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Oscillations and running waves observed in sunspots*

II. Photospheric waves

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Abstract. To continue our study of waves related to sunspots in the photosphere, we analyzed CCD, high resolution sunspot observations obtained in the Fe I 557.6 nm line. We produced "time slice images" which reveal inward slow propagating waves in the photospheric penumbra and outward propagating waves in the area around the sunspot. The phase velocity of the waves is near 0.5 km s^{-1} in both cases and their horizontal wavelength about 2500 km. The waves could be related either to solar p-modes or to the subphotospheric layer large-scale convection.

Key words: Sun: sunspots – Sun: oscillations

1. Introduction

In the high layers, sunspots show oscillatory behavior; 3 min standing oscillations are dominant in the umbra, while running 5 min waves are dominant in the penumbra and superpenumbra. Running penumbral waves (RPW) were first observed in Hα by Zirin & Stein (1972) and independently by Giovanelli (1972, 1974). Since their discovery researchers have tried to determine their nature as well as their relation to other phenomena such as umbral oscillations and p-mode photospheric oscillations.

The horizontal propagation speed of penumbral waves is typically in the range of 10–20 km s^{-1}. This is close to the sound speed in the chromosphere and of the Alfven speed in the photosphere but much less than the Alfven speed in the penumbral chromosphere. Thus, if the waves are not mainly compression waves, the travelling oscillation observed in the chromosphere is the vertical extension of a wave propagating in the photosphere.

A number of authors have tried to examine how deeply situated in the photosphere the waves are. Lites (1988) reports that he was able to clearly observe penumbral waves in the inner penumbra as viewed in the Fe I 543.4 nm line. Fe I 543.4 nm line is believed to be formed in the low umbral photosphere, just above the temperature minimum (Lites & Thomas, 1985). Musman et al. (1976) searched for penumbral waves in the low photosphere using simultaneous measurements in the Hα line and the Zeeman-insensitive line Fe I 557.6 nm. According to the above authors the Fe I 557.6 nm line is formed in the upper penumbral photosphere (between 250 and 530 km above the optical depth unity at 500 nm). They found waves propagating horizontally outwards across the penumbra with about the same period as the RPW in Hα. However, the waves were more intermittent and had a higher horizontal phase velocity by a factor of 2 or more than the chromospheric penumbral waves. Thus, the connection between the photospheric and chromospheric waves is not clear. Lites et al. (1982) were not able to find obvious penumbral disturbances in the Fe I 5576 intensity or Doppler images.

From the above analysis the conclusion is that there is not a clear picture concerning the waves observed at the photospheric level. In a previous paper (Christopoulou et al. 2000, referred to as paper I from now on) we have studied umbral oscillations, running penumbral waves and the relationship between them in the Chromospheric level. In this paper, we present waves related to sunspots observed in the Fe I 557.6 nm line.

2. Observations and image processing

Observations were obtained at the R.B. Dunn telescope of the Sacramento Peak Observatory with a 512 by 512 pixel CCD camera and the UBF filter. The pixel spatial resolution was 0.26″. A large isolated sunspot was observed at N14.7, E26.0 on August 15, 1997. In this work we analyze images obtained in the magnetically non sensitive line Fe I (557.6099) $\pm$0.012 nm. Note that the precision of the UBF filter is of the order of 0.1 pm, while the FWHM is about 12 pm near Fe I (557.6099). The time interval between successive images of the same wavelength was 28 seconds, while the time difference between opposite Fe I wings was 4 seconds. We computed Dopplergrams in Fe I $\pm$0.012 nm by red/blue wing subtraction.

