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Oscillations and waves related to sunspots(*)

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Summary. — In order to study umbral oscillations, running penumbral waves and the relationship between them, we analyzed CCD, high-resolution, sunspot observations obtained at the center and the wings of the Hα line and the Fe I 5576 Å line using a UBF filter. We produced "space/time slice images" which show that there is not a clear relationship between umbral oscillations and running penumbral waves as they observed in upper chromospheric layers. We found that the running penumbral waves are observable at least up to the formation height of the Hα ± 0.5 Å line, but not in the Hα ± 0.75 Å or the Fe I ± 0.12 Å. The correlation between umbral oscillations at various atmospheric heights and running penumbral waves strongly indicates that the latter are excited by photospheric umbral oscillations and not the chromospheric ones.

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PACS 95.75.Mn – Image processing (including source extraction).
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Sunspots show oscillatory behavior; standing oscillations are dominant in the umbra, while running penumbral waves (RPWs) are dominant in the penumbra and the superpenumbra.

In the photosphere two classes of characteristic oscillations are observed in the umbra; one with period around 5 min (response to forcing by the *p*-mode photospheric oscillations) and one with period around 3 min (believed to be related to resonant modes of the spot itself). In the chromospheric layers, 3 min standing oscillations are dominant in

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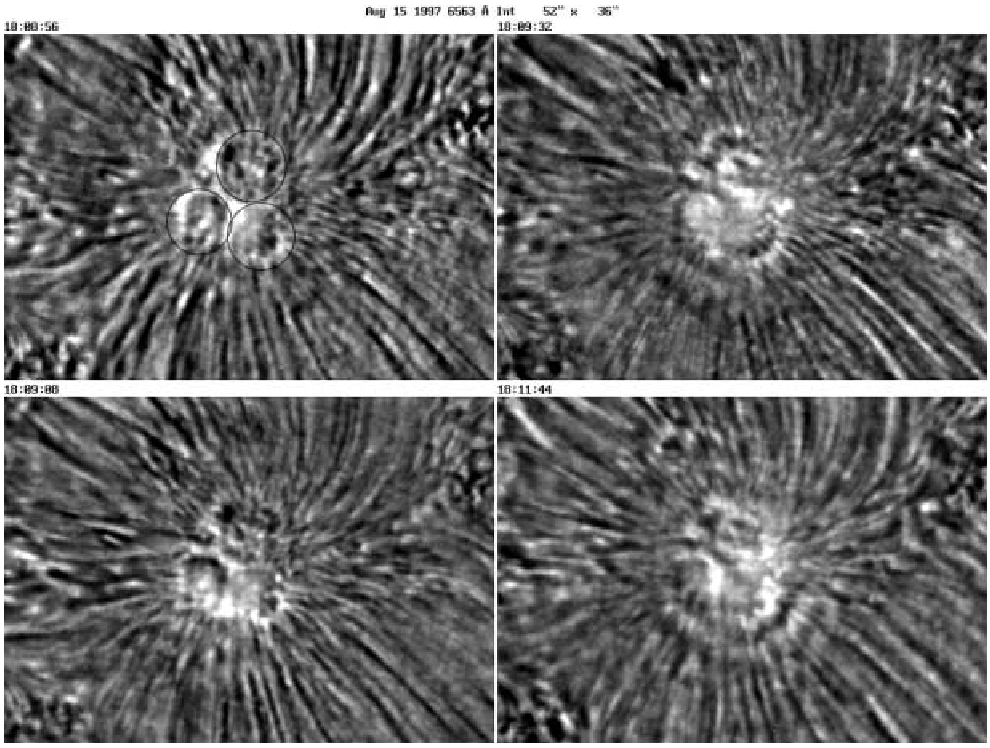

Fig. 1. – "Filtered" Hα -0.35 Å images of a large isolated sunspot observed near disk center on August 15, 1997. Three oscillating elements can be discriminated in the umbra (encircled with black circles in the upper left image) and outward-propagating waves in the penumbra.

the umbra, while the 5 min oscillations have either very low amplitudes or they are not present at all (see Lites [1] and Bogdan [2] for extended recent reviews).

