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Sunspot Dynamics

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ABSTRACT

This report describes recent results of our theoretical and observational work on dynamical phenomena in sunspots. The overall goal of this research has been a better understanding of the various oscillatory, transient, and steady motions in a sunspot and their relation to the basic structure of the sunspot. The principal topics of the research reported here are the following: (i) sunspot seismology, i.e., the study of the interaction of solar p-modes with a sunspot as a probe of the subsurface structure of a sunspot; (ii) local sources of acoustic waves in the solar photosphere; and (iii) siphon flows in isolated magnetic flux tubes and their relation to the photospheric Evershed flow and to intense magnetic elements outside of sunspots.

The method of sunspot seismology, first proposed by Thomas, Cram, and Nye (1982, *Nature*, **297**, 485), promises to disclose the subsurface structure of a sunspot's magnetic field. Our recent observational results (Bogdan, Brown, Lites, and Thomas 1993, *Ap.J.*, in press) confirm the absorption of *p*-mode energy by sunspots measured by Braun, Duvall, and LaBonte (1988, *Ap.J.*, **335**, 1015), but with some important differences. The high signal-to-noise ratio of our data allow us to begin to measure variations of the absorption coefficient with degree (or horizontal wavelength) along individual *p*-mode ridges. Our data also reveal the existence of localized sources of high-frequency acoustic emission (Brown, Bogdan, Lites, and Thomas 1992, *Ap.J.*, **394**, L65), which supports the idea that most of the energy driving the solar *p*-modes comes from a small fraction of the volume of the convection zone.

Our calculations of siphon flows in isolated magnetic flux tubes have now been extended to include standing tube shocks (Thomas and Montesinos 1991, *Ap.J.*, **375**, 404) and the effects of radiative transfer and variable ionization (Montesinos and Thomas 1993, *Ap.J.*, **402**, 314). We have developed a siphon-flow model of the photospheric Evershed flow (Thomas and Montesinos 1993, *Ap.J.*, in press), based on a "deep" penumbra, that resolves two problems previously associated with such models (related to the horizontal extent and darkness of the flux tube). Our specific prediction of the observational signature of a siphon-flow mechanism for producing intense photospheric flux tubes (Thomas and Montesinos 1991, *Ap.J.*, **375**, 404) has been confirmed in recent observations by Rüedi, Solanki, and Rabin (1992, *Astron. Ap.*, **261**, L21).

Sunspot Dynamics

1. INTRODUCTION

This report describes the results of our theoretical and observational research on dynamical phenomena in sunspots, which has been supported by NASA's Solar Physics section since 1978 (Grant NAGW-2123, formerly NSG-7562). The overall goal of this research has been an understanding of the various oscillatory, transient, and quasi-steady motions in sunspots and their relation to the overall structure of a sunspot. The research involves both theoretical modeling and observations of dynamical phenomena in sunspots. Most of the observational work has been done with the vacuum tower telescope at the National Solar Observatory (NSO) in Sunspot, New Mexico. The principal topics of the research described here are the following: (i) sunspot seismology, i.e., the study of the interaction of solar p-modes with a sunspot as a probe of the subsurface structure of a sunspot; (ii) localized sources of acoustic waves in the solar photosphere; and (iii) siphon flows in isolated magnetic flux tubes and their relation to the photospheric Evershed flow and to intense magnetic elements outside of sunspots. The following sections give a brief summary of the research results; more detailed presentations may be found in the published papers, reprints of which are included as appendices to this report.

2. SUNSPOT SEISMOLOGY

Perhaps the most important new ideas and results to arise from the research under this NASA grant are those on "sunspot seismology," the use of p-mode oscillations in and around a sunspot as a probe of the subsurface structure of a sunspot. The concept of sunspot seismology was introduced ten years ago by Thomas, Cram, and Nye (1982) in a brief paper based on spatially unresolved measurements of oscillations inside a sunspot umbra and a simple model of the interaction between the sunspot and the p-modes. Temporal power spectra of these umbral oscillations showed reproducible peaks which were interpreted as representing the response of the sunspot to specific incident p-mode oscillations with energy concentrated at different depths. The simple theoretical model of the nature of this interaction then led to a measure of the radius of the overall sunspot magnetic flux tube with depth. However, because of the lack of spatial resolution, the procedure for identifying specific modes was highly uncertain.

The first spatially resolved measurements in sunspot seismology were carried out by Abdelatif, Lites, and Thomas (1986). We compared the power spectrum of oscillations in a sunspot umbra with the power spectrum of oscillations in an equivalent area in the quiet Sun outside the sunspot and found the following: (i) the dominant 5-minute p-mode oscillations have reduced amplitude inside the umbra, with an rms velocity about half that in the surrounding quiet photosphere; (ii) there is a general shift of oscillatory power to longer horizontal wavelengths in the umbra: and (iii) the umbra acts as a selective filter by transmitting certain frequencies of the incident p-modes in preference to other frequencies. These results were were given a simple theoretical interpretation by Abdelatif and Thomas (1987) on the basis of a model consisting of a vertical cylindrical magnetic flux tube embedded in a field-free, unstratified gas, with resonant p-modes produced by upper and lower reflecting horizontal boundaries. Horizontally propagating p-modes incident upon the flux tube are, in general, partially transmitted into the flux tube and partially reflected. The transmitted wave is a magnetoacoustic wave having greater horizontal phase speed, and hence longer horizontal wavelength, than the incident wave, which explains the shift of power to longer wavelengths in the umbra. The transmission coefficient as a function of horizontal wavelength exhibits peaks and valleys, because of the preferred transmission of waves for which an integral number of wavelengths fit across the diameter of the flux tube; this explains the selective filtering.

