole time series. Figure 3 shows unfiltered signals of the chromospheric LOS velocity in individual elements of the same facula as in Figure 2. Low-frequency oscillations (Figure 3a) dominate in the area that we define as a chromosphere network boundary in accordance with the above rule. Five-minute oscillations (Figure 3b) clearly appear in the region where the quasi-stationary LOS velocity is close to zero. This area is ten arcseconds away from the network boundary.

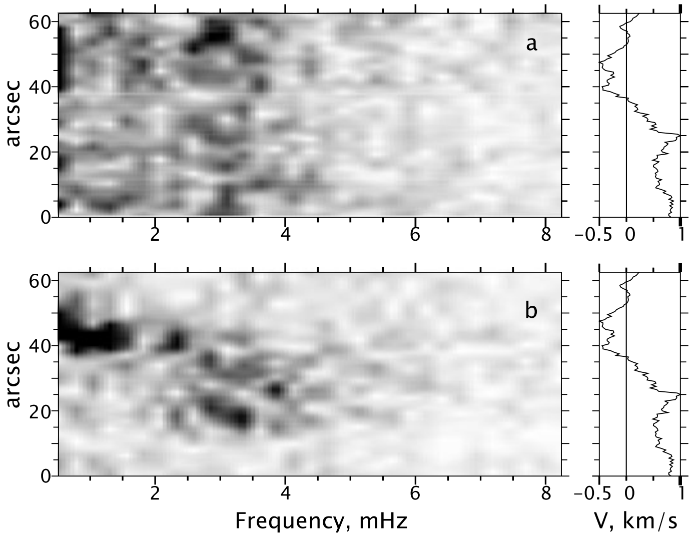
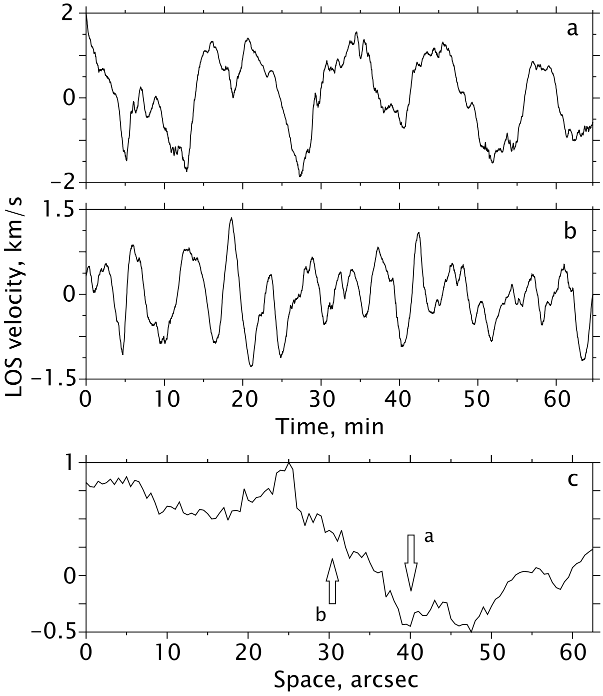


Figure 2 The spatial localization of different frequency modes for a facular area ($\mu = 0.77$), top: photosphere, bottom: chromosphere. Darkest elements indicate strongest oscillations. On the right: spatial slice of chromosphere LOS velocity averaged over the whole time series, the same spatial slice is presented in Figure 3, bottom.

Figure 3 Unfiltered LOS-velocity signals in different parts of the facula (same as Figure 2). (a) The low-frequency mode at 40 arcsec (arrow a in bottom panel). (b) Five-minute oscillation at 30 arcsec (arrow b). (c) Spatial slice of LOS velocity averaged over the whole time series.



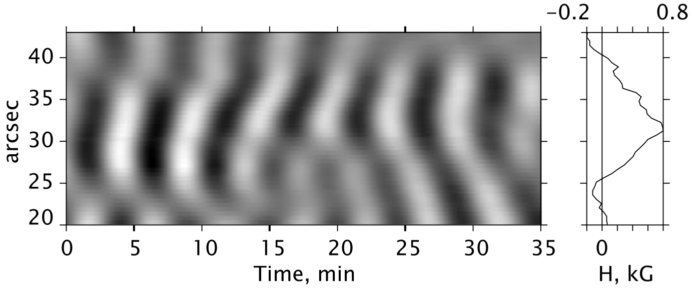


Figure 4 Traveling five-minute waves in chromosphere of a facula (the same facula as in Figures 2 and 3). The dark parts indicate LOS velocity away from the observer. On the right: spatial slice of the longitudinal magnetic field.

Propagating waves in the chromosphere of faculae are observed at 3 mHz (Paper I). We applied frequency filtering as in Kobanov and Makarchik (2004) for the construction of gray-scale space-time diagrams of the Doppler velocity for various frequency modes, to better distinguish propagating waves and establish their parameters. These diagrams reflect the dynamics of the Doppler velocity along a spatial direction, determined by the position of the image on the spectrograph entrance slit. The resulting gray-scale images of space-time distributions of the LOS velocity in the Hα line show a clear periodic structure resembling a chevron. The chevron directly demonstrates the presence of phase propagation in the facula chromosphere (Figure 4). The peak of chevron on the space-time diagram coincides with the local maximum of the longitudinal magnetic field in the photosphere. It is likely that at this point the magnetic field is rooted in the photosphere and is almost vertical. The horizontal phase velocity determined from the chromospheric chevron slope is $50-70\ \mathrm{km\,s^{-1}}$. We have not found a clear phase relationship between chromosphere waves and LOS-velocity oscillations in the photosphere of faculae.

4. Conclusion

The coincidence of the spectral composition of LOS-velocity oscillations in the photosphere and chromosphere of faculae, considered as direct evidence of links between these layers, is observed relatively rarely. Moreover, even in the cases of similarity of mean power spectra, the space-time positions of the power of the modes analyzed do not coincide. We found that the frequency content of LOS-velocity oscillations is not the same in different parts of the facula areas. The power of low-frequency modes (1.2 – 2 mHz) increases at the network boundaries. Three- and five-minute periods dominate inside cells. We observed some cases where propagating waves in the chromosphere above faculae were manifest with a five-minute period. Their initiation point on spatial-temporal diagrams coincided with the local maximum of the longitudinal magnetic field.

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