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Oscillations in Sunspots*

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Abstract

Recent observational and theoretical work on oscillations in sunspots is reviewed. The characteristic 3-minute umbral oscillations and flashes are resonant modes of the sunspot itself, whereas the 5-minute oscillations in the umbra are a passive response to forcing by p modes in the surrounding convection zone. The observational evidence suggests that the fundamental cause of the 3-minute oscillations is the photospheric fast-mode resonance, with chromospheric slow-mode resonances perhaps producing additional oscillation frequencies in the chromosphere. Observations and theoretical models of the interaction of 5-minute p-mode oscillations with a sunspot offer a means of probing the structure of a sunspot magnetic flux tube beneath the solar surface. The observed differences between running penumbral waves in the chromosphere and in the photosphere may be explained by the effect of the Evershed flow on trapped magneto-atmospheric waves in the penumbra.

1. Introduction

Some of Giovanelli's principal contributions to solar physics were concerned with oscillatory phenomena in sunspots. Interest in sunspot oscillations began in 1969 with the discovery of umbral flashes in the Ca II H and K lines by Beckers and Tallant (1969). Then, in the single year 1972, (i) the discovery of running penumbral waves in Hα was reported independently by Giovanelli (1972) and by Zirin and Stein (1972), (ii) 3-minute umbral velocity and intensity oscillations in the photosphere and chromosphere were reported by Giovanelli (1972), Bhatnagar and Tanaka (1972) and Beckers and Schultz (1972), and (iii) 5-minute oscillations in the umbral photosphere were reported by Bhatnagar *et al.* (1972). These discoveries and further work were reviewed by Giovanelli (1974) at the IAU Symposium on Chromospheric Fine Structure. Later, Giovanelli *et al.* (1978) were the first to measure sunspot oscillations simultaneously in two or more spectral lines formed at different heights in the sunspot atmosphere, in order to study vertical propagation and height dependence of the oscillations.

In view of Giovanelli's significant discoveries and contributions to our understanding of sunspot oscillations, it seems especially appropriate to review recent progress in

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this area. Here I summarize current observational and theoretical understanding of oscillations in sunspots, with emphasis on the considerable amount of recent work that has occurred since the reviews by Moore (1981*b*) and Thomas (1981), presented at the meeting on the Physics of Sunspots at Sacramento Peak Observatory in 1981. Considerable emphasis is placed on work by myself and my collaborators and on my own interpretations of sunspot oscillations.

There are two distinct types of oscillations in sunspot umbras: 3-minute and 5-minute oscillations. The 3-minute oscillations, which are manifested both as velocity oscillations and as umbral flashes, are resonant modes of the sunspot itself, whereas the 5-minute oscillations represent the passive response of the sunspot to forcing by the 5-minute p-mode oscillations in the surrounding convection zone (Thomas 1981). The 3-minute and 5-minute oscillations are discussed separately in Sections 2 and 3. Running penumbral waves are discussed in Section 4.

