ENERGY TRANSPORT BELOW SUNSPOTS AND FACULAE

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1. INTRODUCTION

In the classical view of sunspot cooling, Biermann (1941) suggested that convection within sunspots is suppressed by the magnetic field. This would lead to a lower temperature in the umbra. Parker (1974) first noted a difficulty with this model, suggesting that the energy suppressed by the magnetic field should give rise to a bright ring around the sunspot, which is not observed. As an alternative to Biermann's field inhibition mechanism, Parker (1979) later examined the dynamical cooling for sunspots. He showed that in the Sun's upper convection zone, the "superadiabatic" environment is such that downflows with velocities of several km s^{-1} could lower the temperature sufficiently to cool sunspots by 1000 K. Such an inflow and downflow pattern had also been suggested by Meyer et. al. (1974) in order to resolve the problem with the physical stability of sunspots. These authors accepted the Biermann mechanism and proposed also an upflow pattern surrounding the sunspot, leading to its dissolution, but they did not examine the temperature structure. Recent support for a flow pattern has been found by Zirin and Wang (1989) who measured proper motions of 0.5 km/sec from bright features seen in the penumbral region of sunspots, which then disappeared into the umbra.

The high velocity flows that Parker suggested were comparable to those observed by Frazier (1970) and Deubner (1976) within darkened solar features. However, more recently, these high velocities have been viewed as an observing artifact (Beckers, 1976; Miller, Foukal, and Keil, 1984; Cavallini, Ceppatelli and Righini, 1985), and it was shown that smaller vertical flows with speeds of order 10 m s^{-1} can be supported by the observations. Significant cooling from such low velocity flows was suggested by Schatten and Mayr (1985). The energetics of sunspots was compared to that of terrestrial hurricanes, in which latent energy is released in the transition of water vapor to liquid water. For sunspots it was suggested that the latent energy in the ionization of hydrogen could fuel the dynamical cooling. We found that dynamical cooling could occur with particle fluxes of 2×10^{21} particles cm^{-2} s^{-1}, corresponding to small downflow velocities of only 2 m s^{-1} at 2,000 km depth, thereby "rejuvenating" the Parker mechanism. In the present paper we shall reexamine this mechanism and adopt vertical velocities to compute the temperature distributions below sunspots and faculae.

In the flow model of Schatten and Mayr, the amount of material moving downwards below sunspots is replenished by material moving upwards in the surrounding active region, and the associated energy transport can power faculae. The vertical velocities are perceived to be part of a three dimensional circulation in which energy is essentially redistributed between sunspots and faculae: suppressing convection in sunspots, but aiding the heat transport to form faculae. The magnetic field plays the role of guiding these flow patterns. With this picture, the energy deficit in sunspots and the excess energy released in faculae would be in rough balance and indeed this is observed (e.g., Chapman et al., 1984).

Schatten and Mayr (1985) suggested that faculae could have a "hillock" (50 - 200km high) structure, formed as a result of the enhanced scale height and buoyancy of the hot gases below faculae. The suggested flow mechanism and the resulting hillock geometry of faculae are markedly different from the classical field inhibition mechanism in which faculae are perceived to form wells. In an attempt to distinguish between the two models, Schatten et al. (1986) concentrated on studying faculae. Faculae are virtually unobservable at disk center, but show generally an increasingly brighter contrast as they progress in their journey towards the limb. Very near the limb, their contrast may decrease slightly due to obscuration effects from the surrounding photospheric gases; however, they are still significantly brighter than the limb darkened gases. Sunspots on the other hand, with a dark appearance, are viewed most prominently at disk center.

