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# Association of chromospheric sunspot umbral oscillations and running penumbral waves

## I. Morphological study

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**Abstract.** Observations of a sunspot region located near the center of the solar disk were obtained on October 3, 1994, with the Multichannel Subtractive Double Pass Spectrograph (MSDP). This instrument, operating in H$\alpha$, was installed at the focus of the VTT at Tenerife (Canary Islands) and provided H$\alpha$ intensity profiles at every pixel of the field of view. Reconstruction of the H$\alpha$ profile allowed the computation of two dimensional intensity and Doppler velocity images at different wavelengths within the line. We analyse a time series of 1 hour and 8 min, obtained with a cadence of 36 sec and investigate the relation between umbral oscillations and running penumbral waves. The Doppler velocity as a function of time, along radial cuts through the center of the spot, shows several clear cases where waves that originate inside the umbra continue to propagate in the penumbra. In one case we were able to follow the evolution of an oscillating element for 216 sec, from the inner part of the umbra to the penumbra and we describe the propagation characteristics. We confirm the close association between sunspot oscillations and running penumbral waves and suggest that they are probably due to the same resonator.

**Key words:** Sun: chromosphere – Sun: oscillations – Sun: sunspots

### 1. Introduction

Since the discovery of "umbral flashes" in 1969 by Beckers and Tallant, various types of oscillations have been detected in the photospheric, chromospheric and transition region layers of sunspots. In 1972 three kinds of oscillations and wave motions were reported: 5 min oscillations in the umbral photosphere by Bhatnagar et al. (1972), 3 min velocity and intensity oscillations in the umbral photosphere and chromosphere by Giovanelli (1972), Beckers & Schultz (1972) and Bhatnagar & Tanaka (1972) and running penumbral waves by Giovanelli (1972) and Zirin & Stein (1972). Since then, these periodic dynamic phenomena have been observed and studied extensively as they raise many challenging theoretical problems. Their study is important on several grounds: they provide unique information about the structure of the atmosphere which supports them, as well as for the subphotospheric structure of sunspots; they permit us to test models of generation, propagation and dissipation of MHD waves; they offer clues about the energy balance in the sunspot atmosphere.

Umbral oscillations at the photospheric level show enhanced power at several frequencies in the power spectrum with a peak within the 5-minute band (2.5 - 4.5 mHz) and an average rms amplitude of 75 m s$^{-1}$. At chromospheric levels, usually in the H$\alpha$ line, one often sees umbral structures which show periodic velocity oscillations with periods of 150 - 200 sec and typical velocity amplitudes of 3 km s$^{-1}$, although amplitudes as large as 6 km s$^{-1}$ have been reported (Alissandrakis et al., 1998). Large umbrae can have several oscillating elements, not larger than 2 - 3$''$.

There are two competing theoretical approaches for the nature of the chromospheric umbral oscillations (see reviews by Thomas & Weiss 1992, Lites 1992). The one proposed by Scheuer and Thomas (1981) postulates that the oscillations are driven by a sub-photospheric resonance of fast magneto-acoustic waves that are excited by overstable convection ("photospheric resonator"). The other, proposed by Zhugzhda et al., (1983) involves resonant trapping within a cavity, located in the chromosphere of the umbra ("chromospheric resonator"), of slow mode waves, which are excited by broadband acoustic noise from the convection zone. Up to now, observations give support to both pictures. However, Lites (1992) pointed out the non-linear hydrodynamic nature of the chromospheric oscillations and proposed an interpretation in terms of propagating acoustic waves from below that develop into a series of shocks in the atmosphere.

Running Penumbral (RP) waves appear in H$\alpha$ as disturbances moving from the outer edge of the umbra to the penumbra of sunspots with well developed penumbrae. They start out as circular arcs and propagate more or less uniformly outwards,

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becoming gradually invisible when or before they reach the outer boundary of the penumbra. They have periods of 180 - 240 s, radial extents 2300 - 3800 km and azimuthal extents of 90°- 180° and sometimes even 360° around the spot.