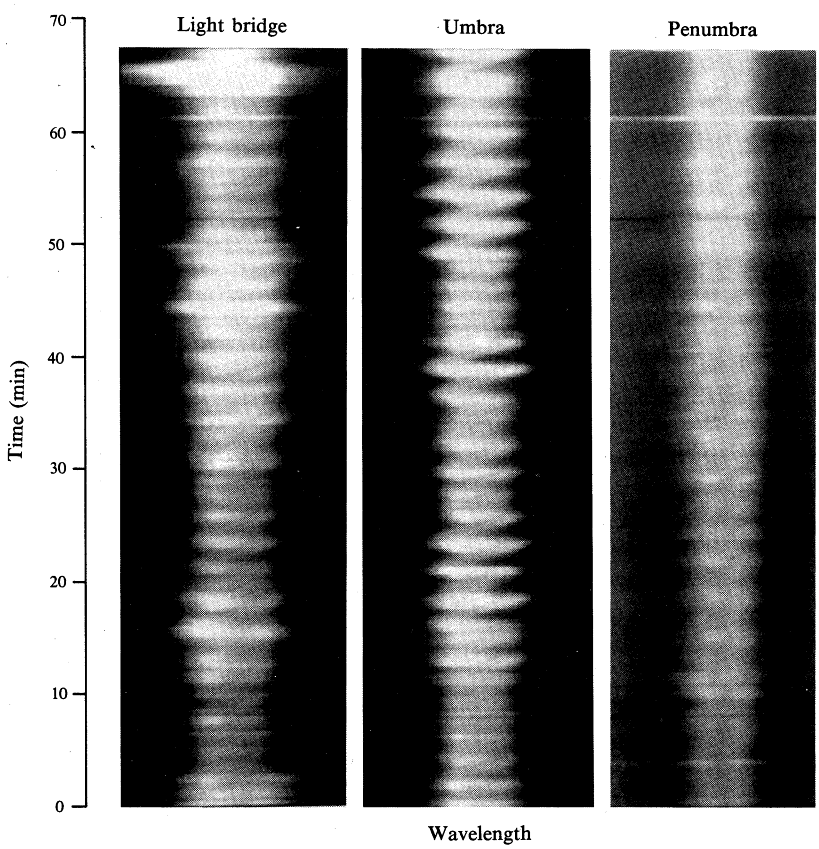

Fig. 1. Computer-generated time-resolved spectra of the Ca II K-line core for three different spatial points in a sunspot: in a light bridge crossing the umbra, in the umbra, and in the penumbra. Three-minute umbral flashes occur regularly in the umbra with a characteristic Z-shaped signature. The umbral flashes are weaker in the light bridge and absent in the penumbra. The light bridge flashes are evident in the light bridge spectrum, with the strongest flash occurring at about $t = 65$ min. A K3 reversal is quite evident in the penumbral spectrum but only weakly evident in the umbral spectrum. [From Thomas *et al.* (1984).]

2. Umbral Flashes and Three-minute Oscillations

The umbral flashes in the Ca II H and K lines were discovered by Beckers and Tallant (1969). These flashes are readily apparent in time sequences of K-line filtergrams of a sunspot umbra and they repeat quite regularly, with periods in the range 140–190 s for different sunspots. The spectrum of the K line during a flash shows a strong brightening of the emission core on the blue side of line centre, which then decays in about 50 s, leaving a weak, narrow emission peak that then shifts to the red side of line centre in about 100 s. This is followed by a new flash on the blue side, and this pattern repeats fairly regularly at a fixed point in the umbra.

The time behaviour of the K-line spectrum is clearly illustrated in the central panel of Fig. 1 (Thomas *et al.* 1984). The three panels show the time-resolved spectrum of the K-line emission core for each of three different spatial points in a sunspot: a point in a prominent light bridge within the umbra, a point in the dark umbra, and a point in the penumbra. The time behaviour of the umbral flashes shows up as a repeating characteristic Z-shaped signature in the time-resolved spectrum for the point in the dark umbra (central panel in Fig. 1). The umbral flashes are weaker in the light bridge and are absent in the penumbra.

A second phenomenon, called *light bridge flashes* (Thomas *et al.* 1984), is evident in the left-hand panel in Fig. 1. These events consist of sporadic, strong brightenings and broadenings of the K-line emission core within the light bridge. The most prominent light bridge flash occurs at about $t = 65$ min. The K-line emission profile during a light bridge flash is broader, more intense, and more symmetric than the profile for a normal umbral flash. It is likely that the light bridge flashes are associated with the surges observed in light bridges in Hα filtergrams by Roy (1973).

Velocity oscillations with periods around 3 minutes have been observed in the umbral photosphere (Beckers and Schultz 1972; Bhatnagar *et al.* 1972; Rice and Gaizauskas 1973; Schröter and Soltau 1976; Soltau *et al.* 1976; Thomas *et al.* 1984; Abdelatif *et al.* 1984; Lites and Thomas 1985; Abdelatif 1985), in the umbral chromosphere (Beckers and Tallant 1969; Bhatnagar and Tanaka 1972; Beckers and Schultz 1972; Giovanelli 1972, 1974; Phillis 1975; Moore and Tang 1975; Kneer *et al.* 1981; Lites *et al.* 1982; von Uexküll *et al.* 1983; Thomas *et al.* 1984; Lites 1984, 1986; Lites and Thomas 1985), and in the transition region above the umbra (Gurman *et al.* 1982; Henze *et al.* 1984). The 3-minute umbral velocity oscillations and the umbral flashes are different manifestations of the same oscillatory phenomenon in a sunspot (Moore 1981 *a*, 1981 *b*).

Fig. 2 (Thomas *et al.* 1984) shows the temporal power spectrum of both (*a*) photospheric and (*b*) chromospheric umbral oscillations in a single sunspot and illustrates the distinct nature of the 3-minute and 5-minute oscillations in a sunspot umbra. In the photospheric power spectrum (measured in Fe I λ6303), the 5-minute oscillations appear as the multiple peaks A, B and C, whereas the 3-minute umbral oscillation appears as the single peak D. The chromospheric power spectrum (measured in Ca II H) shows multiple peaks E, F and G of 3-minute umbral oscillations, with peak E being at the same frequency as peak D in the photosphere.

