Running Penumbral Waves in Sunspots

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**Abstract.** In order to study running penumbral waves, we analyzed high resolution sunspot observations obtained at the center and the wings of the Hα line. The sharp intensity gradient between the umbra and the penumbra has been removed by using an image processing technique.

The processed images show the waves to start out from the umbral oscillating elements and to propagate outwards forming concentric circles around the elements. The propagation velocity is between 6 to 18 km s⁻¹ and the average period is about 190 sec.

1. Introduction

Running penumbral (RP) waves were first reported by Zirin and Stein (1972) and by Giovanelli (1972). Zirin and Stein identified the RP waves as running intensity waves, observed in Hα center, with period around 300 sec and constant velocity around 10 km s⁻¹. On the other hand, Giovanelli (1972) studied the waves as oscillations in velocity using findings from the subtraction of the red-wing of Hα from the blue one. He found that the penumbral wave contains a vertical velocity oscillation which is symmetric about zero and has an amplitude of a few kilometers per second. The propagation velocity was about 20 km s⁻¹.

Since then, the waves are observed in Hα as narrow alternate bright and dark bands, concentric to the edge of the umbra. The alternate darkening and brightening in the wave is produced mostly by doppler shifting of the Hα absorption profile in and out of the filter bandpass due to periodic vertical mass motion (Moore 1981). Most authors found that RP waves start out at the inner edge of the umbra and propagate outward through the penumbra. Each wave gradually decreases in visibility as it propagates outward, and seldom can be followed to the outer edge of the penumbra (Moore 1981). Alissandrakis et al (1992) found that the waves start out as full circles around oscillating umbral elements with a size of 2-3" and propagate in all directions within the umbra; when they reach the penumbra, they propagate in regions with a regular fibril structure.

The horizontal propagation velocity of penumbral waves is typically in the range 10-20 km s⁻¹. In order to understand the nature of the waves, one im-
Figure 1. Hα image of a large isolated sunspot observed near disk center on August 15 1997 (top). The same image processed in order to enhance running penumbral waves (bottom).
important question must be answered: is there an acceleration or deceleration in the propagation of the waves? Unfortunately, the results are inconclusive. Lites (1992) reviewed more recent results; he mentioned observations of a decrease in frequency as the waves move outward. However Brisken and Zirin (1997) found, recently, that the waves decelerate from 25 to 10 km s$^{-1}$ as they travel through the penumbra.

According to Zirin and Stein (1972) the RP waves are best observable in H$\alpha$ center. Moore and Tang (1975) found that they are much more noticeable in the blue wing. The wavelength where they are best observed could clarify the mechanism that makes them identifiable and give us indications about their nature.

2. Observations and Image processing

The observations were obtained at the Vacuum Tower telescope of the Sacramento Peak Observatory with a 512 by 512 pixel CCD camera and the UBF filter. The pixel resolution was 0.26$''$. A large isolated sunspot was observed at N14.7, E26.0 on August 15, 1997. Our observations consist of two sequences of filtergrams: the first one has duration 53 minutes and was obtained in H$\alpha$ center and $\pm0.5$ Å. The time interval between successive images of the same wavelength
Figure 3. Original image (upper left) and subtraction images showing the generation and propagation of a wave.

was 12 sec. The duration of the second sequence was a few minutes; filtergrams was obtained at 9 wavelengths along the Hα profile (±0, ±0.35, ±0.5, ±0.75, ±1.0 Å). The time interval between successive images of the same wavelength was 36 sec.

In order to remove the sharp intensity gradient between the umbra and the penumbra and enhance time varying phenomena, we applied a subtraction image processing technique. First, we used a cross correlation algorithm in order to position the images with great accuracy. Then, we computed a "running local average" over 15 images, 7 before and 7 after the given image, which we then subtracted from this image. The local average covers roughly one period of the waves in order to produce a free of waves background. Subtracting the local average from the original frame results in enhancing the waves (Alissandrakis et al 1992, Briskin and Zirin 1997).

3. Results and Discussion

The filtering technique of the "running local average" has successfully applied in the whole amount of the images and the results are impressive. The running penumbral waves, as well as the details inside the umbra are clearly revealed (figure1). Comparing the original image with the processed one in figure 1 we
verify that the same wavefronts can be observed in both. The only difference is that in the processed image the wavefronts could be better identified. That is the method we used makes the waves much more noticeable and not introducing artifacts.

We observed the running penumbral waves to start out from umbral oscillating elements and to propagate outwards forming full concentric circles around the elements (figure 2). The waves propagate through the umbra and the penumbra and we have indications that they reach beyond the outer edge of the penumbra, at the superpenumbra but this need further investigation. Figure 3 shows the generation and propagation of a wave.

In order to measure the propagation velocity of the waves, we drew the wavefronts on transparencies and subsequently we measured the distance between the position of the same front in consecutive images at a number of points along the front. We found that the velocity is between 6-18 km s\(^{-1}\) and the mean period is 190 sec. The velocity is increasing as the wave is propagating outwards up to a point; subsequently is decreasing. The period shows a similar behavior. If we accept that the disturbance is propagating along the magnetic field, then this behavior could be related to projection effects relative to the geometry of field lines. Another possibility is that the propagation of the disturbance is associated with the reversed Evershed flow. Brisken and Zirin (1995) found that the propagation velocity of the waves on the limbward side of a spot away from disk center was significantly greater than on the side near the disk, which enhances the above possibility.

From the second sequence of images (9 wavelengths along the H\(\alpha\) profile) we found out that the waves are best observable in the H\(\alpha\) center and in the blue wing \(-0.35\AA\), of the H\(\alpha\). This indicates that the vertical mass motion is primarily upward and that the oscillation is not symmetric about zero.

Our analysis is in progress, in order to examine the possible association of RP waves to the Evershed effect.

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References

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