In paper I, in order to study the properties of umbral oscillation and running waves, we took a cross section of every image of a time series, starting from the center of an oscillating

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* Based on observations performed on the NSO/SPO Dunn's Solar Telescope (DST)

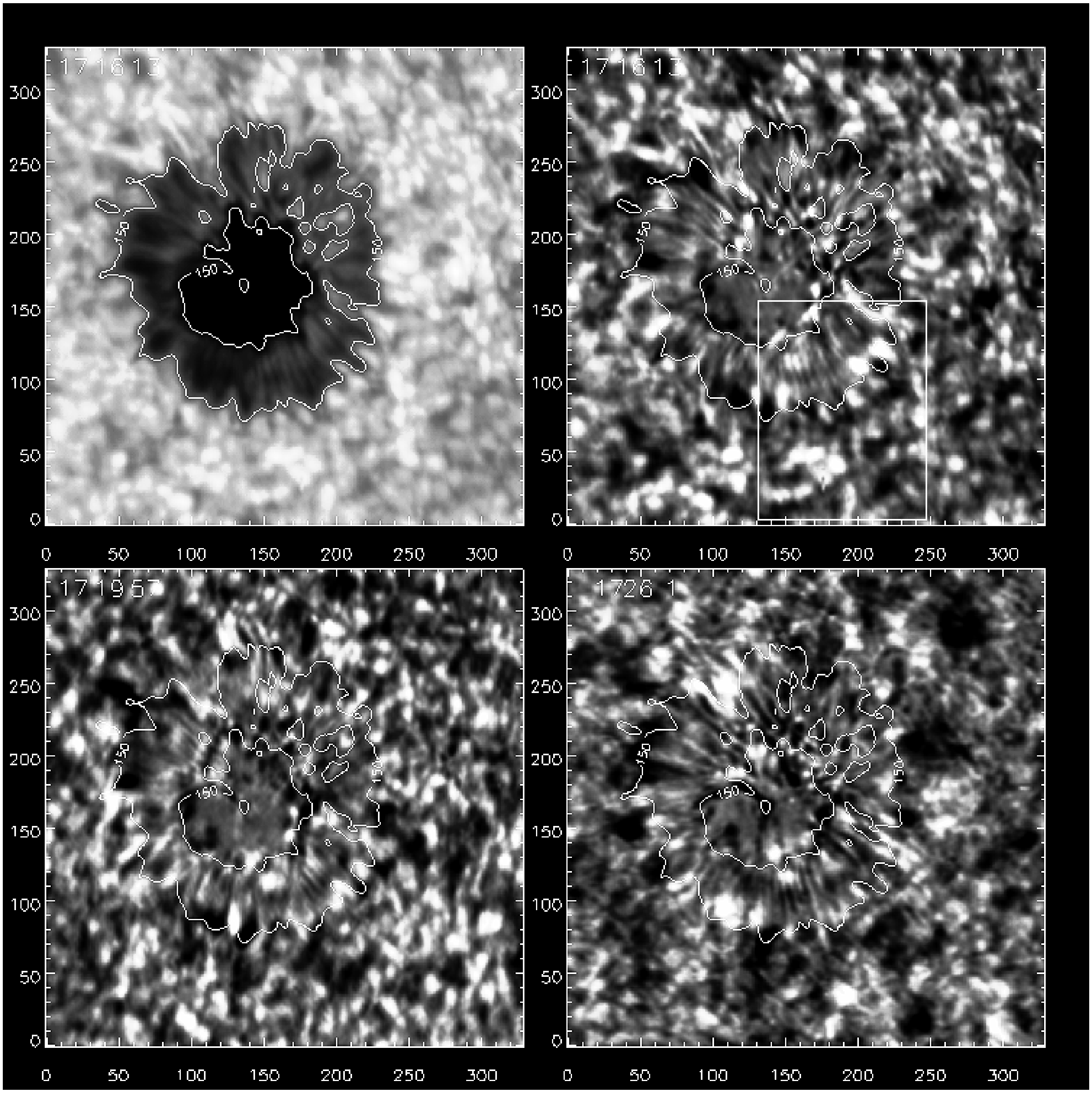

Fig. 1. Original (upper left) and subtracted images in Fe I 557.6 nm −0.012 nm, showing photospheric waves related to sunspots. The waves are particularly obvious in the white frame near the right lower corner of the image.

element and directed outwards, at right angles to the propagating wavefronts. We created a new image with the distance from the center of the oscillating elements as one axis and time as the other (method I). In order to improve this method, we computed the average intensity along circular arcs at right angles to a line directed from the center of an oscillating element outwards (method II). The line is obtained at right angles to the wavefronts so that the arcs are parallel to the wavefronts. The arcs correspond to a stable angle so that their length smoothly increases with distance from the center of the spot. This is a more appropriate method since the waves expand in larger arcs as they propagate outwards. The new method gives significantly better results, much less noise and the oscillating frequency can be determined with significantly higher confidence.