The 3-minute umbral oscillations are generally considered to be a resonant mode of the sunspot itself. There are two types of resonant modes in a sunspot that have periods around 3 minutes. Here we shall refer to these two types as the *photospheric resonance* and the *chromospheric resonance*. The photospheric resonance consists of fast magneto-atmospheric waves that are nearly trapped in the photosphere and subphotosphere (Uchida and Sakurai 1975; Scheuer and Thomas 1981; Thomas

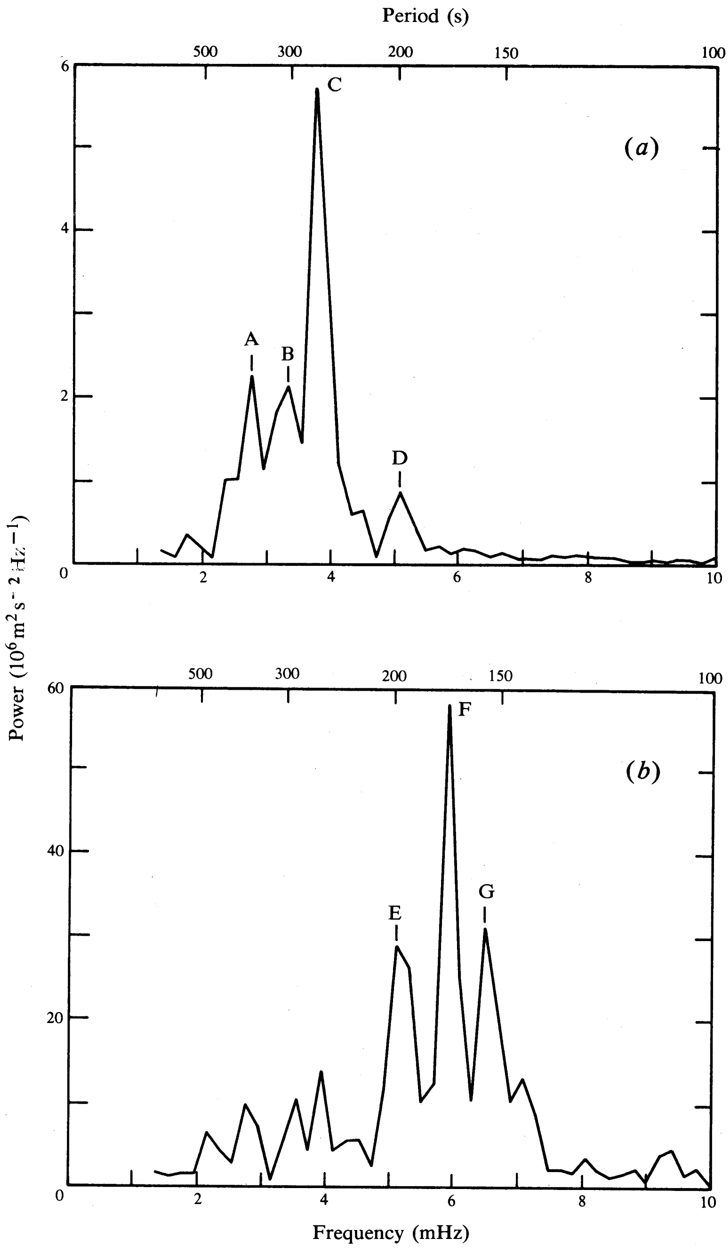

Fig. 2. Temporal power spectra of (*a*) the photospheric velocity (measured in Fe I λ6303 on 21 August 1980) and (*b*) the chromospheric velocity (measured in Ca II H on 21 August 1980) averaged over a single sunspot umbra. The photospheric power spectrum has three distinct peaks A, B and C in the 5-minute band and a single peak D which represents the photospheric signal of the characteristic 3-minute oscillation corresponding to peak E in the chromospheric power spectrum. The periods of the labelled peaks are: A, 366 s; B, 301 s; C, 270 s; D, 197 s; E, 197 s; F, 171 s; G, 155 s. [From Thomas *et al.* (1984).]

and Scheuer 1982). These wave modes can be excited by overstable convection in the umbral subphotosphere (Moore 1973; Mullan and Yun 1973; Antia and Chitre 1979). Alternatively, Moore and Rabin (1984) have suggested that the photospheric resonance is excited by high-frequency components of the 5-minute p-mode oscillations in the surrounding convection zone. The chromospheric resonance consists of slow magneto-acoustic waves that are nearly trapped in the chromosphere, essentially between the temperature minimum and the transition region (Zhugzhda *et al.* 1983; Zhugzhda *et al.* 1984; Gurman and Leibacher 1984). These modes can be excited from below by the photospheric resonance or perhaps by acoustic waves from the convection zone.

Although theoretical models of the photospheric resonance and the chromospheric resonance have for the most part been developed separately, these two resonances should exist simultaneously in a sunspot (Thomas 1984; Zhugzhda 1984). Indeed, both of these resonances occur in the three-layer umbral model of Scheuer and Thomas (1981, Sect. 4.2), although in that paper the emphasis was on the photospheric resonance as the fundamental cause of the 3-minute umbral oscillations. A satisfactory explanation of the 3-minute umbral oscillations seems to be that the photospheric resonance is the fundamental cause of the phenomenon, while the additional chromospheric resonance produces the multiple modes usually observed in chromospheric power spectra (Thomas 1984; Lites and Thomas 1985; Lites 1986).

