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Sunspot Dynamics

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1. INTRODUCTION

This report describes the results our theoretical and observational research on dynamical phenomena in sunspots under NASA Grant NSG-7562 during the entire grant period, October 1978 through September 1990. The goal of this research was an understanding of the various oscillatory, transient, and quasi-steady motions in sunspots and the basic structure of a sunspot. The research involved both theoretical modeling (based on magnetohydrodynamic theory) and observations of dynamical phenomena in sunspots. The principal topics of the research were the following: (i) sunspot seismology, i.e., the interaction of solar p-modes with a sunspot as a probe of the subsurface structure of a sunspot; (ii) three-minute umbral oscillations and their relation to the structure of the umbral atmosphere; (iii) siphon flows in isolated magnetic flux tubes and their relation to the photospheric Evershed flow and to intense magnetic elements outside of sunspots; and (iv) more general theoretical work on magneto-atmospheric waves.

The results of the research under this grant have all been reported in published journal articles. Hence, this report consists only of a brief summary of these results along with references to the appropriate articles. A complete bibliography of the publications supported by this grant may be found at the end of this report. We should also note that our research on these topics is continuing under a new NASA grant, NAGW-2123, which is actually a continuation of NASA Grant NSG-7562 but was assigned a new number by NASA.

2. SUNSPOT SEISMOLOGY

Perhaps the most important research to arise from this NASA grant is that on "sunspot seismology," the use of five-minute oscillations in and around a sunspot as a probe of the subsurface structure of a sunspot. There are two types of oscillations in sunspot umbrae: three-minute oscillations, which have been identified as resonant modes of the sunspot itself (see section 3 of this proposal), and five-minute oscillations, which represent the response of the sunspot to forcing by the p-mode oscillations in the surrounding convection zone (Thomas 1981). Thomas, Cram, and Nye (1982) first showed how the five-minute oscillations in a sunspot might be used as a probe of the subsurface structure of the sunspot magnetic field.

Abdelatif, Lites, and Thomas (1984, 1986) made detailed observations of five-minute oscillations in a sunspot and its surroundings. They showed that the sunspot acts as a selective filter in transmitting certain frequencies in the power spectrum of the five-minute p-mode oscillations in the surrounding convection zone. They also showed that oscillatory power is shifted to longer wavelengths in the umbra. Both of these effects are exhibited by simple theoretical models in which the sunspot is modeled as a magnetic slab (Abdelatif 1985) or magnetic cylinder (Abdelatif and Thomas 1987). The horizontal wavelength of an acoustic wave is increased as it is transmitted into the magnetic region in the form of a fast magneto-acoustic wave, causing a shift of oscillatory power to longer horizontal wavelength (lower horizontal wavenumber), as observed. The transmission coefficient for waves entering the model sunspot umbra varies up and down with wavelength because of the phenomenon of resonant transmission; this explains the observed selective filtering of the p-modes by the sunspot.

Abdelatif and Thomas (1987) modeled the sunspot as a single, monolithic magnetic flux tube, which is the conventional model. In related work, Bogdan (1987; see also Bogdan and Zweibel 1987) studied the interaction of acoustic waves with a sunspot consisting of a cluster of individual, isolated magnetic flux tubes, a model first proposed by Parker (1979). These two complementary theoretical approaches, coupled with observations and the methods of sunspot seismology, promise to determine which (if either) of these two theoretical models of subsurface sunspot structure is correct.

Observations by Braun, Duvall, and LaBonte (1987, 1988) have shown that a sunspot absorbs an appreciable fraction of the energy of incident p-modes, or perhaps scatters the energy into unresolved modes of high horizontal wavenumber. The physical mechanism for this apparent absorption of energy is not well understood, although several possible mechanisms have been proposed.