In order to remove the sharp intensity gradient between the umbra and the penumbra and enhance time varying phenomena in intensity images, we subtracted from each image the average image integrated over the whole time series. Details about

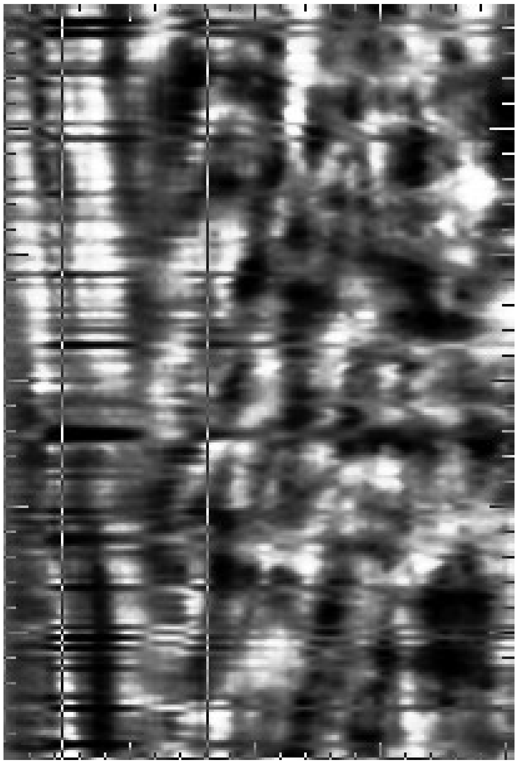

Fig. 2. "Time slice" image in Fe I 557.6 -0.012 nm, produced using method I; The x axis corresponds to the distance from the center of the oscillating element and the y axis to time. Tick marks in the x-axis correspond to $1.3''$ and tick marks in the y axis correspond to 140 sec. Vertical lines mark the umbra and penumbra boundaries, as derived from the Fe I 557.6 -0.012 nm images. Time runs from the bottom to the top.

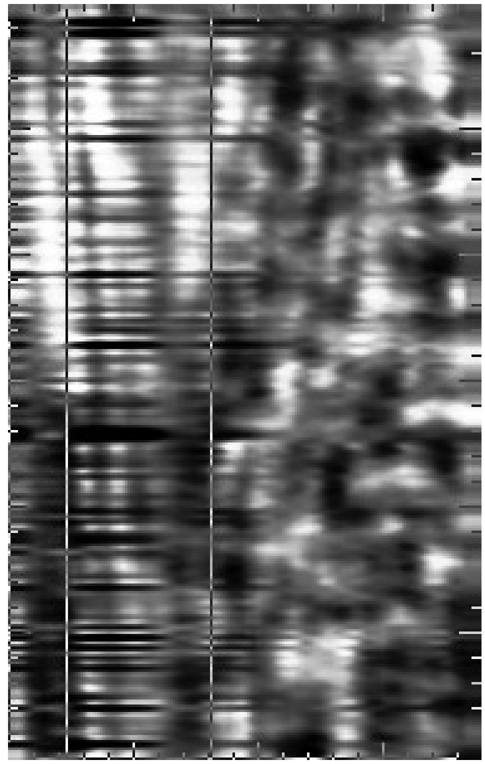

Fig. 3. "Time slice" image in Fe I 557.6 -0.012 nm, produced using method II; the integration angle is 45°.

