OBSERVATIONS OF SUNSPOT UMBRAL VELOCITY OSCILLATIONS

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Abstract. Sunspot umbral molecular lines have been used to look for the oscillatory velocities in the umbra. Power spectrum analysis showed conspicuous power for periods in the range between 448 and 310 s. The maximum peak-to-peak amplitude of the umbral oscillatory velocity component is observed to be in the order of 0.5 km s^{-1}.

1. Introduction

It has been a long standing problem in solar physics to explain the missing energy due to the presence of sunspots on the Sun. Several theories have tried to explain the energy transport in sunspots, assuming unstable convective, radiative transport or oscillatory (overstable) modes in the presence of strong magnetic fields. This last mode of the energy transport, proposed by Danielson and Savage (1968), seems to be a very promising one and it is possible to observationally test the theory. It has been established by Howard (1967), Sheeley (1971), and Sheeley and Bhatnagar (1971) that in the presence of a magnetic field, such as in plages and in active regions, the amplitude of the oscillatory velocity field is considerably reduced compared to the non-magnetic regions on the Sun. In the stronger sunspot fields the amplitude may be further reduced if it is a monotonic function of the magnetic field strength. The first indication of such a reduction was seen in the observations of Howard *et al.* (1968). In an earlier work one of us (Bhatnagar, 1971) tried to look for the oscillatory velocity field in sunspot umbrae, using the Mount Wilson magnetograph and the λ 5250 and λ 5123 ($g=0$) lines. The amplitude of the oscillatory velocity observed with these lines is considerably reduced in umbrae and, also, some evidence for a fluctuating velocity field was noticed. However, as it was not possible to completely remove the influence of the photospheric stray light from the velocity data, the results of the observed oscillatory velocity were considered very tentative.

In the present study we have used lines which are formed only in the sunspot

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umbrae and show no Zeeman splitting. Thus our present velocity measurements are free from any cross talk introduced by photospheric and penumbral scattered light. In addition, since the lines show no Zeeman splitting, there can be no modulation introduced by varying field strength as might occur with a slight change of position within the umbra.

2. Observations

The magnetograph in conjunction with the 82-cm image of the Kitt Peak National Observatory was used for the velocity field observations in sunspot umbrae (Livingston, 1968). In the Doppler mode the velocity signal is obtained as the encoder readout of the Doppler servo. The error signal for this servo is derived from the difference of the wing intensities. Simultaneously the sum of the wing intensities is also obtained. The Doppler (difference) and the intensity (sum) signals are displayed on a CRT and recorded on magnetic tape for later data analysis. These observations were made using a fixed, i.e. non-scanning, aperture of $2.5 \times 2.5''$. The sunspot umbra was centered on the aperture and the solar image was photoelectrically guided. To compensate for solar rotation, the image was periodically moved eastward. Visual monitoring of the wing intensity channel greatly helped in following the same region of the umbra. Most of the observations were made for a period of 4096 s, with a sampling interval of 1 s in time. The same spot was observed both on November 22 and 23, 1971. The spot was isolated and round, located at E4, S6 with a maximum magnetic field strength of +2500 G on November 23, according to Mount Wilson measurements. The umbral diameter was about 14″. As the spot was near the central meridian on November 23, the measured umbral velocity component is essentially vertical, normal to the solar surface.

Three sunspot umbral lines, λ 6021.037, λ 6525 and λ 6910 were selected from a photographic sunspot atlas made by one of us (JWH). Because the lines were not detectable in the photosphere and showed no Zeeman effect, we believe that they are molecular in origin, but no definite identification is available (Sotirovski, 1972). For comparison purposes and to determine the spectrograph drift and noise characteristics due to atmospheric pressure, temperature changes and seeing, we have interlaced the umbral velocity observations with similar runs on telluric lines. Figure 1 shows a typical run of the velocity and the wing variations in sunspot umbra in the λ 6021.037 line observed on November 23. Figures 2 and 3 show the velocity and intensity runs on the telluric line λ 6290.2 and photospheric line λ 6518.6 (Fe I), both taken at the center of the disk and outside of an active region. The velocity run in the sunspot umbra (Figure 1) shows conspicuous velocity oscillations, although considerably reduced in amplitude (maximum peak-to-peak amplitude of 0.5 km s^{-1}) compared to the photospheric 5-min oscillations (Figure 3). The velocity data also contain a slow drift which is due to spectrograph drift in wavelength. A careful examination of the wing intensity runs show a periodic brightness variations of small amplitude in both phtospheric and telluric lines. We believe that this is a manifestation of the known continuum brightness oscillations (cf. Tanenbaum *et al.*, 1969).