Our more recent observational research on sunspot seismology has been done in collaboration with Bruce Lites, Tim Brown, and Tom Bogdan of the High Altitude Observatory. Our approach has been to measure the oscillatory velocity field in an isolated sunspot and in a surrounding region of substantial size. In order to probe subsurface structure over a range of depths, we observe the oscillatory velocity field over a wide range of horizontal wavenumbers. For this purpose, we carried out two complementary and simultaneous observational programs using two different instruments: high-wavenumber (or, high spatial resolution) measurements with the vacuum tower telescope at NSO/Sunspot, and low-wavenumber measurements with the HAO/NSO Fourier tachometer at Tucson. These observations are directed at probing the structure of a single sunspot at different depths in the convection zone through measurements of high and medium wavenumber p-modes inside and outside the sunspot. The results should allow us to distinguish between models of the sunspot based upon a single, large magnetic flux tube or a cluster of smaller individual flux tubes, and to measure the overall diameter of the sunspot magnetic field as a function of depth. We obtained five good data sets of four to seven hours duration on three different sunspots during the period 14-23 March 1989, plus a control run on quiet sun at disk center. Reduction of the best of these data sets has produced a time series of velocity maps that is as free of instrumental artifacts as possible. With support from the continuation grant (NAGW-2123), we are currently analyzing the absorption of p-modes by the observed sunspot. Preliminary results show that we are able to measure this absorption as a function of frequency and wavenumber with much better resolution than has been achieved previously. These new results, together with the advances in the theoretical interpretation of the absorption mechanism that have been made recently, suggest that some of the goals of sunspot seismology will be achieved soon.

3. THREE-MINUTE UMBRAL OSCILLATIONS

A major part of the research effort under this NASA grant over the years was devoted to theoretical and observational studies of the characteristic three-minute umbral oscillations in sunspots. A detailed theory was developed (Scheuer and Thomas 1981; Thomas and Scheuer 1982) in which the three-minute umbral oscillations are identified as a resonant mode of fast magneto-atmospheric wave that is nearly trapped in the umbral photosphere and subphotosphere. Although most of the wave energy is trapped in the photosphere and subphotosphere, some of the energy escapes in the form of acoustic waves propagating upward along nearly vertical magnetic field lines. These acoustic waves can produce an additional resonance in the chromosphere (Zhugzhda, Locans, and Staude 1983; Gurman and Leibacher 1984). These later authors suggested that the chromospheric resonance alone, excited by acoustic noise from the convection zone, is responsible for the three-minute umbral oscillations. However, our subsequent observations detected the three-minute umbral oscillations at photospheric heights, where the kinetic energy density of the oscillations is at least five times greater than in the chromosphere (Thomas, Cram, and Nye 1984; Abdelatif, Lites, and Thomas 1984, 1986; Lites and Thomas 1985). Furthermore, the results of Lites and Thomas (1985) show that the three-minute umbral oscillation is a coherent vertically standing wave in the photosphere. These results confirm the presence of the photospheric resonance in sunspot umbrae. A summary of the observational evidence (Thomas 1984b, 1985a; Lites 1984, 1986) indicates that the photospheric resonance is the fundamental source of the three-minute umbral oscillations, but that additional higher-frequency peaks usually observed in the power spectra of chromospheric velocity are produced by the chromospheric resonance.

The photospheric resonance may possibly be excited internally by overstable convection in the umbral subphotosphere (Moore 1973; Mullan and Yun 1973). Alternatively, Moore and Rabin (1984) have suggested that the three-minute umbral oscillations are excited by high-frequency components of the solar p-modes outside the sunspot. Some observational evidence argues against external excitation by the p-modes and favors internal excitation (Lites and Thomas 1985; Lites 1986), but this evidence is not conclusive. Further work on identifying the excitation mechanism of the three-minute umbral oscillations is needed.