There have been basically two kinds of theoretical models for the RP waves. Nye & Thomas (1974, 1976) presented models interpreting these disturbances as magneto-acoustic waves that are vertically trapped at photospheric levels (due to reflection by the increasing Alfven speed up into the chromosphere and increasing sound speed down into the convection zone). According to these models, such waves are evanescent at the height of formation of H$\alpha$, but have their largest amplitude there due to the rapid decrease of density with height (Cally & Adam 1983). More recently, Evans & Roberts (1990) associated penumbral waves with fast and slow surface modes, the fast surface waves being a subproduct of the fast body-modes produced at the umbra and the slow surface waves, a consequence of granular buffeting of the quiet photosphere.

An obvious question is whether umbral oscillations and RP waves are due to a different resonator or form part of a the same travelling wave system. Alissandrakis et al. (1992) detected waves which started in umbral elements with a size of a few arcseconds, and propagated through the penumbra. Tsiropoula et al. (1996) detected, for the first time in velocity images, waves which started in the outer 0.3 of the umbral radius and propagated through the inner part of the penumbra with velocities of 13-24 km s$^{-1}$. They also found that the propagation velocity as well as the velocity amplitude was greater for waves closer to the center of the spot and diminishes as one moves outward. Brisken & Zirin (1997) also found deceleration in the propagation velocity of RP waves. Recently, Alissandrakis et al. (1998) analysed a part of the time series used in this work and provided a clear evidence that umbral oscillations and RP waves belong to the same wave system.

In the present work we investigate velocity oscillations in the umbra and the penumbra of a sunspot. We are looking for spatial changes of the oscillatory behavior and investigate the propagation characteristics as well as the association between umbral oscillations and running penumbral waves.

## 2. Observations and data reduction

A sunspot region (NOOA 7783), located near the center of the solar disk (S07 W12), was observed on October 3, 1994. The observations were obtained with the MSDP installed at the focus of the VTT in Tenerife (Canary Islands) during an observing campaign in the framework of the International Observing Time. The MSDP (Mein, 1991) observes simultaneously in two lines, H$\alpha$ and CaII 8542Å. In this work we are only concerned with the H$\alpha$ observations. The data were obtained with a 1024 x 1024 pixel CCD camera and flat fielding and dark current corrections were applied. The MSDP records a two dimensional field of view on the solar surface with good spatial and temporal resolution in 9 channels simultaneously, 0.3 Å apart in the H$\alpha$ profile.

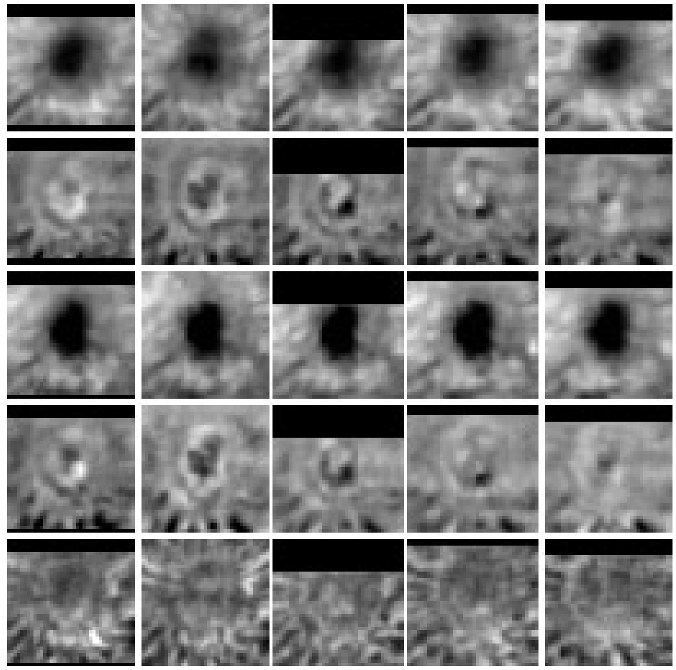

**Fig. 1.** A sequence of 5 intensity (first and third row) and velocity (second and fourth) images of the spot at $\pm$0.3 Å and $\pm$0.6 Å observed from 9:58:51 UT with a cadence of 36 sec. In the velocity images bright is towards the observer (positive velocities). In the fifth row the intensity obtained by the subtraction technique is shown