RPWs are observed in Hα as narrow alternative bright and dark bands, concentric to the edge of the umbra. They propagate in the penumbra and inner superpenumbra with a constant velocity around 13 km s^{-1} and having a frequency of about 3 mHz (see Christopoulou *et al.* [3] for an extended review).

Although RPWs and umbral oscillations have been studied for decades, their nature and more important their association is still not clear. In this work we present a study of oscillations and waves related to sunspots in different atmospheric layers. Although we are going to present examples from one sunspot, the results for an extended sample of 7 sunspots obtained from the Big Bear Solar Observatory during 2000, and 3 sunspots obtained from the Sacramento Peak Observatory are similar.

2. – Observations image processing

The observations were obtained on August 15, 1997, with the R. B. Dunn telescope of the Sacramento Peak Observatory using the UBF filter; our target was a large isolated sunspot (N14.7, E26.0). The spatial resolution was $0.26''$ and we analyzed two sequences of filtergrams. The duration of the first one was 53 minutes and filtergrams were obtained in Hα center and ± 0.5 Å. The time interval between successive images of the same

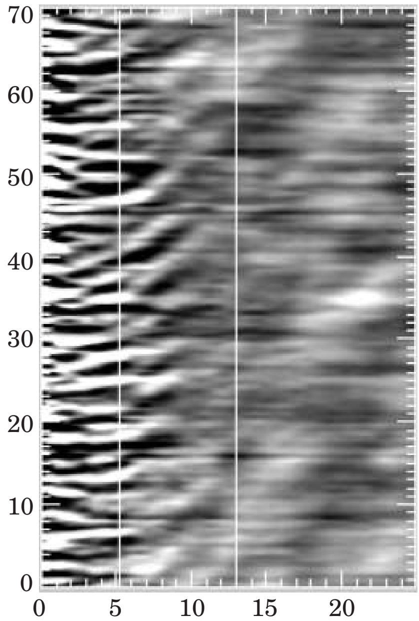

Fig. 2. – "Space/time" slice image computed from Doppler velocity images at H$\alpha\pm$ 0.35 Å and an integration angle: 360° (see text for details). White lines mark the umbra and penumbra boundaries, as derived from an Fe I 5576 Å image. Although the large integration angle, the RPWs can be easily discerned as diagonal streaks in the area of the penumbra, curving forward in time. The scale in the x-axis is in arcseconds and in y-axis in minutes.

wavelength was 12 s. The duration of the second sequence was 70 minutes and filtergrams were obtained in Hα center, Hα ±0.35, Hα ±0.75, and in the photospheric, magnetically non-sensitive line Fe I (5576.099) ±0.012 Å. The time interval between successive images of the same wavelength was 28 seconds. For both sequences the time difference between opposite Hα wings was 4 seconds. Apart from correcting the raw images for dark current and flat field, we computed also Dopplergrams in Hα and in Fe I by red-blue wing subtraction.

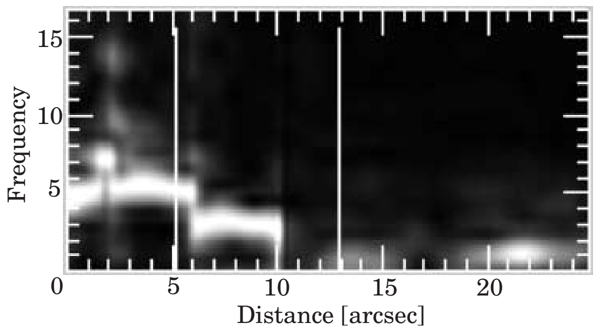

Fig. 3. – "Power/space" map corresponding to the "space/time" slice image of fig. 2.