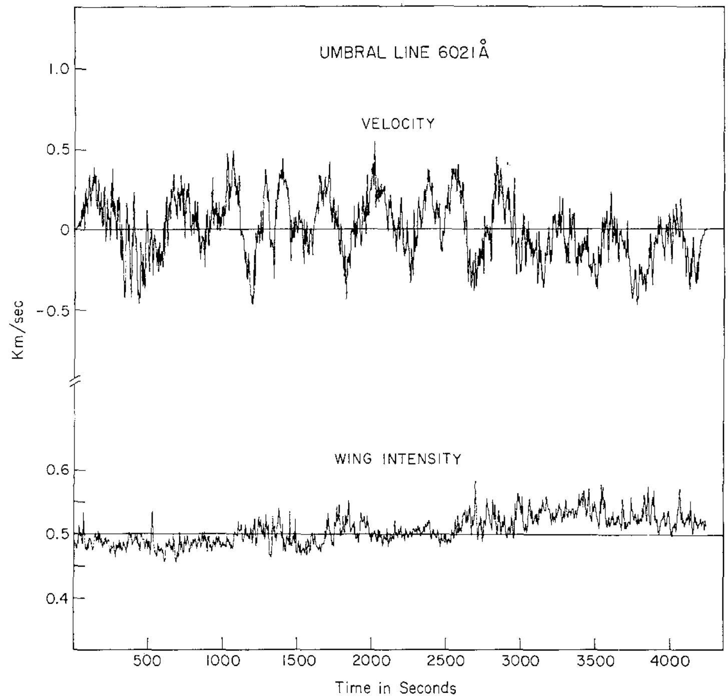

Fig. 1. Velocity oscillations and line wing intensity variations with time in a sunspot umbra, using the umbral line λ6021.037.

3. Power Spectrum Analysis and Discussion

For the power spectra analyses we have used the program described by Brault and White (1971). The total number of data samples in each observation was generally 4096 but for some runs we had only 2048 samples. Power spectral analyses of all the raw data runs showed essentially 'white noise' for frequencies higher than 0.06 Hz. To account for the finite length of the observations and to obtain a closer approximation to the true power spectrum, we have smoothed all power spectra runs in the following manner (Blackman and Tukey, 1959);

$$U_h = 0.23\, L_{h-1} + 0.54\, L_h + 0.23\, L_{h+1}\,.$$

In Figure 4a are shown the power spectra of the velocity shift using the umbral line λ 6021.037 and the telluric line λ 6290.2. Both telluric and umbral lines show significant peaks in the low frequency part of the spectrum due to the slow spectrographic drift in wavelength. To see whether there was any 'cross talk' between the velocity and the intensity channels, we have also obtained power spectra for the wing intensity data for both umbral and telluric lines and are given in Figure 4b. Besides the large peak towards the low frequency end of the spectrum and which is due to the systematic increase in brightness with zenith angle of the Sun, there is a fairly significant peak

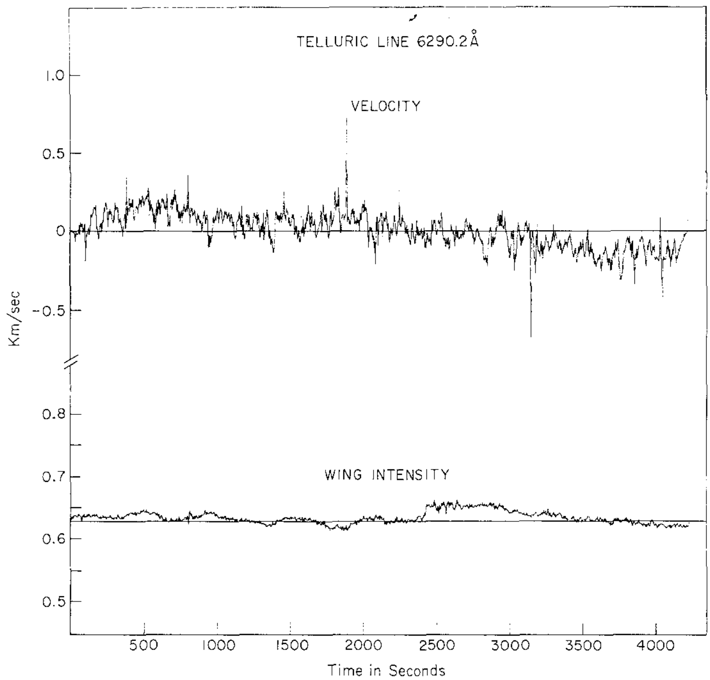

Fig. 2. Observations of velocity and line wing intensity with time, using the telluric line λ6290.2. The spikes in the velocity record are instrumental artifacts.

around 768 s and much less significant peak near 490-s period for the umbral line. The telluric line also shows a less significant peak around 512-s period in intensity power spectrum. The peaks around 768 s and 490 s in the umbral line and around 512 s in the telluric line may be of some real significance, but our interest here is in whether the intensity fluctuations could have appeared in the velocity records. The dissimilar appearance of the velocity and intensity spectral seems to rule out such cross talk.