The duration of the observations was $\approx$ 2 hours 15 min under good seeing conditions for most of the time. From 09:00 to 10:08 UT three adjacent elementary fields of view were recorded every 36 sec, which were combined by two-dimensional cross-correlation techniques to a larger field of view containing the spot. From 10:10:53 UT to 11:14:53 a large region was observed every 4 min, using 20 elementary images. These latter observations have already been described by Tsiropoula et al. (1997).

For the present study we used the high cadence time series consisting of $\approx$ 100 frames. MSDP provides the possibility to reconstruct the H$\alpha$ line profile at every pixel of the field of view. Furthermore, an average profile can be obtained by averaging over quiet or active regions. These profiles can then be used for the computation of intensity and Doppler velocity maps at several depths in the H$\alpha$ line, using a code simulating the "lambdameter" technique (Mein 1977). In Fig. 1 a sequence of 5 frames of intensity and velocity images at $\pm$0.3 Å and $\pm$0.6 Å of the spot region is shown. The evolution of the waves over this $\sim$2.5 min time series is clearly visible in the velocity images. Sometimes a bright patch (velocities towards the observer) or a dark patch cover the whole umbra. Running waves, having azimuthal extent as large as 360°, can clearly be seen propagating from inside the umbra through the penumbra.

## 3. Results

The sunspot was isolated and almost circularly symmetric. The umbral-penumbral boundary was at $\sim$3.3″ from the spot cen-

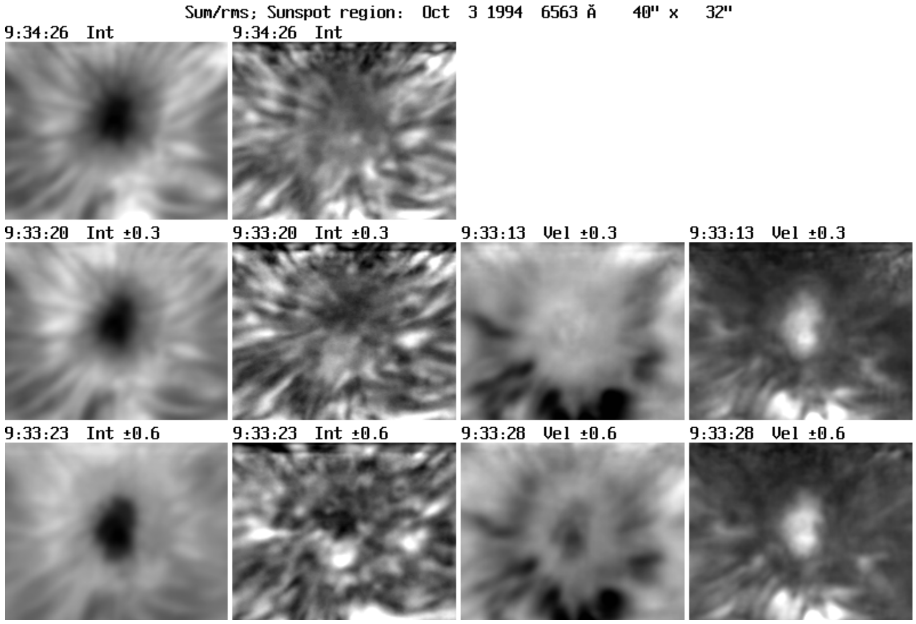


**Fig. 2.** Average (first and third columns) and rms (second and fourth columns) images of intensity and velocity at H$\alpha$ center (top row), H$\alpha$ $\pm 0.3$ Å (middle row) and $\pm 0.6$ Å (bottom row)

ter, while the penumbral-photospheric boundary was at $\sim 12.6''$, measured in images near the H$\alpha$ continuum.