The theoretical arguments for the existence of the two types of resonances in a sunspot may be presented concisely with the help of a simple model of a sunspot umbra. Let us assume that the undisturbed umbral atmosphere consists of a compressible, inviscid, perfectly conducting gas, permeated by a uniform magnetic field B in the vertical direction (z-direction) and in hydrostatic equilibrium under uniform gravity g (in the negative z-direction). The undisturbed pressure, density, and temperature in this atmosphere are functions of z only. The linearized magneto-atmospheric wave equations for small adiabatic perturbations can be reduced in this case to the following pair of equations for the z-dependent amplitudes $u(z)$ and $w(z)$ of the horizontal and vertical velocities (Scheuer and Thomas 1981; Thomas 1983):

$$\left\{a^2\left(\frac{\mathrm{d}^2}{\mathrm{d}z^2}-k^2\right)-c^2k^2+\omega^2\right\}u+\mathrm{i}\,k\left(c^2\frac{\mathrm{d}}{\mathrm{d}z}-g\right)w=0, \tag{1}$$

$$\mathrm{i}k\left(c^2\frac{\mathrm{d}}{\mathrm{d}z}-(\gamma-1)g\right)u+\left(c^2\frac{\mathrm{d}^2}{\mathrm{d}z^2}-\gamma g\frac{\mathrm{d}}{\mathrm{d}z}+\omega^2\right)w=0. \tag{2}$$

Here, c is the adiabatic sound speed and a is the Alfvén speed, both of which vary with height z in the atmosphere, and γ is the ratio of specific heats. The velocity has been Fourier-analysed in time and in the horizontal spatial direction, and ω denotes the frequency and k the horizontal wavenumber. Equations (1) and (2) apply either to cartesian velocity components, in which case

$$u(x,z,t)=u(z)\exp\{\mathrm{i}(kx-\omega t)\}, \qquad w(x,z,t)=w(z)\exp\{\mathrm{i}(kx-\omega t)\}, \tag{3}$$

or to cylindrical velocity components, in which case

$$u_r(r,z,t)=ku(z)\,J_1(kr)\exp(-\mathrm{i}\,\omega t),\ \ u_z(r,z,t)=-\mathrm{i}\,kw(z)\,J_0(kr)\exp(-\mathrm{i}\,\omega t), \tag{4}$$

where J_0 and J_1 are Bessel functions and k is the radial wavenumber.

If we specify the undisturbed temperature $T(z)$ as a function of height z in this atmosphere, then the undisturbed density $\rho(z)$ and pressure $p(z)$ are determined by the equation of state and the hydrostatic equation, and the sound speed c and Alfvén speed a are given in turn by $c^2(z) = \gamma R T(z)$ and $a^2(z) = B^2/\mu\rho(z)$. Note in equations (1) and (2) that, for a specified horizontal wavenumber k and frequency ω, the behaviour of the solution is completely determined by the specified variation of the parameters c^2 and a^2 with height z.

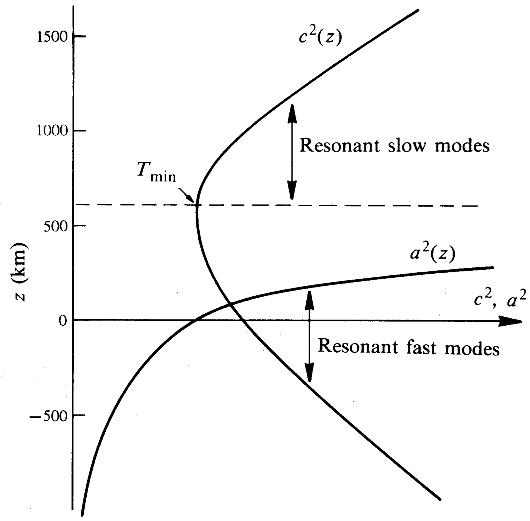

Fig. 3. Sketch of the typical variation of c^2 and a^2 with height z in a sunspot umbra, where c is the sound speed and a is the Alfvén speed. Also shown are the approximate ranges of height in which the photospheric fast-mode resonance and chromospheric slow-mode resonance occur.

Fig. 3 shows a schematic sketch of the variation of c^2 and a^2 with height in a sunspot umbra and identifies the regions of trapping of the photospheric and chromospheric resonances. The photospheric resonance is caused by trapping of fast magneto-atmospheric waves by downward reflection due to the rapidly increasing Alfvén speed with height up into the photosphere and upward reflection due to the increasing sound speed down into the convection zone. Both compressive and magnetic forces play an important part, while buoyancy forces play a minor role. The chromospheric resonance involves slow modes that are essentially pure acoustic waves with motions only along the vertical magnetic field lines. The resonance is caused by trapping of these waves by downward reflection at the chromosphere–corona transition region due to the rapid increase in sound speed and upward reflection at the temperature minimum, which may be thought of crudely as due to an increase in the acoustic cutoff frequency with decreasing temperature toward the temperature minimum.