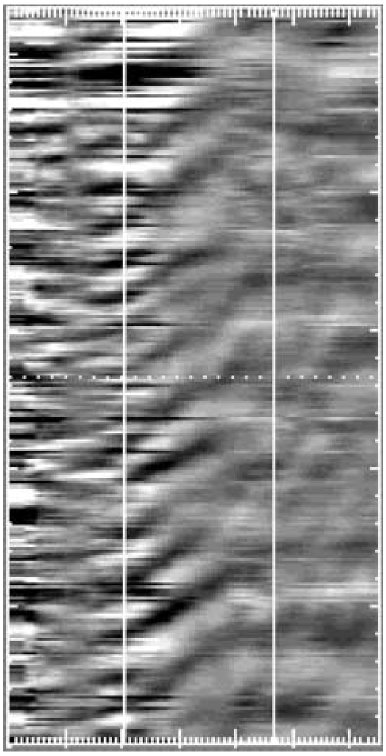

Fig. 4. – "Space/time slice" image computed from Hα -0.5 Å images. The vertical lines mark the umbra and penumbra boundaries as derived from an Fe I -0.12 Å image. RPWs can be easily discerned, in the area of the penumbra, as diagonal streaks curving forward in time. Tick marks in the x-axis correspond to $0.26''$ and tick marks in the y-axis to 120 s.

In order to enhance time-varying phenomena in intensity images, we subtracted from each image the "running local average", computed over a number of images before and after it (covering a time interval of 7 min). We produced "space/time slice" images, having distance from the center of the umbra as one axis and time as the other. In order to create them, we computed the average intensity along circular arcs at right angles to a line directed outwards beginning from the center of the umbra, for every image of a time series. More details about the above two methods can be found in [3] (paper I) and [4] (paper II) and references therein. Figure 1 shows four subsequent "filtered" images in Hα -0.35 Å. Three oscillating elements can be discriminated in the umbra and outward-propagating waves in the penumbra.

3. – Results

In an attempt to better understand the nature of RPWs, we examine their possible association with chromospheric umbral oscillations, we try to identify them in various atmospheric heights and finally we examine their possible association with photospheric umbral oscillations. Figure 2 presents a "space/time slice" image computed from the Doppler velocity images at $\Delta\lambda = \pm 0.35$. Each time row of the image was computed by averaging the velocity along 360° circular arcs, starting from the center of the sunspot

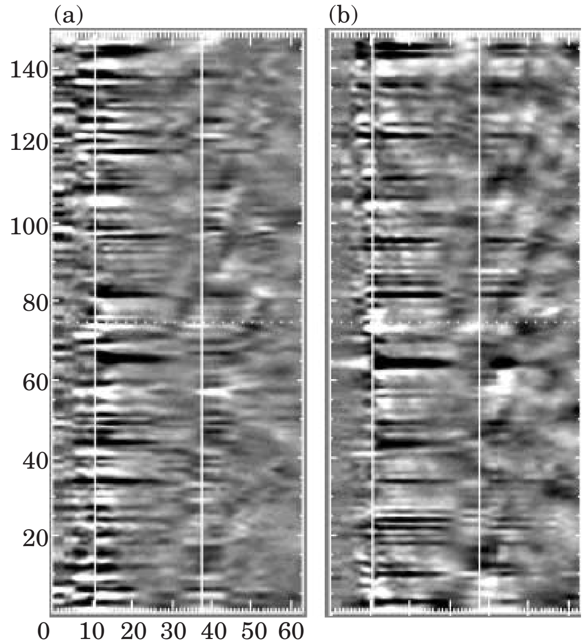

Fig. 5. – “Space/time slice” images showing RPWs in Hα −0.75 Å (a) and Fe I (5576.099) −0.12 Å (b). They start at about 0.7 of the distance between the umbra and the penumbra boundaries and propagate outwards in the region around the sunspot. Tick marks in the x-axis correspond to 0.26″ and tick marks in the y-axis to 140 s.

and propagating outwards. Despite the large integration angle the waves can be clearly discerned. Figure 3 shows a “power/space” map corresponding to the “time/slice” image of fig. 2. We observe that the period of RPWs is about twice that of umbral oscillations. This shows that there is not a clear relationship between the chromospheric umbral oscillations and the RPWs. If we accept that the RPWs are generated by umbral oscillations or by the same cause with umbral oscillations, then a mechanism explaining the different period is necessary.