With this picture, Schatten et al. then developed a conical "hillock" model against which facular contrasts could be compared. In this model, all the photospheric isotherms and isobars were vertically elevated into a 200 km conical hillock shape, ignoring the presumed small temperature changes at the surface that must be associated with the perceived expansion of the facular gas. This model is analogous to the addition of heat applied to a pot of boiling water. This will not significantly raise the temperature, but simply distort the otherwise flat surface. For the photosphere, the distorted geometry enhances the emission by increasing the gradient in temperature and density that the "pencils of radiation" must pass through in exiting the sun. This model provided reasonable agreement with observations at four widely differing continuum wavelengths from 4,000 to 10,000 Å. Further, the disk central low contrast of faculae occurred naturally in this model, since a ray path exiting the facula normally would encounter the same density and temperature profile as a ray path exiting the photosphere normally. Recently, Schatten et al. (1989) also found a statistical relation between sunspot areas and facular plage size, in that faculae appear to "blanket" sunspot areas when they approach the Sun's limbs, consistent with the hillock geometry.

To begin with, in Section 2, we discuss the physical basis for our one dimensional "dynamical" model. The dynamics enters into the present calculations only through the energy equation. Magnetic fields have not been included for three reasons: 1) Static fields do not directly affect the energy balance. 2) Uniform fields, additionally, do not affect the vertical momentum balance. 3) To include fields would require a three-dimensional model, taking into account their complex interaction with a non-uniform convecting plasma, which is beyond the scope of our simplified model. In Section 3, three computer runs are discussed which illustrate the model's behavior. Our model requires some disturbance, and we consider field inhibition to initiate the motions. Thus in Section 4, Biermann's mechanism is considered to suggest that sunspot-field inhibition can complement dynamical cooling. We conclude with a discussion of our findings and suggest new observations that may serve to test the model. We shall emphasize that our one dimensional model cannot describe many of the details in the facular emission such as the brightness relationships discussed by Spruit and Zwaan (1980).

2. DYNAMICAL ENVELOPE MODEL

Stellar envelope models of the Sun (Endal and Twigg, 1982; Cox and Giuli, 1968; Paczynski, 1969) consider the global scale energy balance to describe the vertical temperature and density distributions. Assuming hydrostatic equilibrium, the transfer of radiation is balanced by diffusive (convective) heat transport, with the diffusion coefficients taken from mixing length theory.

For our analysis we adapt the envelope code of Endal and Twigg (1982), but additionally allow for energy advection or flow heating/cooling. In this section, we show how the energy equation applies to a superadiabatic atmosphere with transport occurring via flows, eddy diffusion, and radiation. We assume that these processes occur sufficiently fast so that equilibrium is established and the time dependence can be ignored. In the following, the equations are discussed for an ideal gas, but later, modifications will be made for the non-ideal gas of the real solar atmosphere. For the energy balance of an ideal gas, the change in internal energy can be written (Gill, 1982):

$$\nabla \cdot \vec{F}^{rad} + \nabla \cdot \rho E \vec{U} + p \nabla \cdot \vec{U} = -\frac{\partial(\rho E)}{\partial t} \approx 0 \tag{2.1}$$

where E is the internal energy per unit mass; ρ is the density, p is the pressure; F^{rad} is the radiative energy flux, and U is the velocity. Neglecting the kinetic energy of the bulk motion $1/2\ U^2$, the internal energy can be written as $C_v T$, where T is the temperature.

Considering mass conservation, the perfect gas law and hydrostatic equilibrium, equation (2.1) can then be written as

$$\nabla \cdot \vec{F}^{rad} + \rho C_p \vec{U} \cdot \vec{S} = 0 \tag{2.2}$$

Here, the specific heat at constant pressure is $C_p = C_v + R$, and the potential (superadiabatic) temperature gradient is $S = \nabla T + \Gamma$, where $\Gamma = g/C_p$. We write U = W + V, introducing the vertical and horizontal velocity components, in the vertical, r, and horizontal, x, directions, respectively. In a stratified atmosphere, the vertical variations are normally much larger than the horizontal variations $\partial/\partial r >> \partial/\partial x$. Similarly, the horizontal velocities are usually much larger than the vertical velocities, so that $\partial W/\partial r \approx \partial V/\partial x$. Thus, horizontal as well as vertical energy advection should be important. The energy equation then can then be written in simplified form:

$$\frac{\partial F^{rad}}{\partial r} + \rho C_p W S + \rho C_p V \frac{\partial T}{\partial x} = 0 \tag{2.3}$$

where $S = \partial T/\partial r + \Gamma$ is the vertical component of the vector S.