Comparing the power spectra (Figure 4a) of the velocity shift of umbral and the telluric lines, it is clear that there is a very significant peak around 448 s in the umbral spectrum. In Figures 5 and 6 are shown power spectra of the velocity data using the umbral lines λ 6525 and λ 6910. Both these lines indicate a peak power around 310-s period in the umbra. Figure 7 shows a power spectrum of the photospheric velocity made near the disk center using the λ 6518.6 line. A peak around 350 s is seen corresponding to the resonance peak of the photospheric velocity oscillations.

From the power spectra analysis of the velocity using the three umbral lines, it is clearly seen that conspicuous peak power appears around 448-s and 310-s periods. The fine structure of the power spectra depends on the bandwidth of the observations, e.g. for file No. 2 we had a bandwidth of 4.9×10^{-4} Hz, while for file No. 6 and No. 11, the bandwidths were 1.2×10^{-4} and 2.4×10^{-4} Hz respectively. The file No. 6 shows narrower peak compared to file No. 11. The broad peaks seen in the

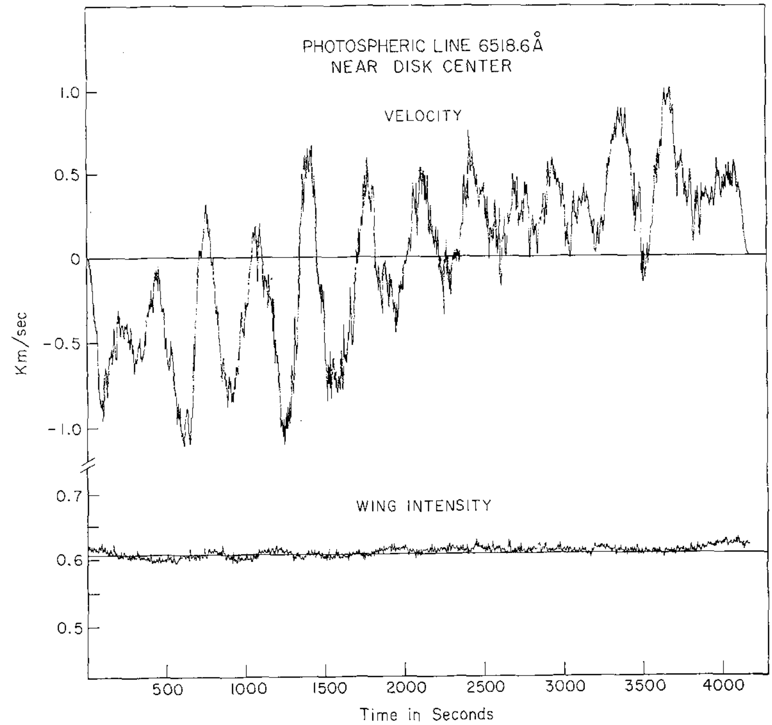

Fig. 3. Velocity oscillations and line wing intensity variations with time at the disk center using the photospheric line λ6518.6.

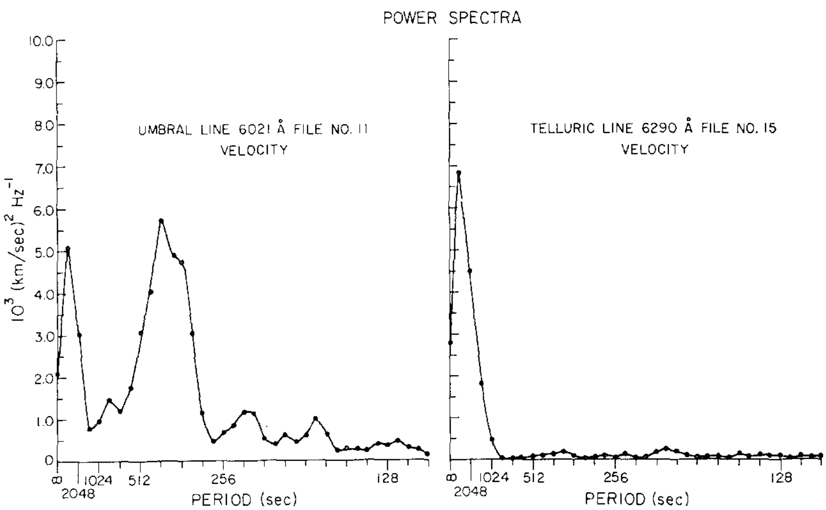

Fig. 4a. Power spectra of velocity shifts using the umbral line λ6021 and the reference telluric line λ6290.2.