Most of the theoretical work on umbral oscillations has assumed a purely vertical magnetic field in the umbra. For the photospheric resonance, this assumption is justified by the fact that the trapping takes place in the low photosphere and subphotosphere, where the magnetic field lines spread very gradually. Cally (1983) studied the effect of spreading magnetic field lines on the three-layer model umbra of Scheuer and Thomas (1981) and found very little change in the resonant modes. [However, Cally did find that the spreading magnetic field allows a greater flux of small-scale Alfvén waves up into the chromosphere, compared with the case of a uniform vertical magnetic field (Thomas 1978).] Spreading magnetic field lines have a greater effect on the chromospheric resonance because the motions in the chromosphere, where $a^2 \gg c^2$, are constrained to be essentially along the magnetic field lines.

The 3-minute umbral velocity oscillations are easily observed in the chromosphere, where their amplitude is large, but are more difficult to observe in the photosphere, where their amplitude is lower and sometimes barely above the noise level in a particular set of observations. Because of the low amplitude of the 3-minute oscillations in the photosphere, some have questioned the validity of the photospheric resonance model. However, because the density is much greater in the photosphere than in the chromosphere, the kinetic energy density of the observed oscillations is actually much greater in the photosphere than in the chromosphere. Using estimates of the density from the 'Sunspot' sunspot model (Avrett 1981), Abdelatif *et al.* (1984) and Lites and Thomas (1985) found that the kinetic energy density of the 3-minute oscillations is at least five times greater in the photosphere than in the chromosphere, consistent with the photospheric resonance theory.

Information about the vertical structure and vertical propagation of umbral oscillations has been obtained by measuring the oscillations simultaneously in two or more spectral lines formed at different heights in the sunspot atmosphere. Giovanelli *et al.* (1978) found positive phase lags between the the oscillation in Fe I λ5233 and Hα, indicating upward phase propagation in the chromosphere. In another study, von Uexküll *et al.* (1983) observed umbral oscillations simultaneously in the chromospheric line pairs Na D_1–Na D_2 and Na D_2–Hα, and found vertical phase speeds in the range 10–25 km s^{-1}, roughly equal to the sound speed at those heights. Although they interpreted this result as being in contradiction to the photospheric resonance model and in agreement with the chromospheric resonance model, Thomas (1984) showed that the opposite was true. In the photospheric resonance there is a leakage of wave energy in the form of acoustic waves propagating upward into the chromosphere, consistent with the upward propagation observed by von Uexküll *et al.* On the other hand, in the chromospheric resonance, the waves are nearly standing waves in the vertical direction in the chromosphere and these modes would produce much larger observed phase speeds. Lites (1984) confirmed upward phase propagation at approximately the sound speed in the chromospheric line pairs Ca II λ8498–Ca II λ8452 and Fe I λ5434–Ca II λ8498.

Lites and Thomas (1985) observed umbral oscillations simultaneously in the line Ti I λ6304, formed in the low photosphere, and the line Fe I λ5434, formed in the low chromosphere just above the temperature minimum. Fig. 4 (Lites and Thomas 1985) shows (*a*) the mean temporal power spectrum of the oscillations in each spectral line (for both the entire umbra and for just the dark inner umbra), as well as (*b*) the coherence and (*c*) the phase spectrum between the velocities in the two lines. Both the λ5434 and the λ6304 power spectrum have a strong sharp peak at about 3 mHz (period about 5 minutes) and multiple peaks in the range 5–7 mHz (periods around 3 minutes). The coherence spectrum in Fig. 4*b* has two distinctive features: a broad, high peak centred on 3 mHz and a narrower peak at about 6 mHz. The coherence

