SLOW SAUSAGE WAVES IN MAGNETIC PORES AND SUNSPOTS

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ABSTRACT

Recently we identified slow sausage waves in a magnetic pore analysing 11-hour series of high resolution white light observations of the sunspot group NOAA 7519 (Dorotovič et al., 2008). The resulted periods were in the range of 20-70 minutes, suggesting that the temporal evolution of the area of the studied pore could be considered as observational evidence of linear low-frequency slow sausage waves in magnetic pores. Here we selected several additional series of images with high angular resolution for purposes of the identification of slow sausage waves in magnetic pores and in sunspots, respectively. Our investigation revealed periods in the range of 3 - 20 minutes.

Sunspots, magnetic pores and other features in the fine structure of the solar photosphere have been intensively studied in last years both from the theoretical and the observational point of view. We witnessed also rapid improvement of high-resolution observations. Solar oscillations are excited in the upper convective boundary layer. Kosovichev (1999) discussed the basic mathematical and computational techniques of helioseismology, a unique tool which provides information about the structure and dynamics of the solar interior. Based on recent results from observations and numerical simulations, Wedemeyer-Böhm et al. 2008) presented a comprehensive picture of coupling mechanisms in the atmosphere of the quiet Sun (from the photosphere to the chromosphere and the corona). Roberts (2006) examined theoretically how the slow mode may be extracted from the magnetohydrodynamic equations, considering the special case of a vertical magnetic field in a stratified medium. The approach demonstrated in that paper for a vertical magnetic field may in principle be generalized to non-uniform magnetic fields, nonlinearity, flows and dissipative effects. Lefebvre *et al.* (2008) have investigated the vertical structure (vertical velocity fluctuations) and time evolution of the solar granulation by means of a novel methodology based on the analysis of the full-disk Sun-as-a-star Doppler velocity observations. They showed that the granulation clearly evolves with height in the photosphere, exciting acoustic (p) modes, but does not present any significant variation with the activity cycle.

Similarly, Stodilka (2005) localized the discrete sources of oscillations in the solar atmosphere and revealed their origin. He found that the photosphere is penetrated by narrow „channels“, where oscillation energy spreadswith minimal losses into the higher layers of the atmsphere (till the temperature minimum) and that such „channels“ arise mostly between ascending (granule) and descending (intergranule) flows. Rajaguru *et al.* (2006) investigated radiative transfer effects on

Doppler measurements as sources of surface effects in sunspot seismology, i. e. contribution of such effects to seismically measured phases or travel times of acoustic waves. They showed that phases of acoustic waves observed within sunspots using Doppler shifts of a spectral line have signatures of physical changes that waves undergo within line forming layers as well as of systematics in Doppler measurements induced by Zeeman split profiles. Study of p-mode absorption in magnetic field concentrations and comparison that with the longitudinal and the computed transverse field configuration in a sunspot has been performed e.g. by Mathew (2008). He presented the spatial distribution of the oscillatory power in a sunspot observed near disk center and he found a structured ring like absorption pattern in Doppler power near the umbral-penumbral boundary. Tian *et al.* (2008) searched for a signature of long-period oscillations in coronal bright points (BPs). Their analysis revealed oscillations with periods ranging from 8 to 64 minutes which might be caused either by propagating magneto-acoustic waves in loop systems associated with the BPs, or are result from recurrent magnetic reconnection powering the BPs.

In our previous paper (Dorotovič *et al.*, 2008) we focused on the investigation of evolution of the pore area in the sunspot group NOAA 7519 (Sobotka *et al.*, 1997; Dorotovič *et al.* 2002). during an 11-hour observing period. The area of the large pore showed permanent decrease with time at an average rate of $-0.23 \mathrm{Mm}^2\mathrm{h}^{-1}$ during the whole observing period. The determined periodicities of magneto-acoustic gravity waves were in the range of 12 – 97 minutes. In this work we continue in identification of slow sausage waves by selecting other series of images (both of the magnetic pore and the sunspots).