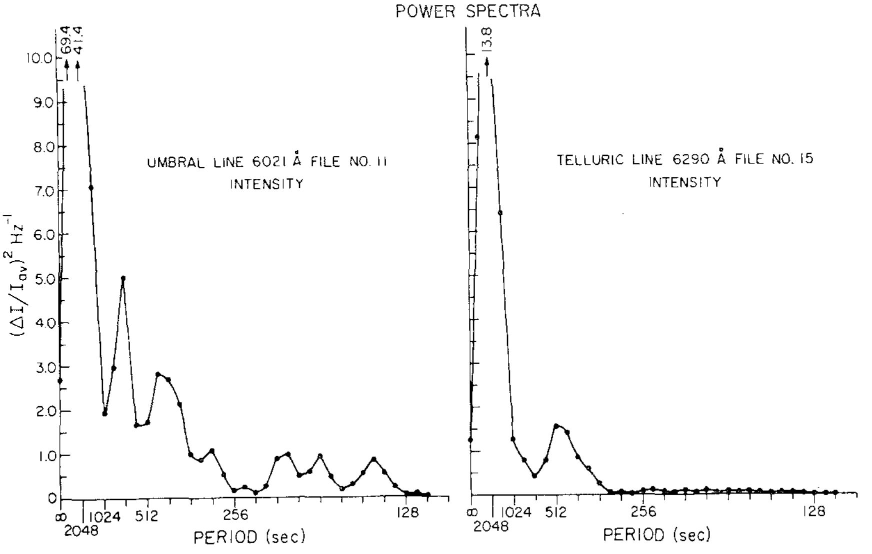

Fig. 4b. Power spectra of the line wing intensity, using the umbral line λ6021 and the telluric line λ6290.2.

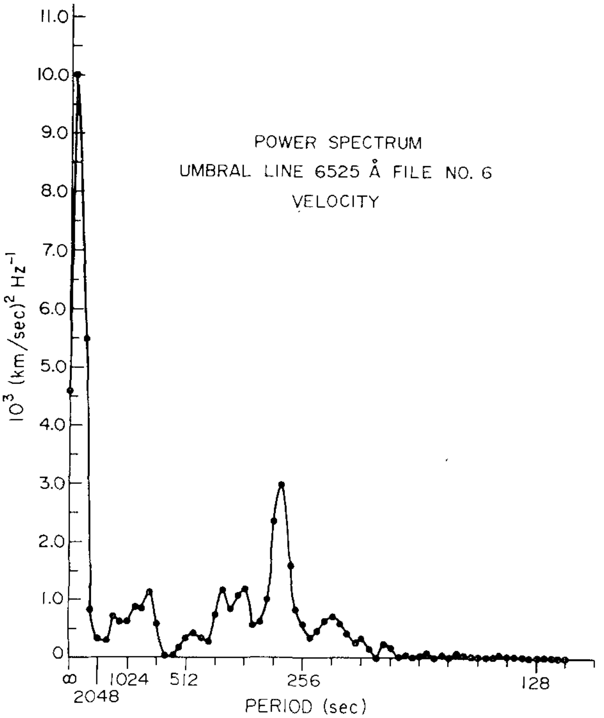

Fig. 5. Power spectrum of the umbral velocity using the umbral line λ6525.