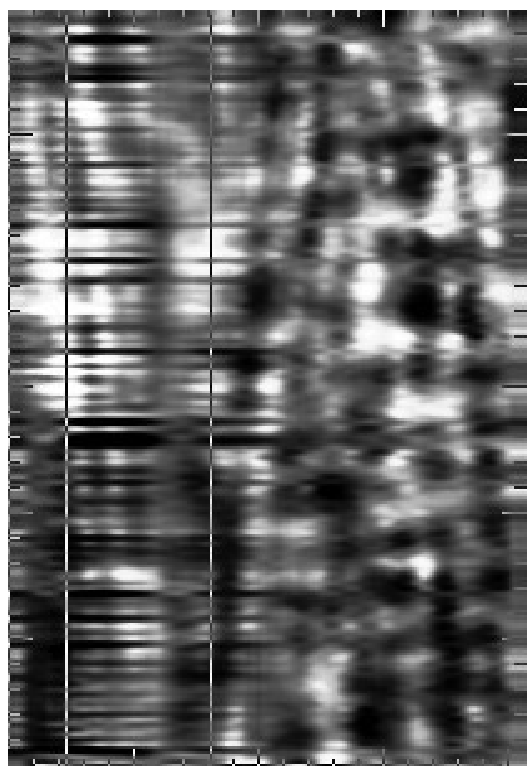

Fig. 4. "Time slice" image (c.f. image 3) in Fe I 557.6 $+0.012$ nm, produced using method II; the integration angle is 45°.

the method can be found in paper I and references therein. We should note that we applied this method only to intensity images and not to the Dopplergrams or the images from which we produced the Dopplergrams. The method that we have used makes the waves much more noticeable without introducing artifacts (see Fig. 1 of paper I).

3. Results

In order to study running waves we produced movies in Fe I $+0.012$ nm and Fe I -0.012 nm, as well as Doppler velocity movies in Fe I ± 0.012 nm. Since the waves seem to be very weak it was very difficult to identify and follow them although in some of the best images they are very clear (Fig. 1). In order to better identify the waves and measure their propagation velocity, we followed the methods described in the previous section in order to create "time slice images". Fig. 2 shows "time slice images" in Fe I -0.012 nm, computed using method I. Figs. 3, 4, 5 and 6 show "time slice images" in Fe I -0.012 nm, Fe I $+0.012$ nm, Doppler images and sum images (Fe I ± 0.012 nm) computed using method II. The integration angle was 45°. We used the region in the white frame in Fig. 1. The waves are clearly identifiable in these images: they appear as diagonal

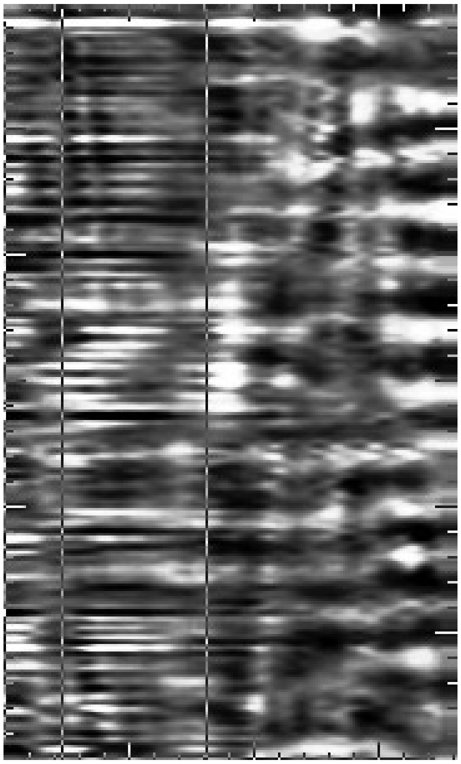

Fig. 5. “Time slice” image from Dopplergrams in Fe I 557.6 ±0.012 nm (c.f. image 3). Five minute oscillations are obvious around the spot (right edge of the photograph).