2. Data and Method of Analysis

Several additional series of images with high angular resolution have been chosen here for purposes of the identification of slow sausage waves, namely images acquired using:

1. Dutch Open Telescope – DOT (La Palma, Canary Islands, Spain) on12 August 2007 – magnetic pore, 82 minutes observation in G band.
2. Swedish Vacuum Solar Telescope – SVST (La Palma, Canary Islands, Spain) on 7 July 1999 – so called "Fermina" sunspot in the active region NOAA 8620 (Bonet et al., 2004), 133 minutes observation in G band.
3. Dutch Open Telescope – DOT (La Palma, Canary Islands, Spain) on 13 July 2005 – sunspot in the active region NOAA 10789, 165 minutes observation in G band.

We performed wavelet analysis according to the computing algorithm of Torrence and Compo (1998) to study effects of MHD waves on the evolution of the area of the observed pore and sunspots, respectively. The standard Morlet wavelet, a plane sine wave with an amplitude modulated by a Gaussian function, has been used here.

3. Results and Discussion

The wavelet spectrum plots for the individual observing sequences and for white noise are depicted in the form of a time-period map in Figs. 1 – 4. The crosshatched area marks the coin of incidence (COI) where edge effects affect the wavelet transform (WT) results, contours show the confidence level of 99% (magnetic pore, 12 August 2007), 95% and 90% (sunspot, 7 July 1999), and 90% (sunspot, 13 July 2005). The same analysis was done also for red and white noise.

3.1. Magnetic pore, 12 August 2007

In this observing sequence we revealed increase of area of the pore with time between the 20th and the 40th minute of the sequence. Checking the WT power spectra (Fig. 1) we identified the following periods: 3 and 4 minutes, 8 and 14 minutes for 99% confidence level (white noise).

In the period 20 – 40 minutes of the sequence, i. e. during an abrupt growth of the pore, were even supressed the 3–4 minute oscillations. Possible explanation might be that the pore is growing from down to higher layers, magnetic field lines at the border of the pore are tilted and this slows down the oscillations by absorbing their power. This effect has been studied e.g. by Mathew (2008). Between the 40th and the 80th minute of the sequence there is a slight increase of a period of oscillations with time, from 14 to 17 minutes, which indicates a change of the magnetic flux in the pore.

3.2. Sunspot, 7 July 1999

In this case we identified in the WT power spectrum (Fig. 2) the following periods: 6, 7, 10, 14 , 30 , 33 minutes for 95% confidence level (white noise). This figure is a result of analysis of non-filtered images, i.e. images without subsonic filtering. Investigation of images processed by a subsonic filter to filter out movement of horizontal brightness features lower than 5 km.s^{-1} (Bonet et al., 2004) showed the periods of 14, 22, and 33 minutes for 90% confidence level (white noise) – Fig. 3. We can see that the subsonic filter did not eliminate for instance 14 minute oscillations that are visible also in the non-filtered data. The reason is that the filter did not eliminate horizontal movements of brightness features larger than 5 km.s^{-1} as one can ascertain using images No. 181 and 182 from the non-filtered series (Fig. 5). Umbral details marked 1, 2, and 3 account at a treshold of 0.4 movement between two subsequent images in the range of 2 – 6 pixels which corresponds to horizontal velocity of 7.5 – 15 km.s^{-1} and hence subsonic filter could not eliminate these velocities originating from the observing period of occurrence of a 14 minute oscillation. By comparing WT power spectra of both the non-filtered and the filtered series we can assume that 14 minute period (frequency of 1.19 mHz) belongs to slow sausage waves.

3.3. Sunspot, 13 July 2005

For this observing sequence we identified the following periods: 3, 7 (5–10), 9 (8-13), 11 (6-13), 11 (9-13), and 20 minutes for 90% confidence level (white noise) – Fig. 4. In this case is interesting besides shorter periods also the period of 11 and 20 minutes (frequency of 1.52 mHz and 0.83 mHz, respectively).

4. Conclusions

Based on the results presented in this paper we can interpreted the observed periodic changes in the area cross-section of a thin flux tube, manifested as pore and sunspot, respectively, as another proofs of existence of linear slow (magneto-acoustic) sausage waves.