In the intensity images there is no indication of structure (such as umbral flashes) inside the umbra. The penumbra-superpenumbra consisted of roughly radial dark fibrils, of variable lengths and widths. The dark fibrils are visible through the whole time series as well as in an image averaged over the entire interval of observation (Fig. 2). This indicates that their lifetime exceeds one hour, in agreement with previous estimates by Tsiropoula et al. (1997). There is a clear dependence of the large scale line-of-sight velocity on the position relative to the sunspot, e.g. the large scale flow pattern is consistent with the Evershed flow. Redshifts are observed at the diskward side of the spot and blueshifts at the limbward side.

Whereas in the velocity images we can clearly see waves starting inside the umbra and propagating through the penumbra (Fig. 1), no waves are visible in the intensity images. A method to study umbral oscillations and RP waves in intensity images is the image subtraction technique. This consists of subtracting the average intensity from each individual image of a time series (Alissandrakis et al., 1992), which removes the sharp intensity gradient between the umbra and the penumbra and enhances the fine structure. We applied the subtraction technique in the intensity frames at H$\alpha$ line center. In most frames fine structures can be seen within the umbra (cf. Alissandrakis et al., 1992), while in some frames dark and white bands appear, reminiscent of penumbral waves (Fig. 1, fifth row). However, no clear correlation was found between these bands and those observed at the Doppler velocity images at $\pm 0.3$ Å and $\pm 0.6$ Å.

A first approximation of the intensity and velocity fluctuations for the entire time series can be obtained from their rms-values. Fig. 2 shows images of the average and rms values of the intensity at the line center and both intensity and velocity at H$\alpha$ $\pm 0.3$ Å and $\pm 0.6$ Å. Inside the umbra the intensity variations are small; they are stronger in the penumbra, where, at the line center and at H$\alpha$ $\pm 0.3$ Å, they are apparently associated with changes in the penumbral fibrils. On the contrary, the velocity fluctuations peak inside the umbra and are apparently associated with the oscillations and the waves.

It is interesting to note that the rms image looks very much like the negative of the sunspot intensity image. A scatter plot of the velocity rms at H$\alpha$ $\pm 0.6$ Å versus the intensity at H$\alpha$ $\pm 0.6$ Å is shown in Fig. 3a. Since the umbral intensity is lowest where the magnetic field is the highest, the anti-correlation between the rms velocity and the intensity is an indirect but still strong indication of their correlation with the magnetic field intensity.

The velocity fluctuations at H$\alpha$ $\pm 0.3$ Å and H$\alpha$ $\pm 0.6$ Å are very similar; however the latter are weaker. A scatter plot is shown in Fig. 3b; linear regression gives a ratio of 0.73.

Going back in the individual velocity images, we notice that they show oscillating elements with spatial sizes of 3 - $4''$. In some frames two elements are apparent inside the umbra simultaneously. Positive velocity sometimes changes to negative, even from one frame to the next (e.g. within 36 sec), indicating that these oscillating elements can have periods as small as $\sim 80$ sec. There are frames in which a bright (positive velocity) patch covers the entire umbra and subsequently changes to a negative velocity patch. The oscillating elements develop into waves, which can clearly be detected inside the umbra and propagate through it to the penumbra, as running penumbral waves. They form concentric arcs, very often having azimuthal extents as large as $360°$. Usually two concentric wavefronts can be detected, one with positive and the other with negative velocities, but sometimes up to 4 wavefronts can be detected (2 with positive and 2 with negative velocities e.g. 10:00:03 UT, 10:00:39 UT). Their radial extent is between 1000 - 3000 km. As they propagate outwards their amplitude decreases in agreement with the behaviour of the velocity rms discussed above.

