OSCILLATIONS AND WAVES IN A SUNSPOT

R. G. GIOVANELLI
CSIRO Division of Physics, National Standards Laboratory, Sydney, Australia 2008

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Abstract. Observations have been made in Hα of the vertical velocity distribution in a sunspot. Over the umbra the pattern consists of structures of scale-size 2–3″. The velocity distribution undergoes oscillations with a period of about 165 s and typical amplitude ± 3 km s^{-1}, but the pattern breaks down after one or two cycles because the period of oscillation varies typically by ± 20 s from place to place. Transverse waves develop in the outer 0.1 of the umbral radius and propagate outwards with a velocity of about 20 km s^{-1}, becoming gradually invisible by or before the outer penumbral boundary; the amplitude is about ± 1 km s^{-1} at the umbra-penumbra border.

The penumbral waves are believed to be basically of the Alfvén type, with $\varrho \approx 3 \times 10^{-8}$ g cm^{-3}. The umbral oscillations presumably represent gravity waves. In both cases the fluxes are inadequate by two orders of magnitude to account for the sunspot energy deficit.

1. Introduction

Beckers and Tallant (1969) described rapidly changing inhomogeneities ('umbral flashes'), of average diameter about 3″, in the H and K lines above sunspot umbras. These were visible in filtergrams obtained with a passband of 0.3 Å centred on the K line, but they were hardly visible, or even invisible, in Hα filtergrams. Many umbral flashes tended to repeat at regular intervals in the same location, one repeating as many as 18 times. The average time interval between repeating flashes was 145 s, but individual flashes had repetition times as short as 110 s or as long as 190 s. Spectra showed vertical velocities which were mainly upwards, of the order of 6–7 km s^{-1} at the time of maximum brightness, but briefly downwards shortly before the rise to the next brightness maximum.

In Hα one can find somewhat analogous phenomena which may be related to the H and K umbral flashes. These are revealed not so much as intensity fluctuations but as oscillations in velocity, seen by comparing narrow-band filtergrams obtained at similar positions in opposite wings of Hα. Since differences are due solely to Doppler shifts, subtraction of one filtergram from the other shows the pattern of line-of-sight velocities (Giovanelli and Jefferies, 1961; Leighton *et al.*, 1962).

Observations of this type have been made with the Culgoora 12-in. telescope and a Halle 0.55 Å Hα filter, modified so as to present side-by-side for simultaneous photography, two images of a portion of the Sun separated in wavelength nominally by 0.55 Å. For this the filter has been reversed from its usual orientation, so that light passes first through the 1.1 Å contrast element. The end polarizer of the 0.55 Å element is replaced by a polarizing beam splitter, this yielding two beams of orthogonal linear polarizations and hence of mean wavelengths separated by the pass-band of the final element (0.55 Å); the transparencies of the two paths in the beam splitter have been made identical to better than one per cent. To tune the filter, a

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$\lambda/2$ plate is rotated between the filter and beam splitter; this is normally adjusted so that the two polarized beams are equally spaced on either side of line centre.

When due allowance is made for the shape of the Hα profile, the mean wavelengths of the two beams then lie at $\Delta\lambda = \pm 0.25$ Å. The advantage of having simultaneous observations in the two wings is compelling: the two images are identically affected by seeing, so that no spurious velocity can be introduced, though the velocity pattern may, of course, be blurred by poor seeing.

2. Oscillations in a Stable Sunspot Umbra

Observations were made on 3 November 1971 to study in some detail the Hα velocity pattern in a stable sunspot, then at 11°N 31°W. This spot had appeared first at the E limb on 28 September, 1971. In its second rotation, the spot retained a fairly uniform size and shape during its passage across the disk. The spot was sufficiently close to disk centre for the observations to refer primarily to vertical components of the motion.

Photographs were obtained on Kodalith Pan film with an exposure appropriate to the normal chromosphere and the brighter sunspot features, followed 3 s later by a denser exposure aimed at showing the Hα umbral core. This sequence was repeated at 0.5 min intervals between 0118 and 0320 UT, during which the seeing was largely mediocre, though with some short good periods. Both exposure times turned out to be adequate for yielding qualitative umbral velocity pictures.

Figure 1a shows a composite Hα photograph of the sunspot obtained by superimposing two low-gamma transparent prints from opposite wings. The effects of Doppler shifts which decrease the intensity in one wing and increase it in the other are thereby greatly reduced (though not completely eliminated), and 1a approximates a filtergram obtained with a pass band of about $\frac{3}{4}$ Å centred on Hα. Figure 1b shows similarly the core of the sunspot in Hα.