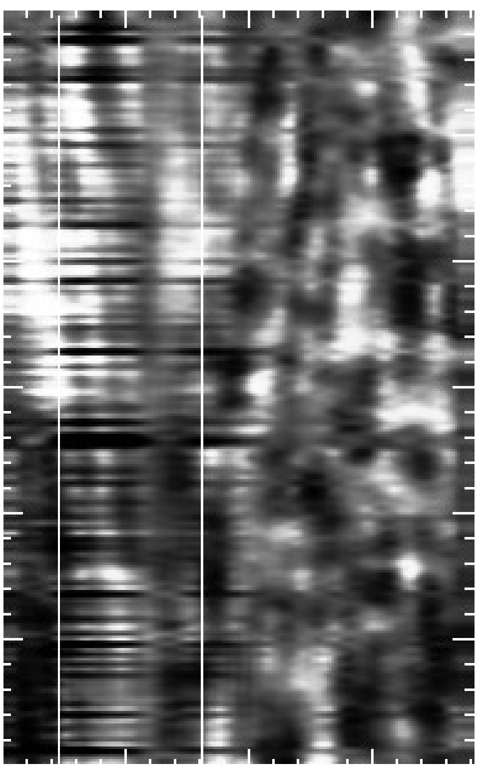

Fig. 6. “Time slice” image computed using the sum of the Fe I 557.6 ±0.012 nm (c.f. image 5). The waves also are obvious in this image, implying that they are not related to velocity perturbations but probably to the propagation of pressure or temperature fluctuations.

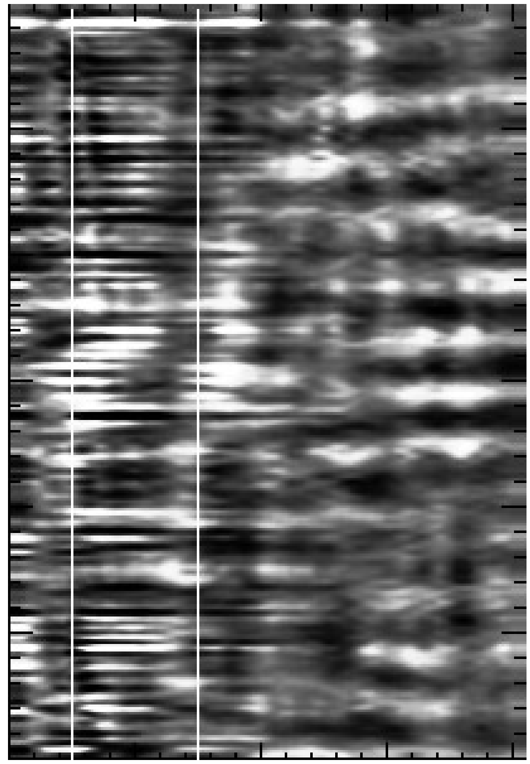

Fig. 7. “Time slices” image from Dopplergrams in Fe I 557.6 ±0.012 nm (c.f. image 3) with an integration angle 180 °. Five minute oscillations are still obvious around the spot (right edge of the photograph).

streaks, curving forward in time. Comparing Figs. 2 and 3, we verify that method II gives better results.

We observe slow waves both in the penumbra and the area around the sunspot corresponding to the chromospheric superpenumbra. The waves appear to begin at the outer part of the penumbra. They are directed inwards in the penumbra (towards the umbra) and outwards in the area around the penumbra. Their propagation velocity is near 0.5 km s^{-1} in both cases and their horizontal wavelengths near 2300 km. We should mention that the horizontal wavelength of the waves observed in the chromosphere for the same sunspot is about 4500 km. The waves clearly appear both in the blue and red wings, and more importantly in the sum of the wings, suggesting that they are not related to velocity perturbations but probably to pressure or temperature fluctuations.

Beside the waves, high frequency oscillations are observed in the time slice images (12 and 15 MHz); they should not be of Solar origin. Lites et al. (1982) analyzing similar observations in the Fe I 557.6 nm line also observed such high frequency oscillations and they related the phenomenon to their sampling rate.