Acknowledgements

Wavelet power spectra were calculated using a modified computing algorithms of wavelet transform original of which was developed and provided by C.Torrence and G.Compo, and is available at URL: http://paos.colorado.edu/research/wavelets/

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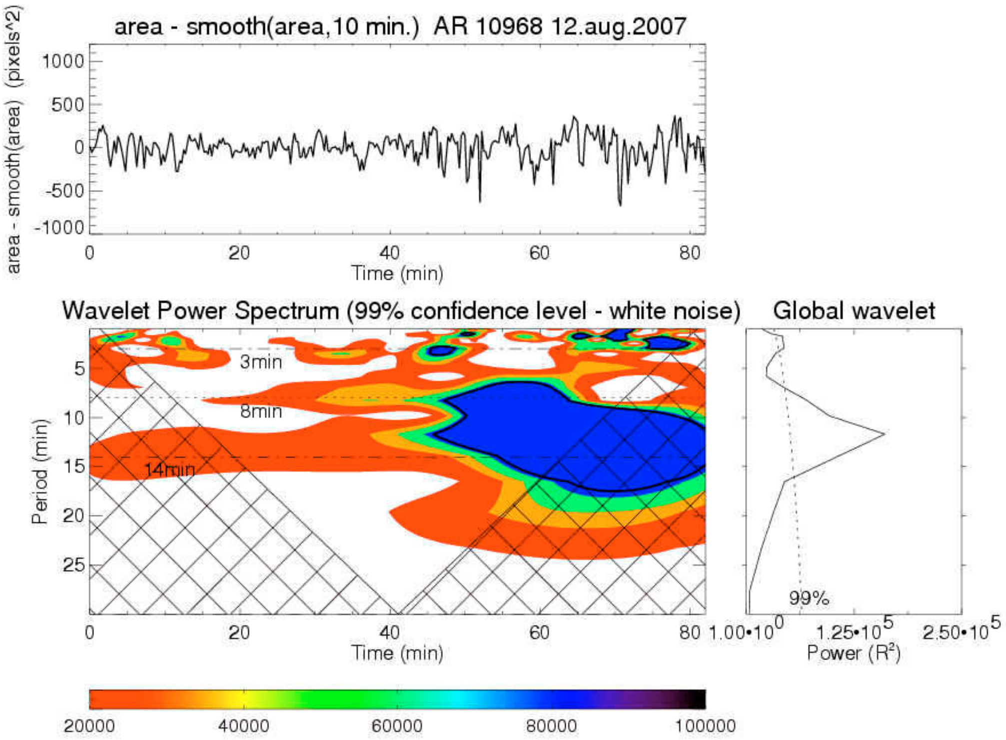

Figure 1. Evolution of the area of the pore, AR 10968, 12 August 2007 (*upper panel*), the wavelet power spectrum for white noise (*lower panel*), and the global wavelet power (*right panel*). COI is marked as a crosshatched area.