We made simultaneous observations of umbral oscillations with the UVSP instrument on the SMM satellite and with the tower telescope, echelle spectrograph, and multi-diode array at NSO/Sunspot (Thomas, Lites, Gurman, and Ladd 1987). With the UVSP we measured the oscillations in the transition region line C IV 1548 and from the ground we measured the oscillations in He I 10830 (upper chromosphere), Ca II K (chromosphere), and Fe I 3969 (photosphere). This gave us a simultaneous measure of the oscillations over a great range of height in the umbral atmosphere and allows us to study the vertical structure and propagation properties of the oscillations in more detail than has been done before. The power spectra of velocity and intensity variations have multiple peaks in the three-minute band (4.5-10 mHz). A strong oscillation at 5.5 mHz is coherent between the chromosphere and transition region. Another strong oscillation at 7.5 mHz is coherent between the photosphere and transition region and appears to have a node in the chromosphere. The rms velocity in the three-minute band is a little over 1 km s^{-1} in both the chromosphere and transition region, but the kinetic energy density is much lower in the transition region (by a factor of ten or more) because of the lower mass density there. This indicates a strong downward reflection of the waves in the transition region.

Our simultaneous measurements of the oscillation amplitude in the chromosphere and transition region provide an independent dynamical test of models of a sunspot atmosphere. At these heights the plasma beta is small and the waves are essentially pure acoustic waves along the predominantly vertical magnetic field lines. For a given atmospheric model, one can calculate the ratio of wave amplitudes at the heights of formation of the chromospheric and transition-region spectral lines and compare the calculated ratio with the observed ratio. This comparison can be extended to include more spectral lines and can be used to fix the value of one or more parameters in a model sunspot atmosphere, such as the steepness of the temperature gradient in the transition region.

In one of our earlier observational papers (Thomas, Cram and Nye 1984) we reported the discovery of light bridge flashes, which are sporadic, strong brightenings and broadenings of the Ca II K line. The K line emission profile during a light bridge flash is broader, more intense, and more symmetric than the profile during a normal umbral flash.

4. EVERSHED FLOW AND PENUMBRAL STRUCTURE

Substantial progress was made in our the study of the phenomenon of siphon flows in isolated magnetic flux tubes, which is related to the photospheric Evershed flow and the filamentary structure of the penumbra as well as to the structure of intense flux tubes in the quiet photosphere. This work is described in a series of papers (Thomas 1984a, 1988, 1989; Montesinos and Thomas 1989; Thomas and Montesinos 1990a,b,1991).

Previous 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 considered steady siphon flows in 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 calculated steady isothermal siphon flows in arched, isolated magnetic flux tubes in a stratified atmosphere (Thomas 1988). 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 slows offer a mechanism for producing concentrated magnetic flux in the solar photosphere. Under a wide range of conditions, the Bernoulli effect is 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. In a critical 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." A critical flow is "choked" in the sense that the mass flow rate is the same for all allowable values of the backpressure at the downstream footpoint. In addition to critical flows, there are purely subcritical and purely supercritical flows which do not require tube shocks.

In collaboration with Benjamin Montesinos (Department of Theoretical Physics, University of Oxford), our study of siphon flows in isolated magnetic flux tubes was extended to the case of adiabatic flow and the results were compared with the isothermal flows (Montesinos and Thomas 1989). The results for these two limiting cases of the energy equation provide insight into the behavior of flows with a more complicated energy equation coupled with radiative transfer. In general, the isothermal and adiabatic flows are qualitatively similar, although the conditions for critical flow are quantitatively different (and we have explored these conditions thoroughly). However, if in the adiabatic case we make the internal temperature at the upstream footpoint either less than or greater than the external temperature, then qualitatively different flows can occur. In a cold tube the cross-sectional area can actually decrease with height near the upstream footpoint, while in a hot tube the velocity can actually decrease with height near the upstream footpoint.

We have calculated the equilibrium path of an arched, isolated, thin flux tube containing a siphon flow (Thomas and Montesinos 1990a). 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).

In further work (Thomas and Montesinos 1991) we computed critical, or "choked," siphon flows including the standing tube shocks in the downstream part of the tube. Determining the detailed structure of the standing tube shock is a complicated problem that cannot be treated within the thin flux tube approximation. However, 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 all allowable values of the backpressure at the downstream footpoint. We also extended our calculations to include a more realistic external atmosphere (Thomas and Montesinos 1991). Currently we are extending these calculations to include radiative transfer between the flux tube and the surrounding atmosphere.