A different approach to sunspot seismology, first advocated on theoretical grounds by Bogdan and Zweibel (1987), is to treat the interaction of a sunspot with the solar p-modes as a classical scattering problem, using only measurements of oscillations in the quiet Sun surrounding the sunspot. This approach was first employed in observational studies by Braun, Duvall, and LaBonte (1987, 1988; hereafter BDL), who made the surprising and important discovery that sunspots absorb an appreciable fraction of the energy of the incident p-modes. This discovery has prompted a number of theoretical papers attempting to identify the absorption mechanism (see the recent review by Bogdan 1992 for a full discussion of these papers). The phase shifts of the scattered waves, which can only be measured using long (> 1 day) data sets (Braun *et al.* 1992) also contain useful information.

We have now independently confirmed the absorption of p-modes by sunspots with our own observations (Bogdan, Brown, Lites, and Thomas 1993), with some differences in detail from the results of BDL. These observations were taken by one of us (JHT) in March 1989 with the vacuum tower telescope, universal birefringent filter (UBF), and multiple diode array (MDA) at NSO/Sunspot (probably the best available system for this purpose). In order to avoid registration problems associated with Dopplergrams constructed from images taken at different times, we used the method perfected by Dunn and November, in which a polarizing beamsplitter is introduced into the UBF optical system allowing us to record the blue and red sides of the spectral line simultaneously. We used two identical 320x256 CCD arrays to record images on both sides of the line simultaneously. Exposure times were short enough (20 ms) to freeze the image motion and allow us to compensate for image motion in the data reduction phase. The observations were made with the magnetically insensitive photospheric line Fe I 5576. Careful reduction of our best data set (from 19 March 1989) led to a time series of velocity maps that are as free of instrumental artifacts as possible.

Our method of measuring the scattering properties of a sunspot makes use of a spherical harmonic decomposition of the p-modes (instead of the Fourier-Bessel decomposition used by BDL), thus allowing for the curvature of the Sun's surface. Consider a spherical coordinate system (r,θ,ϕ) on the Sun with its north pole placed at the center of a sunspot. Our observations of the Doppler velocity at the surface of the Sun in a region centered on the sunspot yield a time sequence of Doppler images, i.e, velocity $v(\theta,\phi,t)$ as a function of position on a discrete grid in θ and ϕ at a sequence of discrete times t. Now consider this velocity over an annular region $\theta_1 < \theta < \theta_2$ centered on the sunspot with θ_1 chosen just large enough to exclude the sunspot from the annulus. The velocity can be represented as a superposition of inward and outward propagating waves on this annulus in terms of solutions of the associated Legendre equation, in the form

$$v(\theta, \phi, t) = \sum_l \sum_m \sum_n V(l, m, n)[P_l^m(\cos\theta) - \frac{2i}{\pi} Q_l^m(\cos\theta)]\exp[i(m\phi + 2\pi\nu_n t)] + \text{c.c.}$$

where c.c. denotes the complex conjugate. Values of the separation constant l are selected so that the wavefunctions are mutually orthogonal on the annulus. The azimuthal index m takes on only integer values (positive and negative), and the index n denotes the discrete frequencies ν_n measured by the discrete time series. By considering the asymptotic form of the associated Legendre functions for large l, it is found that positive values of n correspond to waves propagating radially inward across the annulus and negative values of n correspond to outward propagating waves. Hence, we can define an absorption coefficient

$$\alpha(l, m, n) = \frac{|V(l, m, |n|)|^2 - |V(l, m, -|n|)|^2}{|V(l, m, |n|)|^2} ,$$

which gives the fractional absorption of wave energy as a function of degree l, azimuthal order m, and frequency ν_n. One can then look at the absorption in less detail and, for example, sum the absorption coefficient $\alpha(l, m, n)$ over several azimuthal orders and look at absorption as a function of degree l and frequency ν_n.

Following the approach of BDL, one can sum the absorption coefficient over several azimuthal orders and over all frequencies in the dominant p-mode band and then look at absorption as a function only of degree l (or, equivalently, as a function of horizontal wavenumber $k = [l\,(l+1)]^{1/2}/R_{\odot}$). Figure 1 shows the results of doing this with our data (Bogdan, Brown, Lites, and Thomas 1993), summing over all azimuthal orders m from - 5 to + 5 and all frequencies from 1.74 to 5.04 mHz (the same ranges as in BDL). Our results show the absorption coefficient increasing with increasing degree l (i.e., increasing horizontal wavenumber k) up to a maximum value of about 0.5 at an l of around 500 (horizontal wavenumber about 0.8 Mm^{-1}) and then decreasing to near zero for l around 1000 (horizontal wavenumber about 1.6 Mm^{-1}). Our results in Figure 1 agree remarkably closely with those of BDL (for their 18 January 1983 sunspot) in the range $0 < l < 500$. But they disagree in the range $500 < l < 1000$, where BDL find the absorption coefficient to remain roughly constant at a value of about 0.5 but we find it to decrease nearly linearly to zero over the same range.