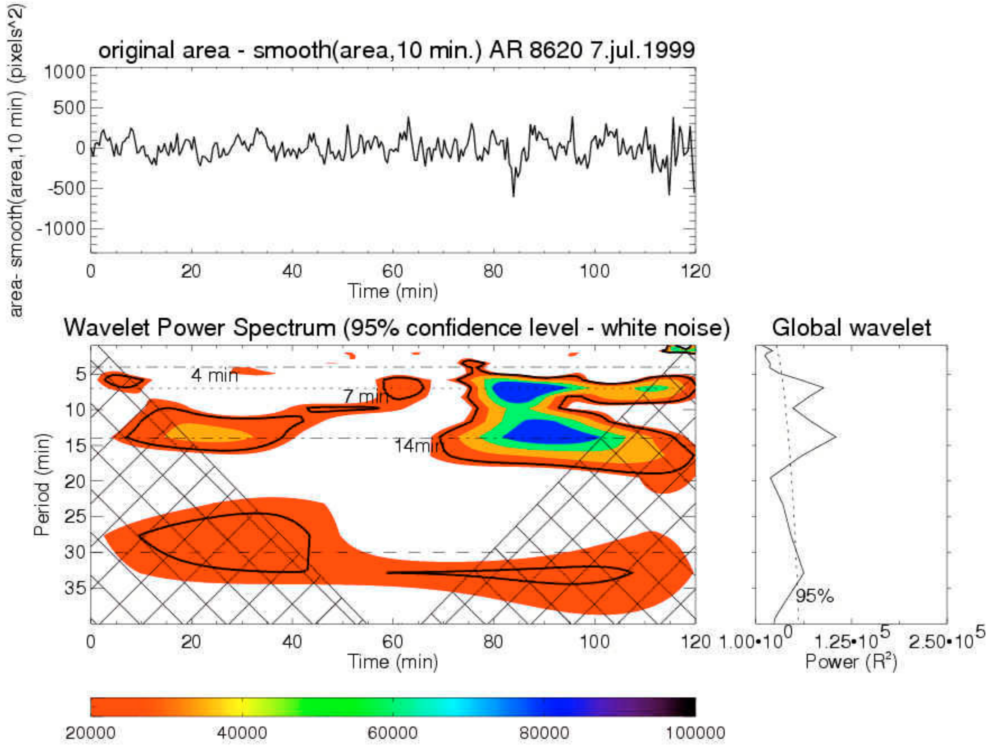

Figure 2. Evolution of the area of the sunspot, AR 8620, 7 July 1999 (*upper panel*), the wavelet power spectrum for white noise (*lower panel*), and the global wavelet power (*right panel*). COI is marked as a crosshatched area.

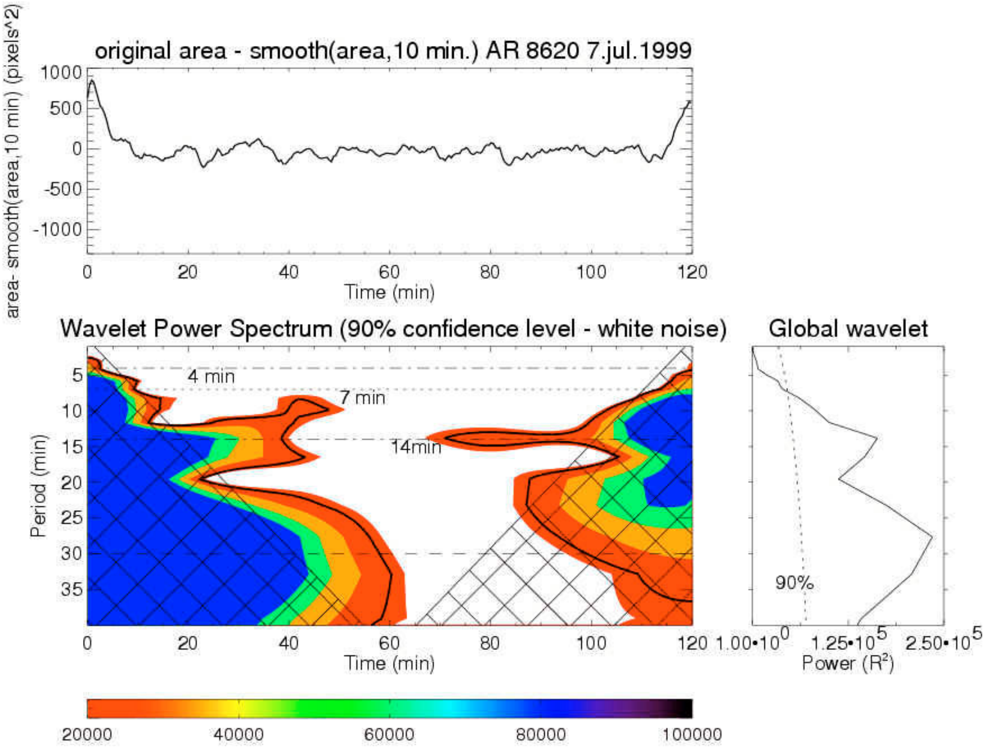

Figure 3. Evolution of the area of the sunspot (filtered data), AR 8620, 7 July 1999 (*upper panel*), the wavelet power spectrum for white noise (*lower panel*), and the global wavelet power (*right panel*). COI is marked as a crosshatched area.