Figures 1c, d show for the umbra the difference between photographs obtained in the two wings; these have been obtained by photographic subtraction and show the umbral velocity pattern in the sense that dark features represent receding (or downwards) motions, and bright features are approaching (or rising). Figures 1c, d were obtained respectively from the denser and lighter exposures with a 3 s time difference. The patterns are intricate and closely similar, differences being due primarily to substantial decreases in photographic gamma for densities below 1.0 in the original negative (lowering the sensitivity in the core of Figure 1d), and to saturation effects which limit the range of the photographic subtraction process in 1c to a slightly smaller part of the umbral core than in 1d. In no case has any significant change in umbral velocities been detected in intervals of 3 s. The agreement leads to substantial confidence in the significance of the velocity patterns.

Figure 2 shows an array of velocity patterns in the umbra, at 0.5 min intervals over a period of 20 min, obtained by TV subtraction of the normal-exposure frames. The pattern is confined to about 75% of the umbral diameter due to the limited dy-

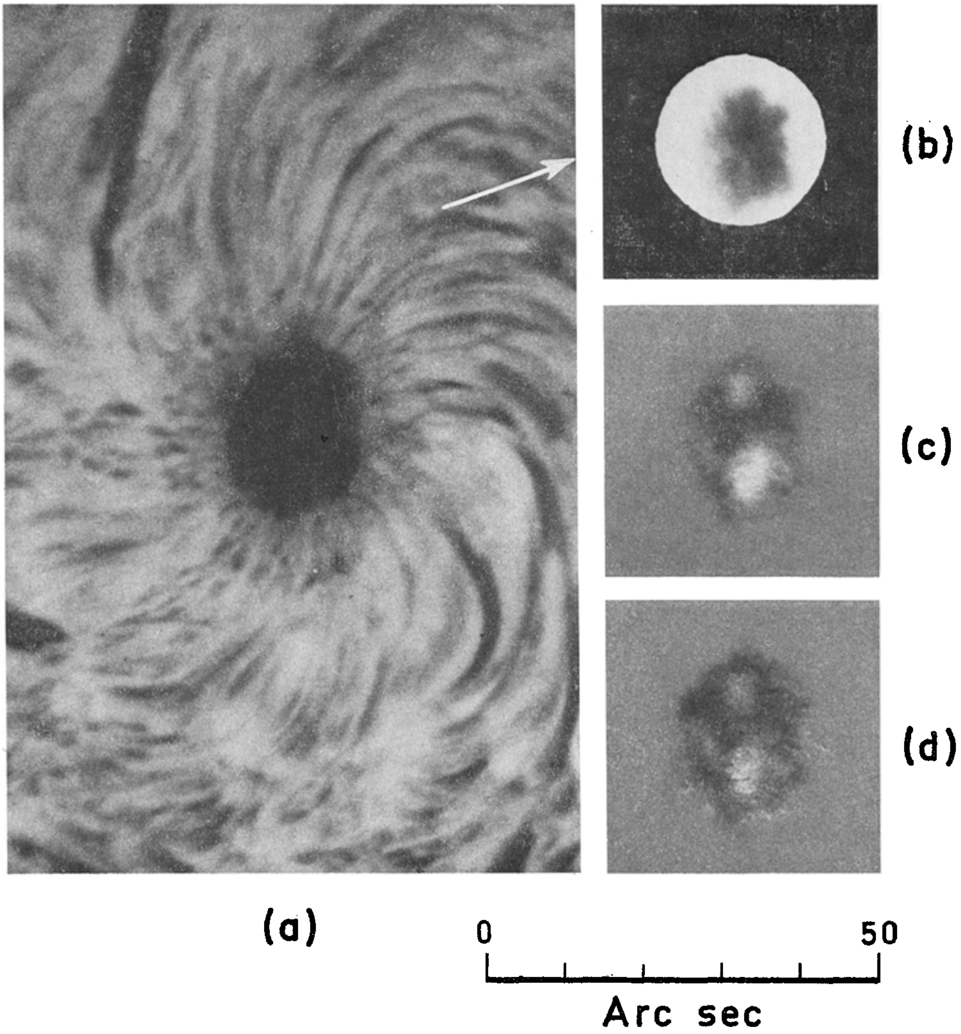

Fig. 1. (a) Composite Hα filtergram of sunspot at 11°N 31°W on 3 November, 1971. Arrow shows direction to solar limb. (b) Core of umbra in Hα. (c) Velocity distribution in umbra, such that dark represents downwards (line-of-sight) motion and bright represents upwards (approaching) motion. (c) was obtained by photographic subtraction of pictures obtained at mean intervals of 0.25 Å from Hα line centre in the red and blue wings. (d) Velocity distribution 3 s after (c); (d) was obtained from denser pictures than (c), but reveals effectively the same velocity distribution as (c).

namic range of the subtractor. The seeing varied considerably over this time, being best in frames 2c–3b, and poor around frame 4e.