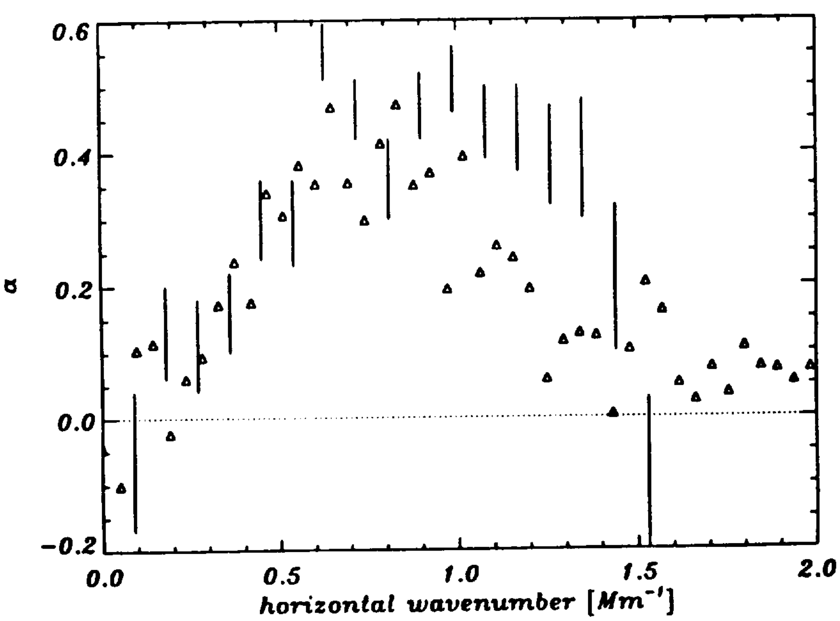

Fig. 1. The absorption coefficient α (summed over frequency and azimuthal order) for the absorption of solar p-modes by a sunspot, as a function of mode degree l (triangles, from Bogdan, Brown, Lites, and Thomas 1992). Also shown are the corresponding results of Braun, Duvall, and LaBonte (1988, vertical line segments) for comparison.

Our data have sufficient spatial and temporal resolution to permit us to begin to examine the absorption as a function of degree l along individual p-mode ridges in a diagnostic (l-ν) diagram. When we do this, we find an apparent sinusoidal-like variation of the absorption along each p-mode ridge. Figure 2 shows the variation of the absorption coefficient α with l along the individual ridges f (the fundamental), p_1, p_2, and p_3. The solid curve represents a local three-point mean of these values. Note the apparent systematic modulation of α along the ridges. If this variation can be confirmed and measured more precisely, it will serve as a very useful diagnostic of the physical absorption mechanism and, ultimately, of the subsurface structure of a sunspot.

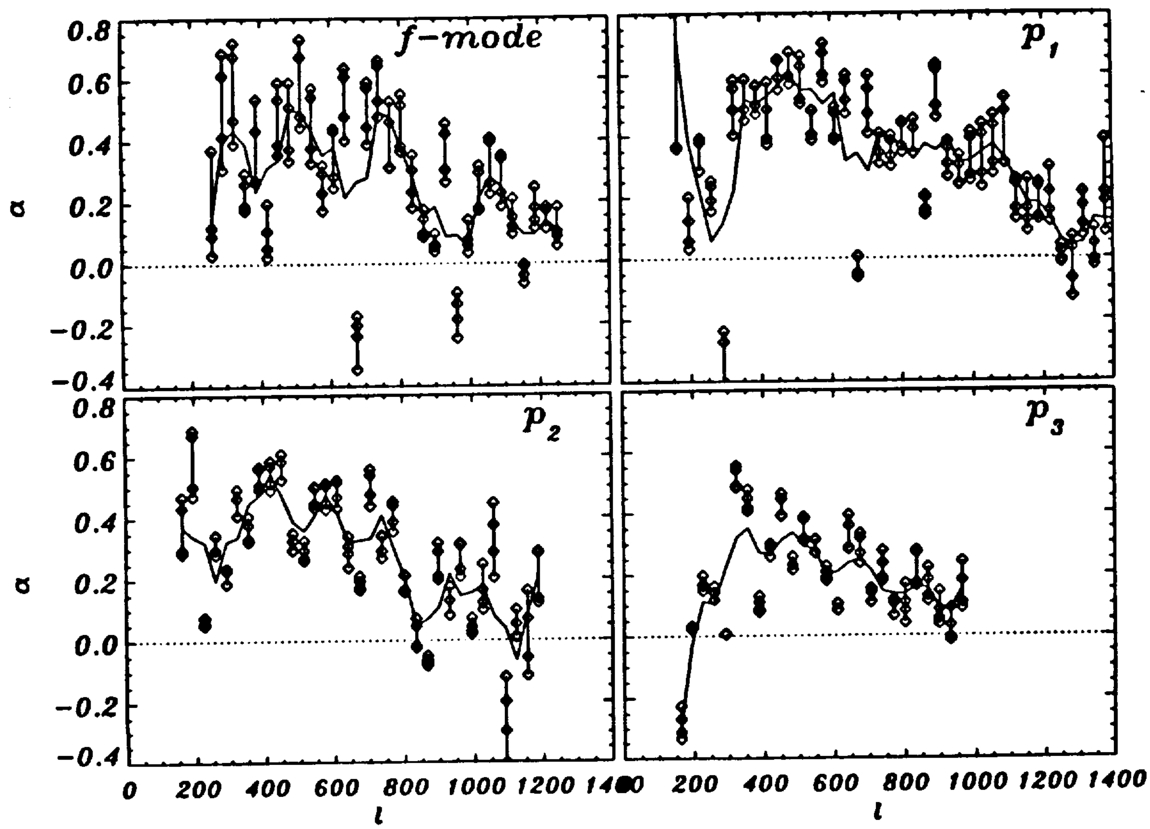

Fig. 2. Variation of the absorption coefficient α with degree l along the individual p-mode ridges f, p_1, p_2, and p_3. Values of alpha at each l are computed in four different ways (corresponding to the four diamonds at each l), based on four different, reasonable ways of identifying the p-mode ridge. (From Bogdan, Brown, Lites, and Thomas 1993)

One important point about the modulation of the absorption with mode degree should be made. When we analyzed our quiet-Sun data (no sunspot in the field of view), we found acoustic *emission* along the p_1 ridge for precisely the same range of degrees ($400 \leq l \leq 600$) where the sunspot shows its maximum absorption. This curious result, along with the decrease in absoprption with increasing l above $l = 500$ (Fig. 1), can be understood by taking into account the decrease in the lifetime and spatial range of the *p*-modes with increasing degree *l* (see Bogdan, Brown, Lites, and Thomas 1993). This effect must be considered in interpreting the results of the "scattering" method in sunspot seismology.