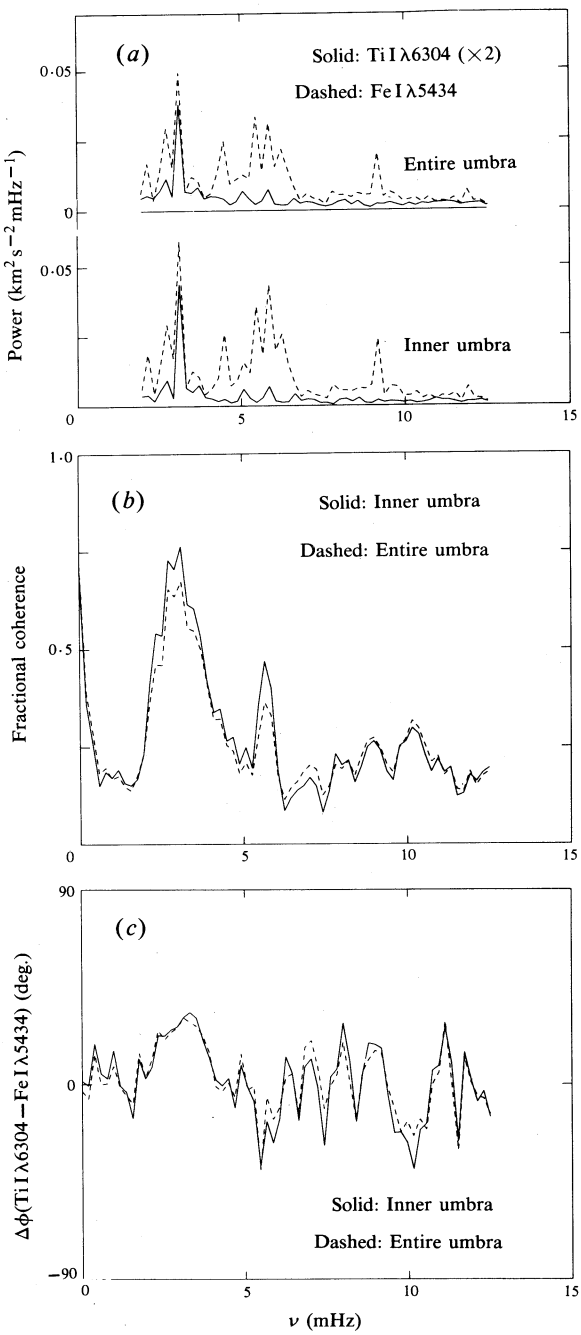

Fig. 4. The (*a*) average power spectra, (*b*) coherence spectrum and (*c*) phase spectrum for both the entire umbra and the dark inner umbra in a single sunspot, for both Ti I λ6304 (formed in the low photosphere) and Fe I λ5434 (formed in the low chromosphere). The power for Ti I λ6304 has been multiplied by a factor of 2 for convenience in plotting. The power peaks, distinct coherence peak, and small phase differences at 6 mHz indicate that the fundamental 3-minute umbral oscillation has the character of a vertically standing wave in the photosphere. [From Lites and Thomas (1985).]

peak at 6 mHz coincides with the dominant power peak of 3-minute oscillation in both $\lambda 6304$ and $\lambda 5434$. The phase spectrum in Fig. 4*c* shows that the phase difference is small ($|\Delta\phi| < 40°$) over the entire 3-minute band (5–8 mHz) and nearly zero at the location of the 6 mHz coherence peak. These results indicate that the dominant 3-minute umbral oscillation has the character of a coherent, vertically standing wave in the photosphere and low chromosphere, consistent with the photospheric resonance model.

In the 3-minute band (5–8 mHz) there are more peaks in the chromospheric power spectrum than in the photospheric power spectrum in Fig. 4*a*, and this result is typical of other observations (see Fig. 2). The additional peaks in the chromosphere could be the result of the chromospheric resonance excited by nonlinear coupling with the photospheric modes or by acoustic waves from the convection zone at those frequencies (Gurman and Leibacher 1984). Alternatively, the additional peaks in the chromospheric power spectrum could correspond to undetected photospheric resonant modes with power below the noise level in the photospheric power spectrum. In the photospheric resonance model, the closely spaced peaks in the 3-minute band can be produced by modes with different horizontal structure across the umbra (Scheuer 1980).

The phase difference is small and positive across the 5-minute band in the umbra (Fig. 4*c*), much the same as in the quiet Sun (Lites and Chipman 1979). This is consistent with a vertically evanescent wave with a small positive phase difference caused by damping, as studied theoretically by Schmieder (1977).

The power, coherence, and phase spectra in Fig. 4 combine to show that the 3-minute umbral oscillations are quite distinct from the 5-minute oscillations in the umbra and are not just a feature of the high-frequency tail of the 5-minute oscillations. This supports the view that the 3-minute umbral oscillations are resonant modes of the sunspot itself, whereas the 5-minute oscillations in the umbra are a passive response to forcing by the 5-minute p-mode oscillations in the surrounding convection zone (Thomas 1981). Further evidence for this interpretation is provided by sunspots still in the stages of formation, in which the 5-minute oscillation is strong but the 3-minute oscillation is absent (Lites and Thomas 1985; Abdelatif 1985). Apparently the sunspot must be fully formed and stable before the internal resonance can occur.

Another recent development has been the measurement of 3-minute umbral oscillations in the chromosphere–corona transition region above a sunspot umbra, using the UVSP instrument aboard the Solar Maximum Mission satellite (Gurman *et al.* 1982; Henze *et al.* 1984). In these observations the oscillations were measured in the ultraviolet spectral line C IV $\lambda 1548$, which is formed at $T_{\text{eff}} \approx 10^5$ K. Gurman *et al.* found significant velocity oscillations in all eight sunspots that they observed, with periods in the range 129–173 s. In the case of one sunspot, nearly simultaneous ground-based observations (Thomas *et al.* 1984) in the Ca II K line showed a dominant oscillation at the same frequency (to within the experimental uncertainty) as in the transition region.