The slow waves should not be related to the Evershed phenomenon since in the photosphere the Evershed flow is directed outwards and is restricted to the penumbra. Muller (1973), from high resolution observations, reported that the penumbra appeared to consist of bright grains moving towards the umbra of the spot. He found that the horizontal velocity of the grains was zero at the border of the penumbra-photosphere and maximum at the umbral border (0.5 km s^{-1}). Sobotka et al. (1999) made a similar analysis and found that there appeared to be a dividing line (DL) in the penumbra, at approximately 0.7 of the distance from the umbra to the photosphere; most penumbral grains outside this line moved toward the photosphere and those inside moved toward the umbra. For inward-moving grains they found a typical proper motion speed of 0.4 km s^{-1} and for the outward moving ones, 0.5 km s^{-1}. Their results are similar to ours concerning the dividing line and the velocity of the grains compared to that of the waves. However, we should note that in our case we refer not to grains but to waves forming arcs around the spot, as is obvious in Fig. 1.

We should further note that the phase propagation velocity of the outward moving waves is similar to the velocity of the moat flows as well as that of Moving Magnetic Features (MMFs), first observed three decades ago on sequences of magnetograms (see Harvey & Harvey, 1973). Finally, let we note that recently Rast et al. (1999) observed systematic bright rings around twelve isolated sunspots, within one sunspot radius of the penumbra.

It is interesting that in Fig. 5 we observe five minute oscillations *around* the spot, although we have integrated along a 45° angle; the oscillations are clear even if we integrate along 90° or 180° (Fig. 7). This implies *a coherent behavior* of the five-minute oscillations *around the spot*.

4. Discussion and conclusions

A number of authors proposed that p-mode oscillations play a fundamental role in the generation of at least part of the oscillations and waves that we observe in sunspots. Abdelatif & Thomas (1987) examined the interaction of solar p-modes with a sunspot. In their treatment they considered the sunspot as a magnetic slab where incident acoustic wave packets from the surrounding photosphere are partially reflected and partially transmitted into the slab.

Lites (1988) observed in Fe I 543.4 nm Doppler amplitude images, a ring of low oscillatory amplitude halfway between the inner and outer edge of the penumbra. He interpreted this ring as a result of the p-mode oscillations becoming increasingly more important in the outer penumbra of sunspots. He also reports that although he was able to clearly observe penumbral waves in the inner penumbra, the p-modes encroaches over the outer penumbra. The low oscillatory amplitude ring he observed seems to be related to the dividing line of Sobotka et al. (1999) and our splitting line where the waves start moving towards opposite directions.

It is possible that p-mode oscillations play a fundamental role in the generation of the waves we observed. Wave packets transmitted into the penumbra would slowly travel towards the umbra. Reflected wave packets would travel outwards in the area around the sunspot. The propagation phase velocity of the waves is very small and does not correspond to the photospheric sound velocity. A possible scenario is that the wave we observe is the result of the superposition of two different waves moving in opposite directions. The result is a nearly standing wave slowly moving towards the umbra in case of the penumbra and outwardly in case of the area around the sunspot. This scenario is enhanced by the fact that the horizontal wavelength of the photospheric waves is about half that of the chromospheric ones, as well as the coherent behavior of the 5-min oscillations around the spot. The power of the waves due to the p-mode oscillations is diminished as we move through higher layers. In the Fe I 543.4 nm line we observe the behavior referred to by Lites (1988), and in the chromosphere we observe waves starting out from the umbra and propagating outwards.

Another possible scenario is that the waves are related to oscillations in subphotospheric layers due to convection. Galloway (1978) modeled the formation of a sunspot by the action of convection on a weak background magnetic field. He found solutions in which steady convection concentrates the field into a strong central rope and subsequently oscillations develop within the rope. Recently Hurlburt & Rucklidge (2000) made numerical experiments modelling the interaction of pores and sunspots with solar convection. They proposed that except for the outflow around sunspots, there is an inflow hidden beneath the penumbrae of large sunspots (cf. their Fig. 8). In this case it is possible that convection drives both the waves we observe and the motions of penumbral grains.

More theoretical analysis and further observations are needed to exploit all possible scenarios. Further analysis is also needed for the clarification of the relation of the photospheric waves with the waves and oscillations observed in the chromospheric level. This will be done based on a new run at the DST.

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