A number of physical mechanisms have been proposed for the absorption of *p*-modes by sunspots, involving such processes as resonance absorption, enhanced dissipation by small-scale inhomogeneities, and coupling of the waves to "leaky" modes of the sunspot's magnetic flux tube. For a full discussion of these proposed mechanisms, the reader is referred to the recent review by Bogdan (1992). Here I shall only mention the recent theoretical model of Spruit (1991) and Spruit and Bogdan (1992), which has many attractive features. It is based on the conversion of incident *p*-modes into slow magnetoacoustic modes of the sunspot flux tube, which then propagate downward out of the *p*-mode cavity in the upper convection zone and thus provide a leak of wave energy and an apparent absorption of the incident *p*-modes. In particular, their model predicts the sort of sinusoidal variation of absorption along individual *p*-mode ridges that we see in our data (see Fig. 2). At this point, neither the observations nor the theory are sufficiently refined for definite conclusions to be drawn. What one can say, however, is that the subject of sunspot seismology, now a decade old, is on the threshold of fulfilling some of its promises.

3. LOCALIZED SOURCES OF ACOUSTIC WAVES IN THE PHOTOSPHERE

Our high-quality Doppler velocity measurements of the solar photosphere can be used for purposes other than sunspot seismology. For example, we used our 19 March 1989 data set in a search for acoustic emission at frequencies above 5.5 mHz, the maximum value of the local acoustic cutoff frequency in the photosphere. We found that, in the frequency range $5.5 \leq \nu \leq 7.5$ mHz, a small fraction of the solar surface area emits a disproportionately large amount of acoustic energy (Brown, Bogdan, Lites, and Thomas 1992). The regions with excess high-frequency emission are only a few arcseconds in horizontal extent and are close to, but not exactly cospatial with, regions of relatively high magnetic field strength. These regions almost certainly correspond to the "haloes" of acoustic emission observed in the Ca II K line by Braun, Lindsey, Fan, and Jefferies (1992). These observations lend support to the conjecture by Brown (1991) that most of the acoustic energy that drives the solar *p*-modes is emitted from localized regions occupying only a small fraction of the volume of the upper convection zone.

4. SIPHON FLOWS AND THEIR RELATION TO THE EVERSHED FLOW AND TO INTENSE MAGNETIC FLUX TUBES IN THE SOLAR PHOTOSPHERE

We have made substantial progress over the past few years in our study of the phenomenon of siphon flows in isolated magnetic flux tubes, which is related to the photospheric Evershed flow in a sunspot penumbra as well as to the structure of intense flux tubes in the quiet photosphere. This work is described in several papers (Thomas 1984a, 1988, 1990; Montesinos and Thomas 1989, 1993; Thomas and Montesinos 1990a,b, 1991, 1993). The recent observational confirmation by Rüedi, Solanki, and Rabin (1992) of a siphon-flow mechanism operating in intense photospheric flux tubes, in accordance with our predictions (Thomas and Montesinos 1991), lends increased importance to this work.

4.1 Siphon Flows in Isolated Magnetic Flux Tubes

Early studies of siphon flows were limited to the case of a low-β plasma, appropriate for an embedded flux tube in the solar corona (Meyer and Schmidt 1968; see also the review by Priest 1981). We have considered steady siphon flows in arched, isolated, thin magnetic flux tubes surrounded by field-free gas, with plasma β of order unity, appropriate for conditions in the solar photosphere. In this case the cross-sectional area and magnetic field strength of the flux tube vary along the tube in response to pressure changes induced by the flow. The critical speed for siphon flows in an isolated flux tube turns out to be the tube speed $c_t = [c^2a^2(c^2+a^2)]^{1/2}$, where c is the internal sound speed and a is the Alfvén speed, instead of the sound speed, which is the critical speed for an embedded flux tube in the low-β limit. Flows with speeds less than c_t (subcritical flows) or greater than c_t (supercritical flows) are analogous to subsonic and supersonic flows in an embedded flux tube.

We have calculated steady siphon flows in arched, isolated magnetic flux tubes in a stratified atmosphere, for both isothermal (Thomas 1988) and adiabatic (Montesinos and Thomas 1989) flow. The Bernoulli effect of the flow reduces the cross-sectional area and increases the magnetic field strength of the tube compared to a static arched tube of the same height. Thus, the siphon flows offer a mechanism for producing concentrated magnetic flux in the solar photosphere. The Bernoulli effect can be strong enough to cause a decrease in cross-sectional area with height above a certain point in the rising part of the arch, producing a *bulge point* or point of local maximum cross-sectional area. We have also calculated the equilibrium path of an arched, isolated, thin flux tube containing a siphon flow (Thomas and Montesinos 1990b; see also Degenhardt 1989). The large-scale mechanical equilibrium of the flux tube involves a balance among the buoyancy force, the net magnetic tension force due to the curvature of the flux-tube axis, and the inertial (centrifugal) force due to the siphon flow along curved streamlines. The presence of a siphon flow causes the flux tube arch to bend more sharply, so that magnetic tension can overcome the straightening effect of the inertial force, and reduces the maximum width of the arch compared to the maximum width of a static arch (first determined by Parker 1975). The width of the flux-tube arch is typically equal to five to ten density scale heights. However, much wider arches are possible if the top of the arch comes into contact with the overlying canopy magnetic field. Along a horizontal top section, the flow variables remain constant and the tube's buoyancy is balanced by magnetic pressure of the canopy.