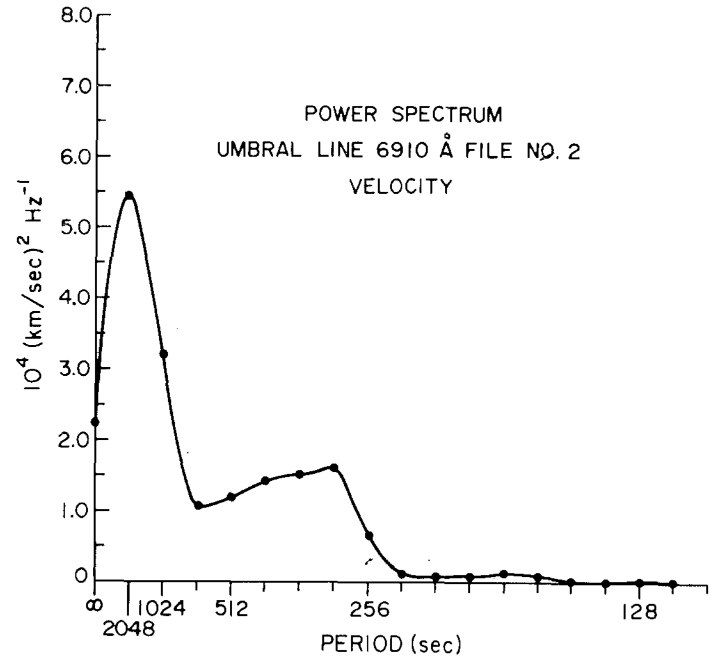

Fig. 6. Power spectrum of the umbral velocity using the umbral line λ6910.

power spectra of λ 6021 and λ 6525 lines perhaps result from an interaction of two or more oscillating wave trains. The resultant spectrum would appear as a modulated wave pattern type of the same general character as found for the photospheric velocity oscillations by Gonczi and Roddier (1969).

The two lines λ 6525 and λ 6910 show periods around 310 s, while the λ 6021 line gives a period around 448 s .This observed difference in the period of these three lines may be either due to the variation in the height of formation of these lines or due to the phase fluctuation of the modulating wave trains from one record to another.

These observations clearly show the presence of purely umbral velocity oscillations with periods around 440 and 310 s. In an earlier investigation one of us (Bhatnagar, 1971) observed using the λ 5250 and λ 5123 lines, a slight indication of umbral velocity oscillations with period on the order of 180–220 s. Recently, Beckers and Schultz (1972) have observed, using a photographic technique, a significant peak around 180-s period in a non-Zeeman line. Bhatnagar and Tanaka (1972) have observed intensity oscillations with period on the order of 190 ± 66 s in sunspot umbra from the time lapse filtergram movies made in the wing of Hα line (H$\alpha - 0.5$Å). It seems that observations of Beckers and Schultz, and Bhatnagar and Tanaka refer to the sunspot atmosphere where the strong absorption lines are formed. At these levels the high frequency (periods on the border of 180–200 s) oscillations become significant, while at the level of formation of the faint umbral lines used in this investigation, the low frequency (periods on the order of 440–310 s) oscillations are more important.

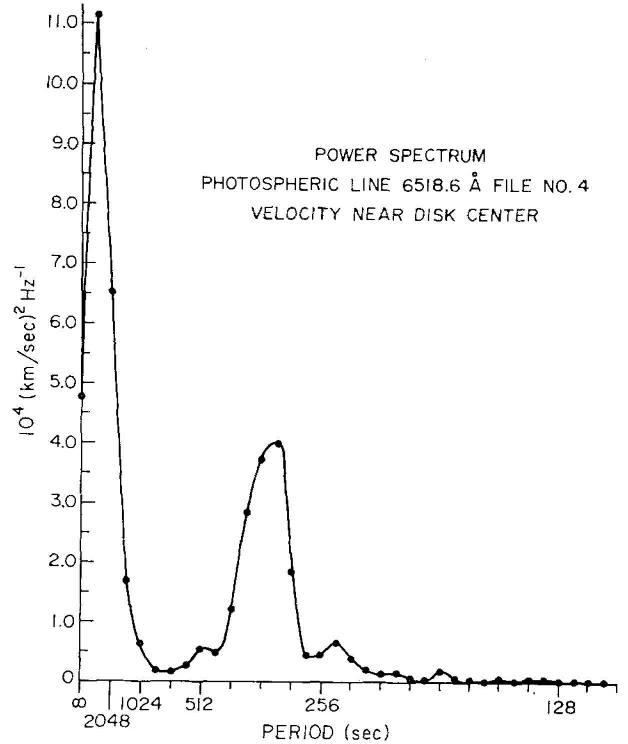

Fig. 7. Power spectrum of the velocity at the disk center using the photospheric line λ6518.

Recently, Stein and Zirin (1972), observed an outward horizontal propagating wave motion in sunspot penumbrae on Hα time lapse movies. These waves have a velocity on the border of 8–12 km s^{-1} and they seems to originate at a quasi-periodic interval of 4–5 min, from the umbra-penumbra border. It appears that the source of this wave motion lies in the umbra. Perhaps the observed vertical oscillatory motion in umbra is responsible for 'pumping' out these horizontal waves in the penumbral region. A transformation of the vertical umbral oscillation into horizontally moving penumbral waves might take place at the interface of the umbra-penumbra border. Further observational and theoretical studies are required to understand these interesting wave phenomena in sunspots.

Acknowledgements

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