Between consecutive frames there are striking changes which do not originate in the seeing. The patterns also exhibit obvious oscillatory tendencies. For example, the pattern in 2b differs only very slightly from 1b, and 6c from 5c. The period is close to 165 s. Figure 2 has been set out in an array in which neighbouring frames in the

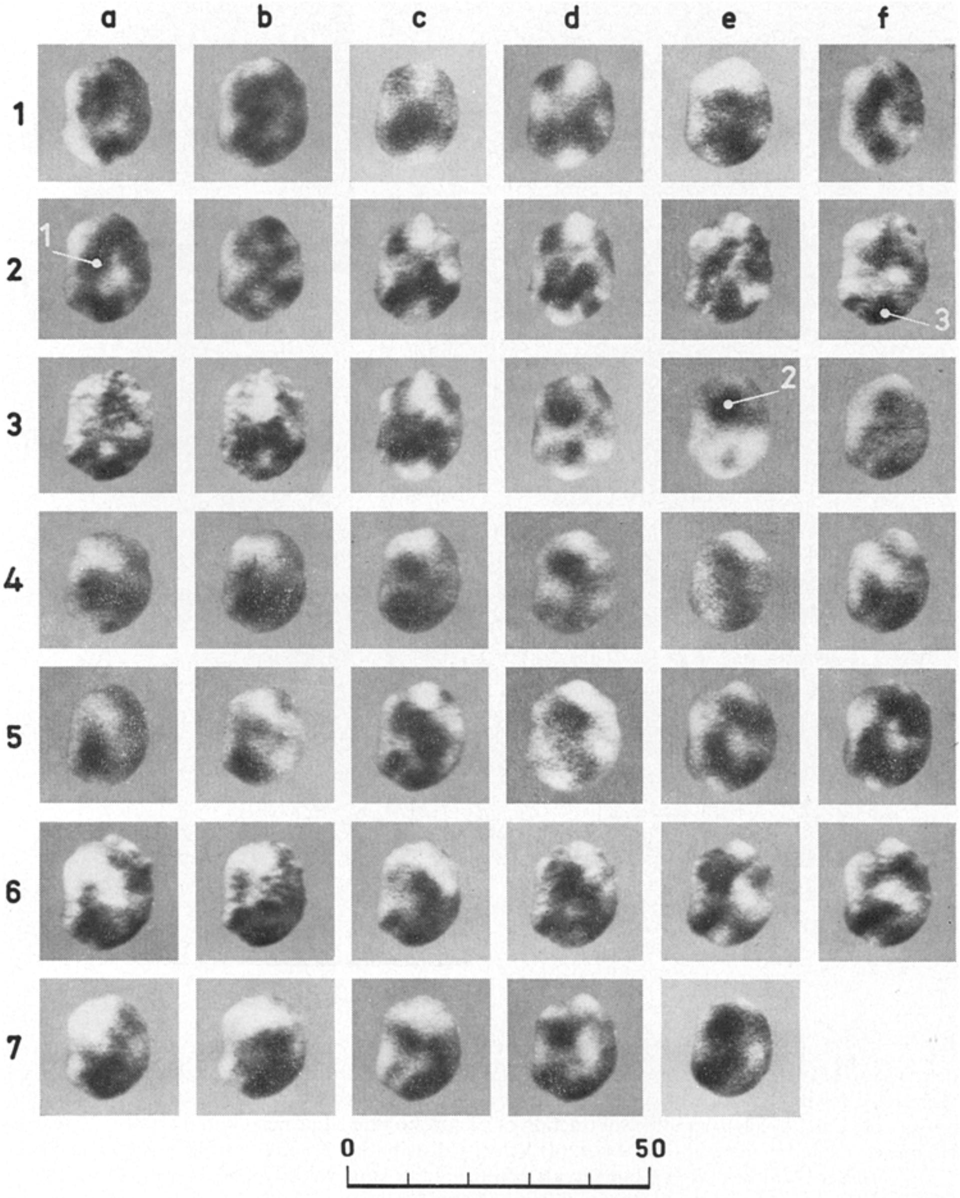

Fig. 2. Array of Hα velocity photographs of the umbra at 30 s intervals, obtained by TV subtraction. The sharp boundary is due to instrumental saturation. Dark (downwards moving) point No. 1 (Table I) indicated on 2a is oscillatory, with maximum downwards velocities on the following frames: 1b, 2a, 2e, 3c, 4b, 5a, 5f, 6d. Two other oscillatory points are 2 (frames 1a, 2a, 2f, 3e, 4d, 5d, 6e) and 3 (frames 1a, 2a, 2f, 3f, 4f, 6a, 7b).

same column represent 3 min time differences, so that the oscillatory tendency becomes evident. However, the time over which a particular oscillating pattern can be followed is about one or two periods at most. Some of the velocity patterns are degraded by seeing, but the general behaviour is clear. Individual elements of the pattern are of the order of 2–3″ in diameter. While the best frames in the original photographs have resolutions of the order of 1″, some resolution is inevitably lost in the subtraction process. Nevertheless the oscillations do appear to be coherent over regions of typical size 2–3″.