A clear-cut relationship between an umbral oscillating element (OE) and the RP waves is shown in the plots of Fig. 4,

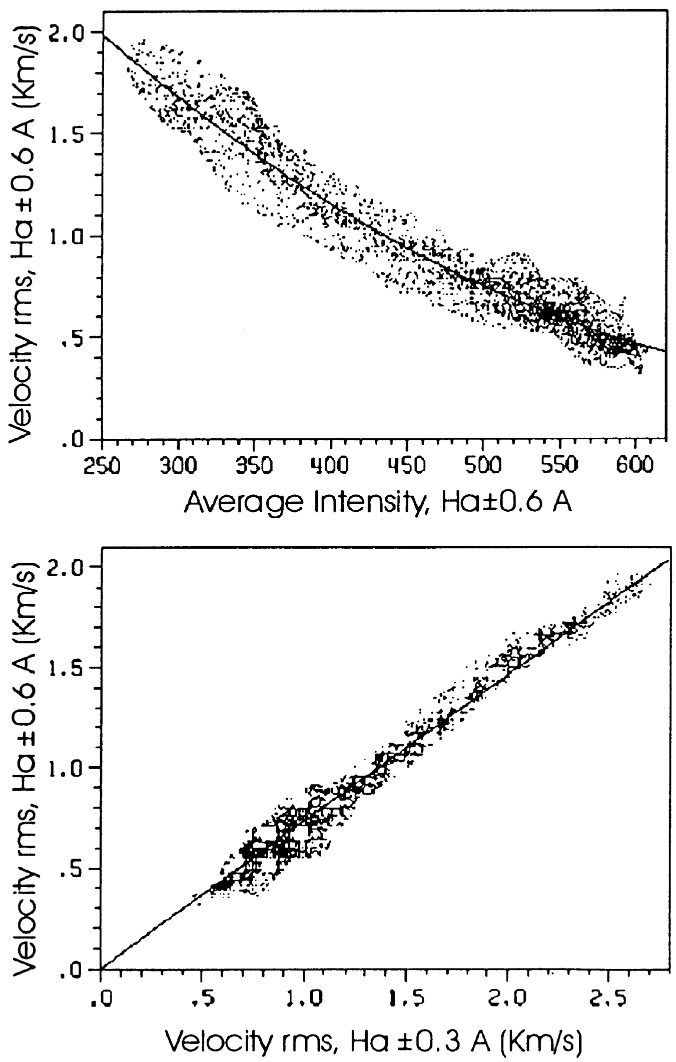


**Fig. 3a and b.** Scatter plots of **a** the velocity rms versus the intensity inside the spot and **b** the velocity rms at H$\alpha$ $\pm$0.6 Å versus that at H$\alpha$ $\pm$0.3 Å

which shows a sequence of 8 frames beginning at 9:20:27 UT and ending at 9:24:39 UT. The plots show the velocity at H$\alpha$ $\pm$0.3 Å along a cut through the center of the spot. The position of the cut is shown in the velocity images in the third column, third row of the figure, where an intensity image at H$\alpha$ line center is also shown.

The maximum (absolute) velocity of the OE, marked as $\alpha$ or $b$ in Fig. 4, is at the same position, at $\approx$ 11.5″ - 12″ in all frames. At 9:21:03 UT the cut passes through the OE, which has a velocity amplitude of 5.5 km s$^{-1}$; on either side of the OE there are peaks with positive velocities, $A1$ and $A2$, at 1.5″ and 3.2″ from the OE, having velocity amplitudes of 4 and 2.7 km s$^{-1}$ respectively.

Subsequently, $A1$ and $A2$ move away from the OE, while their velocity amplitudes decrease. At 9:24:39 UT they are located at 7.6″ and 8.8″ from the OE and have velocity amplitudes of 1.8 km s$^{-1}$ and -0.8 km s$^{-1}$ respectively. From 9:21:39 UT the velocity of the OE decreases gradually and attains a negative value of $-4.5$ km s$^{-1}$ at 9:22:51 UT, while in the next frame (at 9:23:27 UT) the velocity becomes again positive, increasing by $\approx$ 8 km s$^{-1}$ and a new oscillating cycle begins. At 9:22:51 UT a wave with two negative peaks, $\alpha 1$ and $\alpha 2$, on either side of the OE is clearly visible at 1.7″ and 1.3″ respectively. At 9:24:39 UT they are located at 3.8″ and 7″. At 9:23:27 UT a positive peak $B2$ appears with a velocity amplitude of 6.4 km s$^{-1}$. Peak $B1$ is not clearly visible at this time. Both $B1$ and $B2$ propagate outwards at 9:24:03 UT and 9:24:39 UT and their velocity amplitude decreases. In Fig. 5 the position of the velocity peaks A1, A2, $\alpha 1$ and $\alpha 2$ versus time are shown. The propagation velocities range from 4.1 km s$^{-1}$ to 35 km s$^{-1}$.