In a critical siphon flow, the velocity increases to the tube speed at the top of the arch and continues to increase to supercritical speed in the descending part of the arch down to a point where the flow decelerates abruptly to subcritical speed through a standing "tube shock." We extended our calculations to include these critical flows with standing tube shocks (Thomas and Montesinos 1991). The detailed structure of the standing tube shock cannot be treated within the thin flux tube approximation, but one can include the tube shock in the siphon flow by assuming it to be relatively thin and then applying the one-dimensional jump conditions derived within the thin flux tube approximation. These jump conditions have been derived by Herbold *et al.* (1985) and by Ferriz-Mas and Moreno-Insertis (1987). We developed a technique for computing the strength and position of the standing tube shock in adiabatic critical siphon flows for different values of the backpressure at the downstream footpoint. These calculations include a more realistic model of the external solar atmosphere, based on the VAL C model (Vernazza *et al.* 1981) of the visible layers and Spruit's (1974) model of the convection zone.

Our most recent calculations of siphon flows (Montesinos and Thomas 1993) include a realistic treatment of the radiative transfer between the flux tube and its surroundings and also include the effects of variable ionization of the flowing gas. For the radiative transfer we use the Spiegel (1957) formulation (valid in both the optically thick and optically thin limits) and the tabled opacities of Rogers and Iglesias (1992) in the layers below the photosphere, and the formulation of Kalkofen and Ulmschneider (1977) and Ulmschneider *et al.* (1978) for an optically thin flux tube above the solar surface. We show that the behavior of a siphon flow is strongly determined by the degree of radiative coupling between the flux tube and its surroundings in the superadiabatic layer just below the solar surface. We also calculate critical siphon flows with adiabatic tube shocks in the downstream leg; these calculations illustrate the radiative relaxation of the temperature jump downstream of the shock.

Results of our calculations of radiative siphon flows (Montesinos and Thomas 1993) also show that the radiative coupling becomes quite weak in the upper levels of arched flux tubes that reach above a few hundred km above the solar surface. The flow undergoes nearly adiabatic cooling at these levels, leading to quite low temperatures (1000 K or less) near the top of an arch that reaches up to the temperature minimum. This cooling is probably offset somewhat by the nonthermal heating (due to waves, for example) associated with solar magnetic flux tubes, but nevertheless siphon flows along arched flux tubes may well produce a component of low-temperature plasma (T < 4000 K) near the temperature minimum. The existence of such a cool component of gas near the temperature minimum has been inferred from observations in the infrared bands of carbon monoxide at wavelengths 4.6 and 2.3 μm (Ayres and Testerman 1981; Ayres, Testerman, and Brault 1986). These observations led Ayres (1981, 1985) to propose a simplified, two-component, "flux-tube" model of the solar atmosphere near the temperature minimum, consisting of a pervasive cool component with an admixture of hot flux tubes. The flux tubes were presumed to be hot because of preferential nonthermal heating. We suggest that flux tubes may also contribute substantially to the cool component of the atmosphere at the temperature minimum. This contribution would come from arched flux tubes containing siphon flows, in which expansive cooling in the upper levels of the arch leads to low temperatures of the internal gas at those heights. Even though these flux tubes may also be heated by the same nonthermal mechanisms that produce the hot flux tubes (those not containing a siphon flow), the extreme cooling to T < 1000 K we calculate suggests that the cooling due to the siphon flow may well offset the nonthermal heating of these tubes and produce a gas component with T < 4000 K at the height of the temperature minimum. Thus, we propose siphon flows as an alternative (or as a complement) to the enhanced radiative cooling in the CO bands themselves as a mechanism for producing the cool atmospheric component at the temperature minimum. With the siphon-flow mechanism, there is no difficulty in accommodating the possibility that photospheric flux tubes may well have expanded to fill the entire atmosphere at the height of the temperature minimum, forming the "magnetic canopy" (Giovanelli 1980; Jones 1985); the cool component need not be free of magnetic field, but instead could consist of those flux tubes that are sufficiently cooled by siphon flows.

4.2 The Evershed Flow

The horizontal Evershed outflow in the penumbral photosphere is a conspicuous feature of all fully developed sunspots. At low spatial resolution (a few arcseconds) the measured speed of the photospheric Evershed flow is typically 1-2 km s^{-1}. This average flow speed decreases with height at a fixed radial position and the flow reverses above a certain height to form the reversed Evershed inflow in the penumbral chromosphere. At a fixed height the flow speed increases radially outward across the penumbra, reaching a maximum at or near the outer penumbral boundary. Measurements at higher spatial resolution reveal that the Evershed flow is concentrated in the dark penumbral filaments, with flow speeds reaching as high as 4-6 km s^{-1}. (For a more complete account of the Evershed flow, see the recent review by Thomas and Weiss 1992.)

Meyer and Schmidt (1968) first proposed that the Evershed flow consists of a siphon flow along magnetic flux tubes. Their analysis was carried out for the limit of small plasma beta (gas pressure much less than magnetic pressure), which is valid in the penumbral chromosphere. In the low-beta limit, the magnetic field is diffuse and an individual flux tube within this field is effectively rigid, with its path and cross-sectional area unaffected by a siphon flow within. On the other hand, in the penumbral photosphere the plasma beta is of order unity and a siphon flow will affect the cross-sectional area and equilibrium path of an individual flux tube (Thomas 1984, 1988). Calculations of siphon flows in isolated magnetic flux tubes in totally field-free surroundings (Thomas 1988; Montesinos and Thomas 1989, 1992; Thomas and Montesinos 1990, 1991; Degenhardt 1989, 1991) have generally produced flux tube arches whose lateral extent is too short to correspond to the dark filaments in the penumbra. However, over the past few years a new physical picture of the structure of a sunspot penumbra has emerged (see Thomas and Weiss 1992), suggesting a different approach, which is to consider the siphon flow in a flux tube embedded in an atmosphere permeated by an ambient magnetic field of comparable strength, still allowing the flow to affect the geometry of the tube.