While the velocity pattern as a whole changes markedly after about 2 cycles, individual elements can be followed much longer. Table I sets out data for 3 points indicated in Figure 2. Many other examples of long-lived oscillations may be seen in this figure. The ability to follow oscillatory motion at a given point depends very much on seeing and on the behaviour of the motions at adjacent points. Hence the values in column 2 are minima, and are not necessarily approximations to the actual numbers of cycles of the oscillations: observations over much more extensive periods of good seeing are needed to establish this. The uncertainties listed in the final column are estimated on the basis of an uncertainty of ±1.0 min in timing an integral number of oscillations. It appears highly unlikely that an error of twice this magnitude will occur. It follows that the period of oscillation varies significantly from point to point across the umbra.

TABLE I

Oscillations of individual points in the umbra

Point	Number of cycles	Period of oscillation
1	7	137 ± 9s
2	6	185 ± 10
3	6	185 ± 10

No systematic trend in period with location in the umbra has been discovered in these preliminary observations.

3. Penumbral Waves

Figure 3 shows photographic subtractions aimed at revealing velocities in regions of normal chromospheric intensity. These cover penumbral regions also, and many of the features of the umbra.

Near the umbral-penumbral boundary may be noted elongated velocity structures A, B, C where, over regions of length of perhaps 10–20″ and width 2″, the velocity is of the same sense. In some cases a region of downward velocity (dark) is bordered by a similar region of upward velocity. The locations of the velocity maxima change progressively from frame to frame, as may be seen from the change in positions of the arrows pointing to the same velocity structures. These are clearly waves moving