The spatial and temporal characteristics of the waves are better shown in plots of the Doppler velocity, along cuts such as that of Fig. 4, as a function of time. Fig. 6 shows the velocity at H$\alpha$ $\pm$0.3 Å as a function of position and time, along four cuts through the spot center; the cuts are in different directions, 45° apart. Along each cut, the velocity has been averaged over a strip extending 1″ on either side; the step along the direction of the cut was 0.1″. In order to enhance the visibility of the waves far from the center of the spot, the velocity amplitude has been weighted by the inverse of the velocity rms.

The characteristic pattern of alternating dark and bright bands is obvious in this figure, representing the velocity maxima and minima. In all cases waves in the penumbra can be traced inside the umbra. However, the inverse is not always true: sometimes umbral waves propagate on one side of the penumbra only while, occasionally, they fade away near the umbra-penumbra boundary. As a result, more peaks are visible inside the umbra than in the penumbra.

Inside the umbra, velocity amplitudes as large as 8 km s$^{-1}$ are sometimes measured. This velocity is very close to the sound speed in the chromosphere, which is about 8 km s$^{-1}$. The waves are still detectable at a distance of about 12″, more than twice the umbral radius.

Another important characteristic of the wave pattern is that it is concave upwards, which shows that the wave velocity decreases as they propagate from the umbra to the penumbra. This is shown clearly in Fig. 7, where we plotted the position of the wave minima and maxima along a cut as a function of time. The phase velocity is very high in the umbra; in the inner penumbra the velocity is 20 – 30 km s$^{-1}$, while in the outer penumbra we measured values between 10 and 16 km s$^{-1}$.

## 4. Summary and conclusions

Study of periodic phenomena in sunspots such as umbral oscillations and RP waves are important in understanding their physical mechanism and the energy transport in their atmospheres. However, although several works are devoted to this subject no generally accepted explanation has been presented and their driving mechanism is still lacking.

The present MSDP high spatial and temporal resolution observations of an isolated sunspot near the center of the disk provided important information about wave motions in the sunspot region. Our analysis confirms the important conclusion that the