Henze *et al.* (1984) measured the magnetic field as well as the velocity in C IV $\lambda 1548$ and found no significant periodic variations in the magnetic field associated with the umbral oscillations in the transition region. From a theoretical standpoint, this is to be expected, because in the transition region the magnetic pressure dominates the gas pressure ($a^2 \gg c^2$) and the magnetic field lines are essentially rigid compared with the weak inertia of the gas. The oscillatory motions are constrained to be along the magnetic field lines, and the magnetic field itself is undisturbed.

Magnetic field variations associated with umbral oscillations have also been sought in photospheric spectral lines. No significant oscillations in magnetic field strength were detected by Schultz and White (1974) in Fe I λ6173 or by Thomas *et al.* (1984) in Fe I λ6303. However, Gurman and House (1981) did find 3-minute oscillations in magnetic field strength in Fe I λ6303. From theory, one would expect to observe significant magnetic field variations only in the low photosphere where a^2 and c^2 are comparable.

3. Five-minute Oscillations in Sunspots

Oscillations with periods near five minutes occur in sunspots, and these oscillations are distinct from the 3-minute oscillations in the umbra and the running penumbral waves. Thomas (1981) suggested that these 5-minute oscillations are the response of the sunspot to forcing by the 5-minute p-mode oscillations in the surrounding atmosphere.

The unambiguous detection of 5-minute oscillations in a sunspot is made difficult because of the strong possibility of contamination of the signal by the 5-minute oscillations in the surrounding quiet atmosphere, either by means of scattered light or through the use of the quiet photospheric signal as a wavelength reference. Indeed, Beckers and Schultz (1972) were the first to detect 5-minute oscillations in a sunspot, but they had to conclude that this oscillation was quite likely due to oscillations in their wavelength reference, which was determined for each scan by averaging the line profile at several points outside the sunspot. Since then, several observers have used techniques that minimize the effects of scattered light and avoid the use of quiet-Sun line profiles to set the wavelength reference. The result has been to firmly establish the existence of 5-minute oscillations in sunspots.

One way of reducing the problem of scattered light is to use a spectral line that is present in the cooler umbra but absent in the quiet photosphere. These purely umbral lines are usually molecular in origin, and there are a number of them in the visible spectrum. Bhatnagar *et al.* (1972) detected a 310 s oscillation in a sunspot umbra using the umbral lines λ6525 and λ6910. Rice and Gaizauskas (1973) tried to achieve a stable wavelength reference by using an average of line profiles over a very large area of the quiet Sun, thus presumably averaging out any oscillatory signal. They detected a 300 s oscillation in a sunspot umbra in the photospheric spectral line Fe I λ5233.

Soltau *et al.* (1976) used a purely umbral molecular line λ6496 referenced to a nearby telluric line and found both 5-minute and 3-minute oscillations in a sunspot umbra. Livingston and Mahaffey (1981) measured oscillations in sunspot umbras using the umbral molecular line CaH λ6898·8 referenced to the telluric line λ6899·96. The mean power spectrum for 31 sunspots showed a single peak at a period of 315 s.

Thomas *et al.* (1982, 1984) measured umbral velocities using the Stokes V profile of the magnetic line Fe I λ6303 and a nearby telluric line as a wavelength reference. The use of the V profile to measure velocity means that the velocity signal is not contaminated by stray light coming from nonmagnetic regions outside the sunspot. Fig. 2*a* in Section 2 shows the mean temporal power spectrum of the photospheric velocity in the umbra of a sunspot, as measured by this technique. This power spectrum has three distinct peaks (A, B and C) in the 5-minute band (frequencies in the range 2–4 mHz) and a separate distinct peak D at a period of 197 s. Peak D corresponds to a peak at the same frequency in the power spectrum of chromospheric velocity (shown in Fig. 2*b*) in the same sunspot and is interpreted as the photospheric signal of the typical 3-minute umbral oscillation in this sunspot.

The multiple peaks A, B and C in the 5-minute band can be interpreted as the response of the sunspot to distinct p-mode oscillations in the surrounding convection zone. If this interpretation is correct, then it allows us to use the multiple 5-minute modes in a sunspot umbra to probe the structure of the sunspot magnetic flux tube below the solar surface (Thomas *et al.* 1982). Different p modes (with different radial mode numbers) have different depth dependence and thus excite the sunspot magnetic flux tube at different depths. The response of the sunspot will depend on the diameter of the flux tube as compared with the horizontal wavelength of the exciting p mode. Based on their observations, Thomas *et al.* made the crude assumption that the peak response occurs for a horizontal wavelength equal to twice the tube diameter. This led to the physically plausible result that the diameter of the sunspot flux tube is about 60% of the surface diameter at a depth of 10 000 km.