For some time it was thought that the penumbra consists of a shallow layer of nearly horizontal magnetic field overlying nearly field-free gas (see, e.g., Schmidt, Spruit, and Weiss 1986). But theoretical arguments demonstrate that more than three-quarters of the total magnetic flux of a sunspot must emerge from beneath the solar surface within the penumbra, requiring that the penumbra be a deep structure with an appreciable fraction its magnetic field highly inclined to the horizontal (Schmidt 1987, 1991; Weiss 1990). The observations of Adam (1990) showed that the mean magnetic field at the outer edge of the penumbra is inclined at about 20° to the horizontal, and more recent observations at higher spatial resolution (Degenhardt and Wiehr 1991; Title et al. 1992) reveal that this inclination varies substantially (by ±10-20°) in the azimuthal direction around the penumbra.

In particular, the high-resolution observations of Title et al. (1992) show that the inclination of the penumbral magnetic field varies substantially in the azimuthal direction (by ±15-20°) on the same spatial scale as the bright and dark filaments, while the magnetic field strength shows very little azimuthal variation. They also show that the dark filaments correspond to the more nearly horizontal magnetic field, and the Evershed flow is concentrated in the dark filaments (thus confirming an older observations by Beckers 1968 and Beckers and Schröter 1969). Near the outer edge of the penumbra the average inclination of the field to the horizontal is 15-20°, in agreement with Adam's measurements at lower resolution, while the magnetic field in the bright filaments is inclined at about 40° and the magnetic field and Evershed flow in the dark filaments are both essentially horizontal.

This new physical picture of a "deep" penumbra suggests that the photospheric Evershed flow should be modeled as a siphon flow along magnetic flux tubes embedded in an external atmosphere permeated by a magnetic field of strength comparable to the flux tube, still allowing the flow to affect the cross-sectional area and equilibrium path of the flux tube. Our preliminary work (Thomas and Montesinos 1993) has shown that this approach resolves the problem of the flux-tube arches being too short, because the addition of the magnetic pressure to the surrounding atmosphere reduces the magnetic buoyancy of the flux tube and hence reduces the curvature of the arch required for equilibrium.

Another problem with siphon-flow models based on a shallow penumbra has been to explain how a flux tube containing the Evershed flow can appear dark. The reduced density in a flux tube containing a siphon flow makes it essentially optically thin, and if it lies above gas at nearly normal photospheric temperature (as in a shallow penumbra) it should appear bright (see Cram, Nye, and Thomas 1981 and Degenhardt 1991). But in the new picture of a deep penumbra, the bright and dark filaments are considered to be manifestations of an overall convective process involving a continuous interchange between rising hot and sinking cold vertical flux sheets (Schmidt 1991; Wentzel 1992; Jahn 1992). The surface brightness differences between the bright and dark filaments persist with depth some distance below the visible surface. A thin siphon-flow flux tube embedded in the dark component of the penumbra will appear dark to us in spite of its transparency because we see through to a deeper layer that is also relatively dark. So far we have considered only steady siphon flows in our model, although the convective interchange process is time dependent and in reality the siphon flows will be at best quasi-steady. Our assumption of steady flow is justified as a first approximation by the fact that the observed vertical motions in penumbral filaments, which are at least in part due to the convective interchange, are slow compared to the Evershed flow.

Our siphon-flow model of the photospheric Evershed flow (Thomas and Montesinos 1993) thus far treats only a single arched flux tube. In reality, the Evershed flow must consist of siphon flows along many individual flux tubes. We intend to construct models of spatial arrays of penumbral flux tubes carrying siphon flows in an attempt to match the observed variation of the Evershed flow speed with radius and height in the penumbra.

4.3 Intense Photospheric Flux Tubes

We have suggested that siphon flows in isolated magnetic flux tubes are a mechanism for producing some of the intense, discrete magnetic elements observed in the solar photosphere (e.g. Thomas 1988, 1990). Indeed we have given a specific description of the observational signature that would be associated with magnetic elements produced by the siphon-flow mechanism (Thomas and Montesinos 1991), which we repeat here (quoted from the abstract): "The observational signature of such a structure at the solar surface would be a pair of magnetic elements of opposite polarity, separated by a distance of from one to several arcseconds, with slightly inclined magnetic fields and with an upflow in one element (the upstream footpoint of the arch) and a downflow and a somewhat greater magnetic field strength in the other element (the downstream footpoint)." This specific prediction has now been confirmed by the recent observations of Rüedi, Solanki, and Rabin (1992). Observing in the infrared Fe I lines near 1.5 microns, they find regions straddling magnetic neutral lines where the field strength drops from 1500 G on the positive polarity side to 1200 G on the negative polarity side. They also observe nearly vertical flows in both polarities, an upflow of 1 - 2 km s^{-1} in the negative polarity and a downflow of 0.5 - 1 km s^{-1} in the positive polarity. Thus the stronger magnetic field is associated with the downflow. They suggest that the simplest and most natural explanation of their results is a siphon flow along small arched flux tubes crossing the neutral line, as we have predicted. (They caution, however, that they cannot say for sure that they are seeing the two footpoints of the same flux tube.) The observed association of the stronger magnetic field strength with the element containing the downflow is in accord with our model, and the observed values of the field strength are consistent with our calculations.

We are continuing our theoretical modelling of the production of intense photospheric flux tubes by the siphon-flow mechanism, in collaboration with Benjamin Montesinos (Oxford), Sami Solanki (ETH, Zurich), Doug Rabin (NSO/Tucson), and Detlev Degenhardt (HAO/NCAR).