Meyer and Schmidt (1968) first suggested that the Evershed flow is a siphon flow along magnetic flux tubes. Their analysis and other analyses based on an embedded flux tube in the low-β limit are not appropriate for photospheric levels, however, whereas our analysis of flows in isolated flux tubes is. We have considered the possibility that the photospheric Evershed flow is a siphon flow along the dark penumbral filaments (Thomas 1988; Montesinos and Thomas 1989). Using the penumbral model of Nye and Thomas (1974), we found good agreement between observed flow speeds and the predicted maximum flow speed (the tube speed) in the rising part of the arched flux tube. The siphon flow also provides a mechanism for concentrating the magnetic flux and keeping it thin. We are now extending our model to include the effect of an ambient magnetic field in the atmosphere outside the flux tube, which gives a more realistic model of the situation in the penumbral photosphere.

There is a theoretical difficulty in identifying the photospheric Evershed flow with siphon flows along the dark filaments, however, as pointed out by Cram, Nye, and Thomas (1981). From the point of view of radiative transfer, it is difficult to reconcile the darkness of the filament with the fact that the gas density inside an isolated magnetic flux tube must in general be lower than the surroundings (magnetic buoyancy). More realistic computations of penumbral siphon flows with an ambient external magnetic field and realistic radiative transfer may well resolve this difficulty. We are currently doing these calculations.

In an observational paper (Nye, Thomas, and Cram 1984) we reported measurements of downdrafts within moving magnetic features which move outward across the moat surrounding a large sunspot. This discovery has recently been confirmed by Lites (private communication), who has also made the interesting suggestion that these downdrafts could be the continuation of the photospheric Evershed flow outside of the sunspot. This idea fits in very well with a siphon-flow model of the Evershed flow in which the downstream footpoint of the flux-tube arch is the moving magnetic feature outside the penumbra.

Siphon flows in isolated magnetic flux tubes also offer a possible mechanism for creating some of the intense magnetic elements observed in the quiet solar photosphere. We have discussed this application in two papers (Thomas 1989; Thomas and Montesinos 1990b).

5. MAGNETO-ATMOSPHERIC WAVES

Theoretical work on oscillations in sunspots generally involves the study of magneto-atmospheric waves (or magneto-acoustic-gravity waves), which are waves in a stratified, compressible, electrically conducting atmosphere under gravity, permeated by a magnetic field. These waves are supported by a combination of the restoring forces due to compression, buoyancy, and distortion of the magnetic field. Our research under this NASA grant has led to a better general understanding of magneto-atmospheric waves.

We have shown the limitations of the local dispersion relation for magneto-atmospheric waves and proposed a new, self-consistent form for this relation (Thomas 1982). We calculated the asymptotic far-field solution for magneto-atmospheric waves generated by a spatially concentrated time-harmonic source (Adam and Thomas 1984). We summarized our knowledge of magneto-atmospheric waves in two review articles (Thomas 1983, 1985b); the second of these reviews covers waves in structured magnetic fields and magnetic flux tubes.

In our analysis of theoretical models of the interaction of p-modes with a sunspot (Abdelatif and Thomas 1987), we found it necessary to solve the problem of the reflection and transmission of compressive waves across a nonmagnetic-magnetic interface. Previously this problem had been solved only for a very special case (Cram and Wilson 1975). An acoustic wave incident upon the interface can excite a fast magneto-acoustic wave, a slow magneto-acoustic wave, or an evanescent wave in the magnetic region, depending on the direction of incidence and on the values of two parameters: the ratio of the sound speeds in the two regions and the ratio of the Alfvén speed to the sound speed in the magnetic region. We solved the linearized problem in complete generality (Abdelatif and Thomas 1989). The results have wide application in solar physics and more generally in astrophysics.

Our expertise in magneto-atmospheric waves was also applied in a collaborative study of nonradial oscillation modes of a magnetic neutron star (Carroll *et al.* 1986).

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