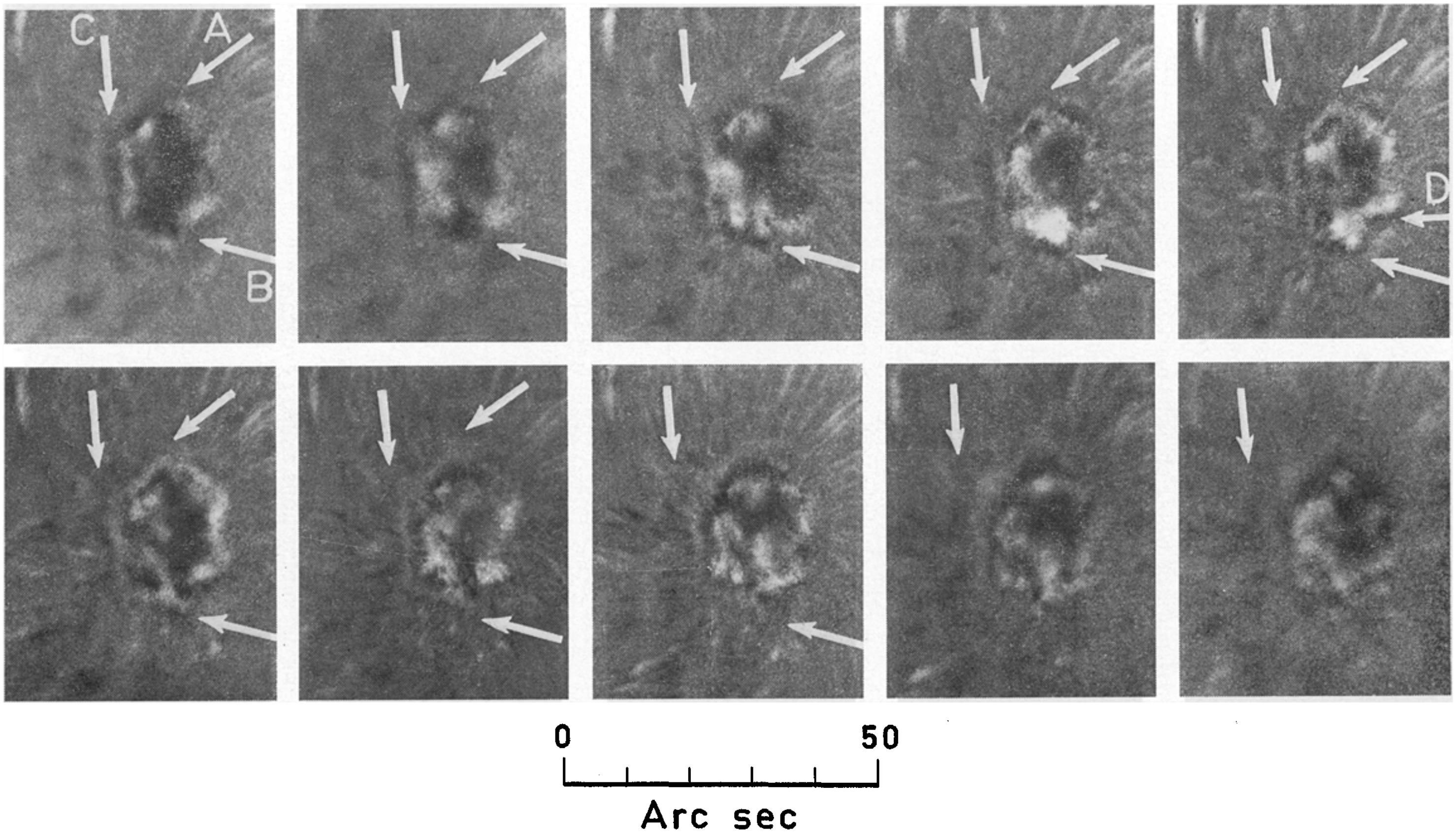

Fig. 3. Array of photographic subtractions showing velocity distribution across sunspot and surrounding regions at 30 s intervals. A, B, C and the corresponding arrows on the various frames point to and lie in the same lines as progressive positions of wave fronts moving outwards from the umbra across the penumbra. The wave velocity has also been measured for wave D.

outwards across the penumbra, the velocities being listed in Table II. The period is of the order of 210 s, but it is difficult to measure precisely and the difference from the typical period of the umbral oscillations is not necessarily significant.

The location of these waves has been established by blink comparator. The regions shown as A, B and C all lie in the penumbra, near its boundary with the umbra. Near region B it has been possible to detect the waves out to about half-way from the inner to the outer penumbral boundary, and at C they have been followed to about the outer edge of the penumbra. The amplitude of the waves drops rapidly as they progress outwards. Attempts have been made to search for accelerations in the wave fronts, but the results are inconclusive.

TABLE II
Velocities of penumbral waves

Feature	Velocity (km s^{-1})	
	Uncorrected	Corrected for foreshortening
A	15	15
B	18	18
C	17	20
D	25	25

The origin of the waves is in the outer part of the umbra, between about 0.9 R and 1.0 R, where R is the umbral 'radius'. Inside 0.9 R the velocity pattern in the umbra does not appear to show systematic wave motions across the umbra. However, near the umbral-penumbral boundary there is sufficient continuity for the penumbral waves to run smoothly out of the umbral oscillations.

4. Line-of-Sight Velocities

The line-of-sight velocity is not easy to measure, particularly as no density strips were incorporated in the observations. Approximate calibrations show that, in the umbra, the typical velocity amplitude is of the order of ± 3 km^{-1} s. In the penumbral waves, the line-of-sight velocity is less, of the order of 1 km^{-1} s near the umbra-penumbra boundary and dropping off rapidly as the waves progress outwards.

5. Discussion

The energies or powers involved in the oscillations or waves can be deduced if we make some likely assumptions about the modes involved.