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SUNSPOT SEISMOLOGY

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Sunspot seismology is the branch of heliosiemology that makes use of observations and theoretical models of the interaction between a sunspot and the resonant acoustic oscillations (*p*–modes) of the Sun in order to deduce something about the structure of the sunspot below the solar surface.

Application of the techniques of sunspot seismology may help us solve the puzzle of the subsurface structure of a sunspot's magnetic field. Although sunspots have been known to be a magnetically dominated phenomenon ever since Hale's discovery of the intense magnetic field in a sunspot in 1908, we still do not know what the geometric configuration of this magnetic field is below the solar surface, nor do we understand exactly how a sunspot can hold together for a month or more in spite of the several physical mechanisms tending to break it apart. In particular, sunspot seismology may well settle the current controversy as to whether a sunspot's magnetic flux is fairly smoothly distributed over its cross–sectional area (the so–called monolithic model) or is clumped into individual flux tubes separated by field–free gas (the so–called cluster model). (For an extensive discussion of this and other issues concerning the physics of sunspots, see the recent volume edited by Thomas and Weiss 1992). Beyond our immediate desire to understand sunspots, research in sunspot seismology has much broader implications because sunspots are the natural test bed for astrophysical magnetohydrodynamics. Surely we must have a firm theoretical understanding of an object so immediate and well observed as a sunspot before we can confidently extrapolate our theory to such phenomena as stellar magnetic fields or interstellar jets.

As with nearly all new methods in astronomy, sunspot seismology will surely unveil new phenomena as well as shed light on known phenomena. This has already proved to be true, with the remarkable discovery by Braun, Duvall, and LaBonte that sunspots absorb an appreciable fraction of the energy of the incident acoustic oscillations (*p*–modes) of the Sun. This phenomenon will be discussed in more detail a few paragraphs below.

The concept of sunspot seismology was introduced ten years ago by Thomas, Cram, and Nye (1982) in a brief paper based on spatially unresolved measurements of oscillations inside a sunspot umbra and a simple model of the interaction between the sunspot and the *p*–modes. Temporal power spectra of these umbral oscillations showed reproducible peaks which were interpreted as representing the response of the sunspot to specific incident *p*–mode oscillations with energy concentrated at different depths. The simple theoretical model of the nature of this interaction then led to a measure of the radius of the overall sunspot magnetic flux tube with depth. However, because of the lack of spatial resolution, the procedure for identifying specific modes was highly uncertain.

The first spatially resolved measurements in sunspot seismology were carried out by Abdelatif, Lites, and Thomas (1986). They compared the power spectrum of oscillations in a sunspot umbra with the power spectrum of oscillations in an equivalent area in the quiet Sun outside the sunspot and found the following: (i) the dominant 5–minute *p*–mode oscillations have reduced amplitude inside the umbra, with an rms velocity about half that in the surrounding quiet photosphere; (ii) there is a general shift of oscillatory power to longer horizontal wavelengths in the umbra: and (iii) the umbra acts as a selective filter by transmitting certain frequencies of the incident *p*–modes in preference to other frequencies. These results were were given a simple theoretical interpretation by Abdelatif and Thomas (1987) on the basis of a model consisting of a vertical cylindrical magnetic flux tube embedded in a field–free, unstratified gas, with resonant *p*–modes produced by upper and lower reflecting horizontal boundaries. Horizontally propagating *p*–modes incident upon the flux tube are, in general, partially transmitted into the flux tube and partially reflected. The transmitted wave is a magnetoacoustic wave having greater horizontal phase speed, and hence longer horizontal wavelength, than the incident wave, which explains the shift of power to longer wavelengths in the umbra. The transmission coefficient as a function of horizontal wavelength exhibits peaks and valleys, because of the preferred transmission of waves for which an integral number of wavelengths fit across the diameter of the flux tube; this explains the selective filtering.

A different approach to sunspot seismology, first advocated on theoretical grounds by Bogdan and Zweibel (1987), is to treat the interaction of a sunspot with the solar *p*–modes as a classical scattering problem, using only measurements of oscillations in the quiet Sun surrounding the sunspot. This approach was first employed in observational studies by Braun, Duvall, and LaBonte (1987, 1988; hereafter BDL), who made the surprising discovery that sunspots absorb an appreciable fraction of the energy of the incident *p*–modes.

To illustrate the method of observing the scattering properties of a sunspot, let us consider the problem as formulated by Bogdan *et al.* (1992), which makes use of a spherical harmonic decomposition of the *p*–modes. Imagine a spherical coordinate system (r,θ,ϕ) on the Sun with its north pole placed at the center of a sunspot. Observations of the doppler velocity at the surface of the Sun in a region centered on the sunspot will yield a time sequence of Doppler images, i.e, velocity $v(\theta,\phi,t)$ as a function of position on a discrete grid in θ and ϕ at a sequence of discrete times t. Now consider this velocity over an annular region $\theta_1 < \theta < \theta_2$ centered on the sunspot with θ_1 chosen just large enough to exclude the sunspot from the annulus.The velocity can be represented as a superposition of inward and outward propagating waves on this annulus in terms of solutions of the associated Legendre equation, in the form

$$v(\theta, \phi, t) = \sum_l \sum_m \sum_n V(l, m, n)[P_l^m(\cos\theta) - \frac{2i}{\pi} Q_l^m(\cos\theta)]\exp[i(m\phi + 2\pi\nu_n t)] + \text{c.c.}$$

where c.c. denotes the complex conjugate. Values of the separation constant l are