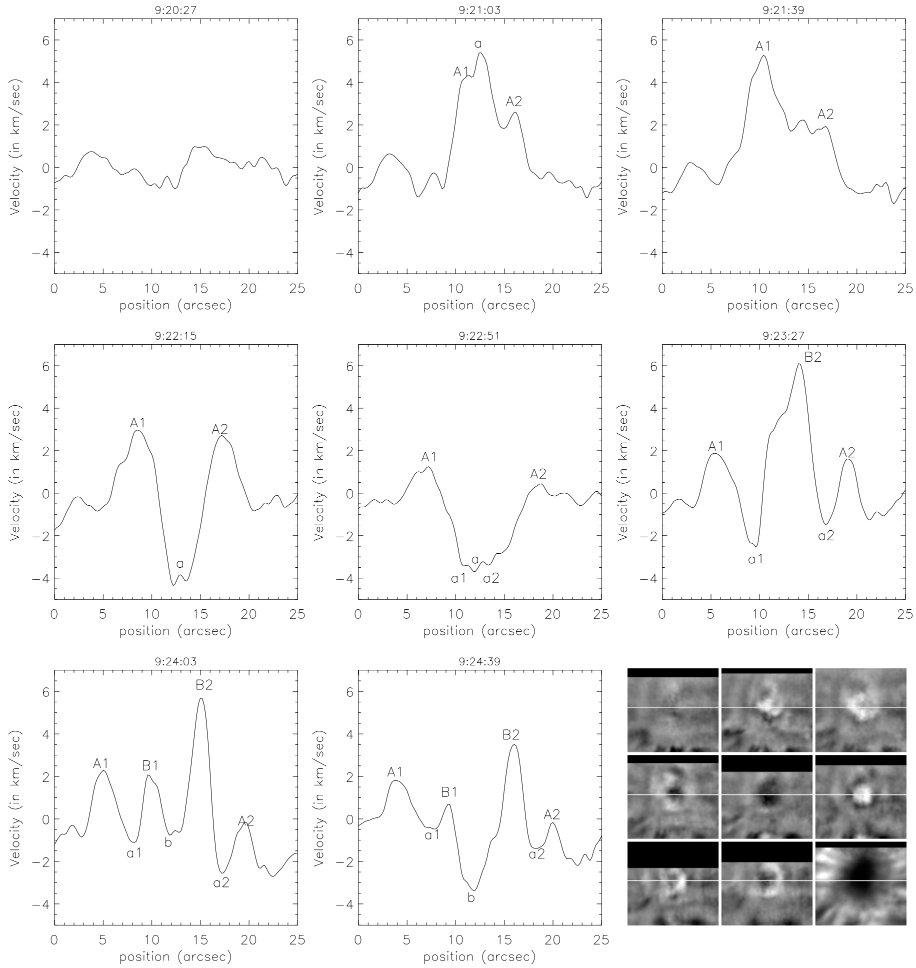


**Fig. 4.** Temporal evolution of the Doppler velocity along a cut through the center of the spot from 9:20:27 UT to 9:24:39 UT showing the behavior of an oscillating element and the propagation of the RP waves. The position of the cut is shown in the velocity images in the third row, third column, where an intensity image at H$\alpha$ center is also included

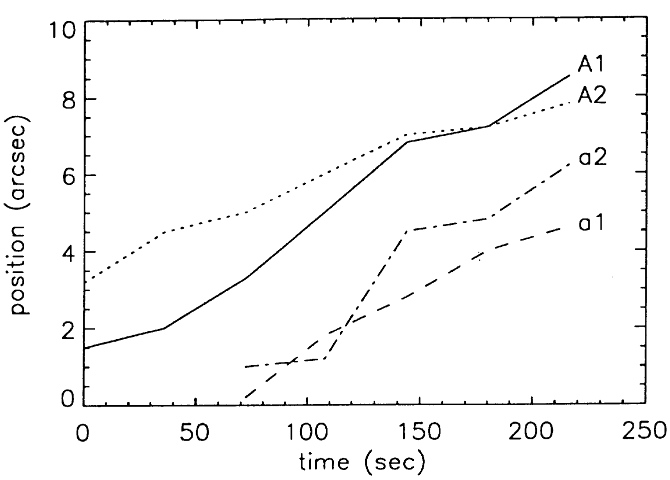


**Fig. 5.** Position of the velocity peaks $A1$, $A2$, $\alpha1$ and $\alpha2$ versus time

waves originate from oscillating elements inside the umbra. We found several cases in which penumbral waves appeared as the continuation of umbral oscillations. In one case, in particular, we have been able to follow for 216 s the evolution of an oscillating element inside the umbra as well as the associated waves propagating outwards. These findings suggest that they belong to the same travelling wave system and are probably due to the same physical mechanism.

In all cases waves in the penumbra can be traced inside the umbra, but not vice-versa; there are waves which propagate on one side of the penumbra only, while others fade away near the umbra-penumbra boundary. Probably not all umbral waves carry sufficient energy to sustain their propagation through the penumbra. This fact can explain differences in the periods of the waves observed in the umbra and those observed in the penumbra, which have been considered as different phenomena in the past. Additional reasons for the differences in the periods could be differences in the physical conditions and in the strength and inclination of the magnetic field too.