Theoretical models propose the possible association of RPWs with counterparts in the photosphere (see [3, 4, 1]); however up to now there have not been observed running waves in the photosphere with similar properties to the chromospheric ones (see [4] and references therein). In order to investigate how deeply the waves are situated, we computed “space/time slice” images at various positions across the Hα line and the Fe I (5576.099) line. Figure 4 shows a “space/time slice” image computed from Hα −0.5 Å images; RPWs are obvious in the area of the penumbra. The propagation velocity of the waves is similar to that observed in Hα center. Also from “filtered” images in Hα −0.5 Å (not shown here) it can be verified that the waves are coherent over large angles.

Continuing our research at lower atmospheric layers, we did not found RPWs similar to the ones observed at higher chromospheric levels (with a comparable period) beyond the Hα ±0.5 Å. In the photosphere we found inward-propagating annular intensity variations in the inner penumbra and outward-propagating annular intensity variations in the outer penumbra and in the area around the sunspot (paper II). The phase velocity of the waves is near 0.5 km s^{-1} in both cases and their horizontal wavelength is about

2500 km. The image processing technique of the "running local average" results in washing out waves with periods larger than the integration time. Thus, searching for waves with longer periods we experimented increasing the integration time of the "running local average". We found out another category of photospheric waves apparent in Hα -0.75 Å and Fe I (5576.099) -0.12 Å (fig. 5). The waves appear to begin at approximately 0.7 of the distance between the umbra and the penumbra boundaries. They propagate beyond the penumbra area around the sunspot and they are weak. Their propagation velocity is around 3-4 km s^{-1} in the penumbra reduced to about 2 km s^{-1} in the area around the sunspot. These waves are not as prominent as the chromospheric ones in filtered images and it is difficult to decide if the are coherent over extended arcs.

Apart from the waves, in fig. 5, 3 min standing oscillations are obvious in the inner penumbral area in H$\alpha$$-0.75$ Å, while those oscillations are absent (or have much less power) in Fe I (5576.099) -0.12 Å. The existence of those oscillations was also verified by frequency/space maps like the one of fig. 3. This confirms that more than one oscillating modes coexist in the inner penumbra (see [3, 5]).

Moore [6] suggested a mechanism for the generation of umbral oscillations and RPWs; both phenomena are a manifestation of overstable oscillations beneath the visible layers of the umbral surface. He estimated periods and growth rates of these oscillations at two particular atmospheric heights of the umbral convection zone. At the shallower depth 125 km, he found a period of about 138 s, considered that can be related to umbral oscillations. In the deeper layer at about 650 km, he found a period of about 270 s, considered appropriate for RPWs. Zhugzhda and Dzhalilov [7] proposed a model of penumbral waves based on the theory of transformation of magneto-acoustic gravity waves in an oblique magnetic field. Penumbral waves are considered to be the result of transformation of the five-minute waves, trapped in the convection zone. These waves tunnel through the photosphere to the transformation region and convert into upgoing and downgoing slow waves. The upgoing waves in the chromosphere run to the outside of the sunspot.

As we analyzed in the beginning of this section there is not a clear association between umbral oscillations and RPWs in the upper chromospheric layers. In an attempt to investigate if there is an association of RPWs with umbral oscillations in different layers of the solar atmosphere and especially the photosphere, we computed "correlograms", similar to that of fig. 6. In order to produce the "correlogram" between two "time/slice" images, we computed the correlation coefficient for each point of every row of the first image, shifting the second one over the first, from minus to plus half the duration of the time series. More details about the technique can be found in Christopoulou *et al.* [5]. Initially we used the "correlograms" in order to identify the nature of RPWs (intensity or velocity oscillations?). Figure 6b shows a "correlogram" between the Hα -0.35 Å and the Hα $+0.35$ Å. We observe a phase difference of about half a period ($180^\circ \pm 12^\circ$) indicating a pure Doppler shift.