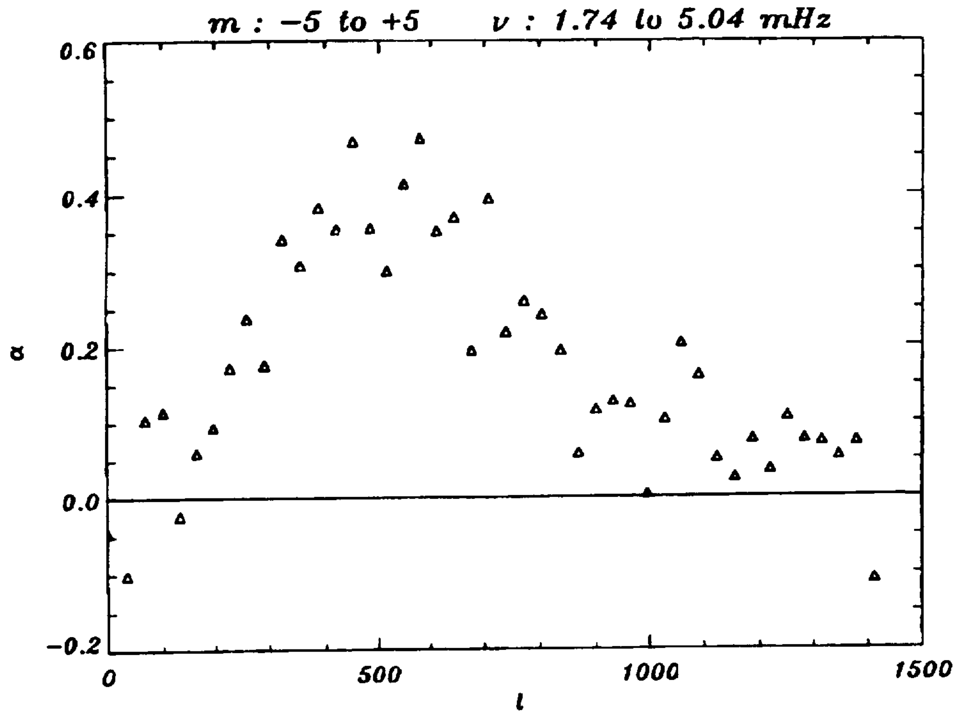

Fig. 1. The absorption coefficient α for the absorption of solar *p*–modes by a sunspot, as a function of mode degree *l* (from Bogdan *et al.* 1992).

selected so that the wavefunctions are mutually orthogonal on the annulus. The azimuthal index m takes on only integer values (positive and negative), and the index n denotes the discrete frequencies ν_n measured by the discrete time series. By considering the asymptotic form of the associated Legendre functions for large *l*, it is found that positive values of n correspond to waves propagating radially inward across the annulus and negative values of n correspond to outward propagating waves. Hence, we can define an absorption coefficient

$$\alpha(l, m, n) = \frac{|V(l, m, |n|)|^2 - |V(l, m, -|n|)|^2}{|V(l, m, |n|)|^2} ,$$

which gives the fractional absorption of wave energy as a function of degree *l*, azimuthal order *m*, and frequency ν_n. One can then look at the absorption in less detail and, for example, sum the absorption coefficient $\alpha(l, m, n)$ over several azimuthal orders and look at absorption as a function of degree *l* and frequency ν_n.

Following the approach of BDL, one can sum the absorption coefficient over several azimuthal orders and over all frequencies in the dominant *p*–mode band and then look at absorption as a function only of degree *l* (or, equivalently, as a function of horizontal wavenumber $k = [l(l+1)]^{1/2}/R_0$). Figure 1 shows the results of doing this with our data (Bogdan *et al. 1992*), summing over all azimuthal orders *m* from – 5 to + 5 and all frequencies from 1.74 to 5.04 mHz (the same ranges as in BDL). Our results show the absorption coefficient increasing with increasing degree *l* (i.e., increasing horizontal wavenumber k) up to a maximum value of about 0.5 at an l of around 500 (horizontal wavenumber about 0.8 Mm^{-1}) and then decreasing to near zero for l around 1000 (horizontal wavenumber about 1.6 Mm^{-1}). Our results in Figure 1 agree remarkably closely with those of BDL (for their 18 January 1983 sunspot) in the range $0 < l < 500$. But they disagree in the range $500 < l < 1000$, where BDL find the absorption coefficient to remain roughly constant at a value of about 0.5 but we find it to decrease nearly linearly to zero over the same range. The reason for this disagreement is not yet understood; it could be a consequence of the better spatial resolution of our data, or perhaps it could be due to truly different behavior of the two different sunspots.

Our data have sufficient spatial and temporal resolution to permit us to begin to examine the absorption as a function of degree l along individual p–mode ridges in a diagnostic (l–ν) diagram. When we do this, we find an apparent sinusoidal–like variation of the absorption along each p–mode ridge (Bogdan *et al.* 1992). If this variation can be confirmed and measured more precisely, it could serve as a very useful diagnostic of the physical absorption mechanism and, ultimately, of the subsurface structure of a sunspot.

A number of physical mechanisms have been proposed for the absorption of p–modes by sunspots, involving such mechanisms as resonance absorption, enhanced dissipation by small–scale inhomogeneities, and coupling of the waves to "leaky" modes of the sunspot's magnetic flux tube. For a full discussion of these proposed mechanisms, the reader is referred to the recent review by Bogdan (1992). Here I shall only mention the recent theoretical model of Spruit and Bogdan (1992), which has many attractive features. It is based on the conversion of incident p–modes into slow magnetoacoustic modes of the sunspot flux tube, which then propagate downward out of the p–mode cavity in the upper convection zone and thus provide a leak of wave energy and an apparent absorption of the incident p–modes. In particular, their model predicts the sort of sinusoidal variation of absorption along individual p–mode ridges that we see in our data. At this point, neither the observations nor the theory are sufficiently refined for a definite conclusion to be drawn. What one can say, however, is that the subject of sunspot seismology, now a decade old, appears to be on the threshold of fulfilling some of its promises.

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