The velocity amplitude and the propagation speed of the waves decrease with distance from the centre of the umbra. We measured velocity amplitudes as large as 8 km s$^{-1}$ in the umbra, and propagation velocities between 20 – 35 km s$^{-1}$ in the inner penumbra and between 4 – 16 km s$^{-1}$ in the outer penumbra. The propagation speed of the RP is usually much larger than the sound speed in the chromosphere and it is close to the photospheric Alfvén speed but much less than the chromospheric Alfvén speed. Thus no conclusion about the character of these disturbances can be drawn at this time. It is interesting to note, however, that the anti-correlation we found between the rms

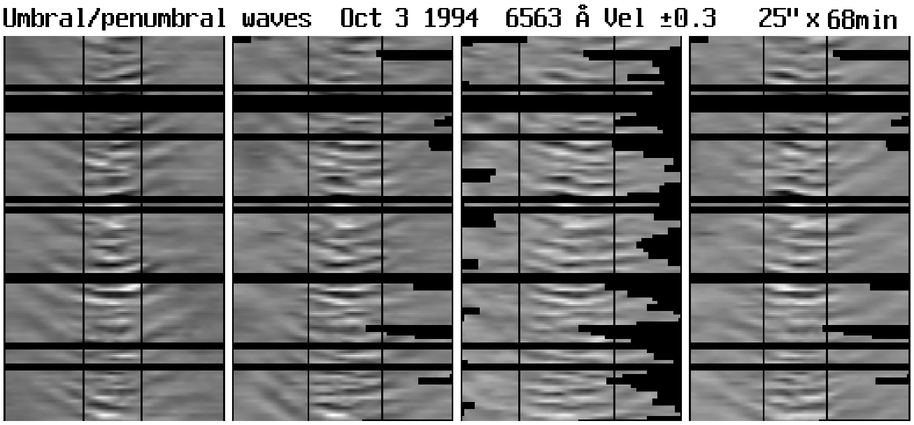


**Fig. 6.** The velocity as a function of position (horizontal axis, from $-12.5''$ to $12.5''$) and time (vertical axis, increasing upwards, over 1h and 8 min). Four cuts through the center of the spot are shown, oriented 45° apart. Dark vertical lines mark the approximate boundaries of the umbra; dark areas are due to missing data.

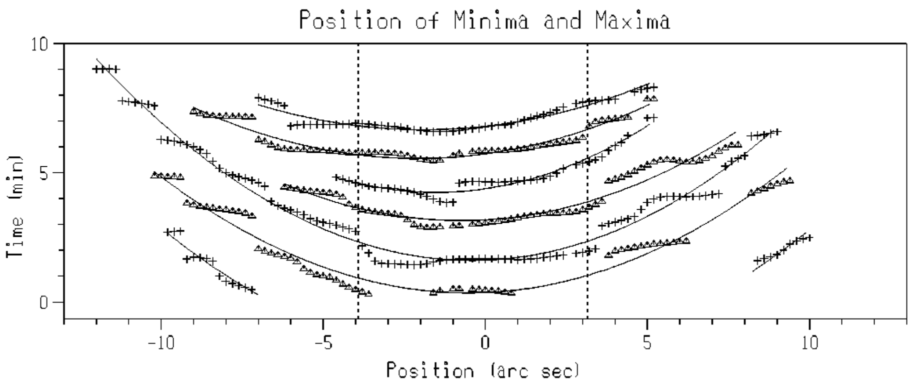


**Fig. 7.** Position of the maxima (crosses) and minima (triangles) of waves in the lower part of the rightmost cut of Fig. 6 as a function of time; the continuous curves are parabolic fits. Dashed vertical lines mark the boundaries of the umbra.

velocity and the intensity provide a strong indication of the correlation of the velocity with the magnetic field intensity and/or inclination.

Power spectrum analysis of this time series which is currently in progress will give more information on the different modes of the oscillations and clarify the spatial changes of the oscillatory behavior. On the other hand, it is obvious that significant progress in theory is needed in order to incorporate in the same model the nature and driving source of umbral and RP oscillations and lead to a global understanding of wave phenomena in sunspots.

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