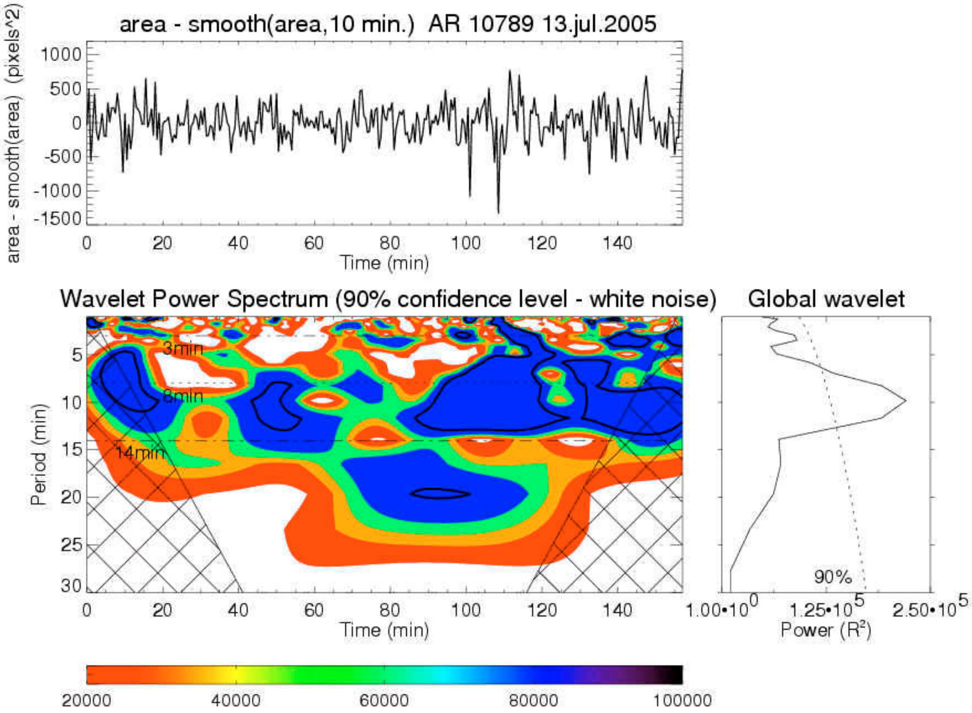

Figure 4. Evolution of the area of the sunspot, AR 10789, 13 July 2005 (*upper panel*), the wavelet power spectrum for white noise (*lower panel*), and the global wavelet power (*right panel*). COI is marked as a crosshatched area.

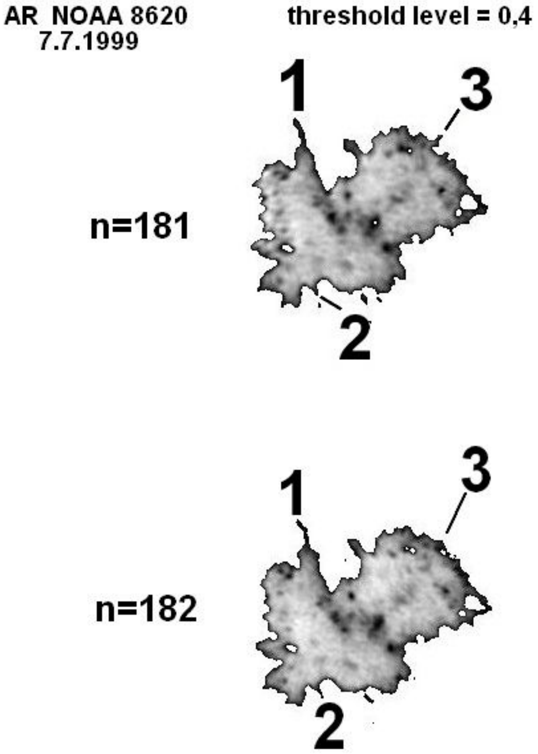

Figure 5. Images of umbra No. 181 and 182 from the non-filtered series, AR 8620, 7 July 1999, treshold value is 0.4.