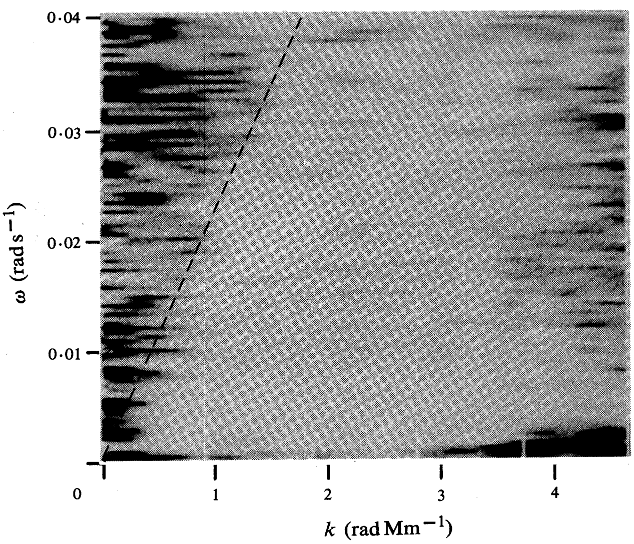

Fig. 5. Diagnostic k–ω diagram depicting the attenuation of waves inside a sunspot umbra according to a grey scale, with black representing no attenuation and white representing total attenuation. The dashed line roughly separates the region of low attenuation from the region of high attenuation and has a slope corresponding to a horizontal phase speed of about 25 km s^{-1}. [From Abdelatif (1985).]

Abdeltaif (1985) has studied the theoretical problem of the interaction of p modes with a sunspot magnetic flux tube through the use of some simple models. He found that the transmission of wave energy into the sunspot is a function of the horizontal wavenumber as compared with the tube diameter, as expected. He also found another important effect that must be taken into account in interpreting the observations: the horizontal wavelength of the wave is changed upon transmission into the magnetic flux tube. This has the effect of shifting power along the k axis in a diagnostic diagram of oscillations inside the sunspot as compared with a diagnostic diagram for the surroundings.

Abdelatif *et al.* (1984; see also Abdelatif 1985) have observed the spatial properties of the 5-minute oscillations in a sunspot and the surrounding photosphere by means of long time sequences of two-dimensional spatial scans. They computed oscillatory power as a function of frequency ω and horizontal wavenumber k for both the sunspot umbra and an equivalent patch of quiet photosphere just outside the sunspot, and then plotted the ratio of power inside and outside the sunspot on an 'attenuation diagram'. An example of such an attenuation diagram is shown in Fig. 5. The most striking aspect of this diagram is the fact that there is a region with dark bands of low attenuation (dark) and a region of overall high attenuation, roughly separated by the dashed line. The slope of the dashed line corresponds to a phase speed of about 25 $\mathrm{km\,s^{-1}}$. This result is in good agreement with the theoretical analysis of Abdelatif (1985), which predicts high attenuation of all p-mode waves with horizontal phase speeds less than the fast-mode speed in the umbra.

4. Running Penumbral Waves

The running penumbral waves seen in Hα were discovered independently by Giovanelli (1972) and by Zirin and Stein (1972). They consist of circular wavefronts that originate at the umbra–penumbra boundary and propagate radially outward with horizontal phase speeds in the range 8–25 $\mathrm{km\,s^{-1}}$ and repeat with periods in the range 200–300 s.

Running penumbral waves have been interpreted theoretically as a vertically trapped mode of fast magneto-atmospheric wave (Nye and Thomas 1974, 1976; Antia *et al.* 1978). The trapping is caused by the increasing Alfvén speed up into the chromosphere and the increasing sound speed down into the convection zone. Most of the wave energy is trapped in the photosphere and subphotosphere. The wave is evanescent in the chromosphere at the heights of formation of Hα but the amplitude is large there because of the low density.

Observations suggest that the running penumbral waves are generated near the umbra–penumbra boundary, but the relation between umbral oscillations and penumbral waves is not clear (Moore 1981*a*, 1981*b*). Galloway (1978) has suggested that the penumbral waves are generated within the penumbra itself through overstable convective instability in the nearly horizontal magnetic flux ropes.

Penumbral waves have also been observed in the photosphere (Musman *et al.* 1976), where they appear to be more intermittent and to have higher radial phase velocity (40–90 $\mathrm{km\,s^{-1}}$) than the waves in Hα. Thus, the relation between photospheric and chromospheric penumbral waves must be more complicated than in the trapped wave theories mentioned above. It was suggested (Thomas 1981) that the different horizontal phase speeds in the photosphere and chromosphere might be caused by the convection of the wavefronts in the shearing Evershed flow in the penumbra. Cally and Adam (1983) studied the effect of the Evershed flow on penumbral waves by calculating the trapped modes of Nye and Thomas (1974) in the presence of a horizontal shear flow with a sinusoidal vertical variation. They found that the periods of the trapped modes are changed only slightly by the shear flow but the eigenfunctions are distorted, in the sense that the maximum vertical velocity occurs higher in the chromosphere and the vertical velocity in the photosphere is reduced. This theory does not account for the filamentary nature of the penumbral Evershed flow and magnetic field. Presumably, this causes the wavefronts to become ragged as they move outward across the penumbra, which indeed is observed.

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