The penumbral waves appear to be more-or-less horizontal with velocities substantially above the presumed velocity of sound, so that acoustic modes and other modes involving gas pressure (such as horizontal gravity waves) can be eliminated. Since the line-of-sight velocities are more-or-less perpendicular to both the direction of propagation and the presumed direction of the penumbral magnetic field, almost certainly the observed penumbral waves are basically of the Alfvén type, with wave velocity V given by

$$V^2 \approx B^2/4\pi\varrho .$$

For the mean observed $V \approx 20$ km s^{-1}, and an assumed magnetic field $B \approx 1250$ G,

$$\varrho \approx 3 \times 10^{-8} \text{ g cm}^{-3} .$$

The wave energy density is $\frac{1}{2}\varrho v^2$, where v is the peak line-of-sight velocity, and the wave energy flux is $\frac{1}{2}\varrho v^2 V$ per unit area normal to the direction of propagation or 3×10^8 erg cm^{-2} s^{-1} for $v = 1$ km s^{-1}. The corresponding figure for photospheric radiation is 6.4×10^{10} erg cm^{-2} s^{-1}, so that the power per unit cross section in the *penumbral* waves is small by comparison with that of photospheric radiation; these particular waves carry inadequate power to account for the energy deficit of a sunspot.

The reduction in the observed amplitude as the penumbral wave progresses outwards is most unlikely to be due to dissipation. Also, the total flux in the wave is given by $\frac{1}{2}\varrho v^2 VA$, where A is the cross section. But A varies as B^{-1}, so that $\varrho v^2 VB^{-1}$, and hence $\varrho^{1/2} v^2$, is invariant. Since the density must decrease as the wave rises gradually upwards along the field lines as it travels outwards, we would expect v to increase, not decrease! The difficulty may possibly be resolved by noting that the optical depth in Hα is very likely to decrease following the (inclined) field lines outwards and therefore upwards, so that the effect of v on the Hα profile becomes less and less and is probably negligible outside the penumbra.

Although we have no direct evidence as yet that in the core of the umbra the observed oscillations form part of a travelling wave system, the observed penumbral waves originating in the outer 10% of the umbral radius make this seem very probable. There is certainly no evidence that the energy of oscillations in the umbral core is dissipated *in situ*. Because the observed velocities are more-or-less vertical with no detected horizontal propagation, it appears highly probable that, at least in parts of the umbra, the motions are parallel to the magnetic field. In such cases, coupling with the magnetic field is reduced, and may be negligible; the wave mode is effectively identical with that in the well-known photospheric oscillations. If the oscillations are adiabatic in a medium where the undisturbed temperature is isothermal, the vertical group velocity is (e.g. Lamb, 1932)

$$U = C_s (1 + \tfrac{1}{4} k^{-2} H^{-2})^{-1/2} ,$$

where C_s is the velocity of sound, $2\pi k^{-1}$ is the wavelength, and H the scale height of the atmosphere. This may be rewritten

$$U = C_s (1 - \tfrac{1}{16} \pi^{-2} t^2 \gamma^2 g^2 C_s^{-2})^{1/2} ,$$

where t is the period, γ the ratio of the specific heats and g the acceleration due to gravity. With $t = 165$ s, $\gamma = \frac{5}{3}$, $g = 2.74 \times 10^4$ cm s^{-2} and $C_s = 8.3 \times 10^5$ cm s^{-1} (corresponding to a neutral hydrogen gas at 5×10^3 K), then

$$U = 5.8 \times 10^5 \text{ cm s}^{-1}.$$

Since the velocity is real, we have confirmation that the observed umbral oscillations may be part of a running wave system. The appropriate density is uncertain, but if we adopt the same value as found in the penumbral waves, the power per unit area in the umbral waves, with a peak amplitude $\approx 3 \text{ km s}^{-1}$, becomes $8 \times 10^8 \text{ erg cm}^{-2} \text{ s}^{-1}$, appreciably greater than in the penumbral waves but still quite inadequate to account for the sunspot energy deficit. One cannot give a precise temperature for the Hα umbra either, though it may be well below 5000K. Van 't Veer's (1966) and Zwaan's (1968) sunspot models both indicate that at low enough optical depths in the continuum the temperature may be of the order of 3000K, at which U is substantially reduced. If this temperature applies to the Hα umbra, the power in the umbral waves is $3 \times 10^8 \text{ erg cm}^{-2} \text{ s}^{-1}$, effectively the same as in the penumbral waves. It is unlikely that the error in Hα umbral density is so great as to invalidate the conclusion that the umbral waves are not the main cause of the spot energy deficit.

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