We further produced "correlograms", similar to the previous ones, but "correlating" the average variation of umbral oscillations (computed from velocity images at various atmospheric levels) with every row of a "space/time" slice image in the Hα center. The variation of umbral oscillations was computed averaging the points along the space dimension of the "space/time slice" image corresponding to the central part of the umbra. Further, we computed the correlation coefficient for each point of every row of the Hα center "space/time" slice image', shifting the variation of umbral/penumbral oscillations over the row, from minus to plus half the duration of the time series. Figure 7 shows the correlation of the variation of umbral oscillations computed from Doppler images at

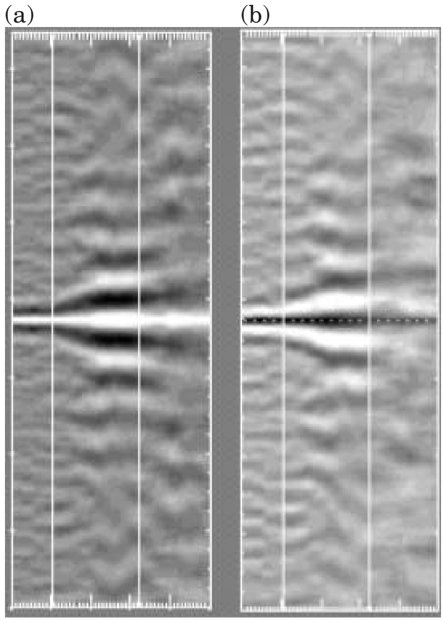

Fig. 6. – "Autocorrelogram" of the Hα -0.35 Å "time-slice" image (a), "correlogram" between Hα -0.35 Å and Hα $+0.35$ Å(b). Tick marks in the x-axis correspond to $0.26''$ and tick marks in the y-axis to 140 s.

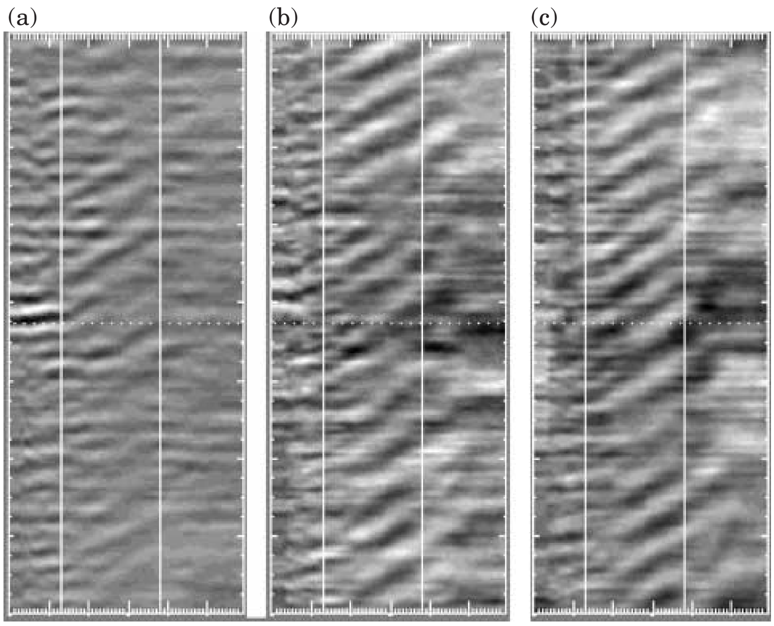

Fig. 7. – Correlation of the variation of umbral oscillations computed from Doppler images at Hα ± 0.35 Å (a), Hα ± 0.75 Å (b), and Fe I ± 0.12 Å (c), with a "space/time slice image" at Hα center (see text for further details). Tick marks in the x-axis correspond to $0.26''$ and tick marks in the y-axis to 140 s.

Hα ±0.35 Å (a), Hα ±0.75 Å (b), and Fe I ±0.12 Å (c), with the "space/time slice image" at Hα center. From fig. 7a we observe that there is a significant correlation between the variation of umbral oscillations in Hα ±0.35 Å Doppler images and in Hα center but not between the variation of umbral oscillations and that of RPWs. The variation of umbral oscillations in Hα ±0.75 Å Doppler images shows a moderate correlation with both the variation of umbral oscillations and that of RPWs in Hα center (fig. 7b). Finally, the variation of umbral oscillations in Fe I ±0.12 Å Doppler images shows a significant correlation with that of RPWs in Hα center (taking into consideration the lag in the propagation of the oscillations). Since the formation heights of Hα ±0.35 Å, Hα ±0.75 Å and Fe I ±0.12 Å are in the upper chromosphere, lower chromosphere and lower photosphere, respectively, this is an indication that RPWs are excited from photospheric umbral oscillations; further investigation is needed.

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