In Equation (2.3), the first term describes the net contribution from the radiative flux, the second term describes the contributions from the vertical advection, and the third term from the horizontal advection. The vertical and horizontal advections can dominate in different regions and can have opposite signs. Consider a downflow of moving material in the Sun's convection zone. In the upper portions of the convection zone, near the photosphere, the atmosphere is highly superadiabatic; thus, the downflow results in a large cooling (as cooler material from above replaces the warmer material below). This cooling diminishes with depth since the superadiabatic temperature gradient goes to zero there. For the horizontal advection we must consider the horizontal temperature gradient. As the material cools and descends, it is surrounded by hotter gases. Thus, the inflow of energy will produce heating. At higher altitudes near the photosphere, in the presence of a strong vertical magnetic field, this horizontal flow heating will be greatly diminished. Deeper down, however, where the vertical advection is small the horizontal advection may dominate.

In addition to the steady flow, we must also consider the usual eddy fluctuating component, w'. The latter enters in the expression:

$$\overline{C_p\rho' W'S'} = \frac{\partial(\rho C_p KS)}{\partial r} \tag{2.4}$$

which contains the vertical eddy diffusion coefficient, K. With (2.4), we can then describe the energy equation for localized disturbances within the Sun:

$$\frac{\partial F^{rad}}{\partial r} + \frac{\partial(\rho C_p KS)}{\partial r} + \rho C_p W S + \rho C_p V \frac{\partial T}{\partial x} = 0 \tag{2.5}$$

Relating to standard envelope theory, we write equation (2.5) in the form:

$$\frac{\partial F^{rad}}{\partial r} + \frac{\partial(\rho C_p KS)}{\partial r} + Q_{eff} = 0 \tag{2.6}$$

where

$$Q_{eff} = \underbrace{\rho C_p WS}_{\substack{\text{vertical}\\ \text{advection}}} + \underbrace{\rho C_p V \frac{\partial T}{\partial x}}_{\substack{\text{horizontal}\\ \text{advection}}} \tag{2.7}$$

With Q_{eff} we basically add the influence of flow (vertical and horizontal) to the standard envelope theory (in which $Q_{eff} = 0$). This allows us to investigate the effects of flow on the vertical distributions of temperature, pressure, density and surface irradiance. For simplicity, a perfect gas was considered in the above equations. Variations in the specific heat associated with an imperfect gas, however, were incorporated into the computer code.

When a real gas is considered, the contribution from the latent energy becomes important for the energy equation. There are two ways to account for this effect. The astrophysical approach is to combine the changes in latent energy (release of ionization energy) with the specific heat and modify the adiabatic lapse rate accordingly. This approach is actually used in the envelope code presented in Section 3 (Endal and Twigg, 1982). Here, we provide a brief review of the equivalent but simpler meteorological approach which separately accounts for the changes in the latent energy (e.g.. water vaporization in the earth's atmosphere) and thermal energy.

The energy equation (2.1) is modified to include latent energy release for a terrestrial pseudo-adiabatic process in which the mass of air changes by precipitation. After (Gill, 1982), the additional term is:

$$Q_H = -\frac{\rho L_v}{1 - q_w} \frac{Dq_w}{Dt} \tag{2.8}$$

where L_v is the latent energy, and q_w is the specific humidity. For hydrogen ionization, where $a = [H]^+/([H]^+ + [H]) = [H]^+/H_T$ is the fraction ionization, and the ionization energy I = 13.6 eV/particle = 21.8×10^{-12} erg/particle = 1.31×10^{13} erg/mole, equation (2.8) is modified, assuming that the reactants do not leave the volume element:

$$Q_H = -I\rho \frac{D\alpha}{Dt} = -I\rho\, U \cdot \nabla\alpha \tag{2.9}$$

Temporal variations are ignored here. Following the earlier described procedure for the ideal gas, equation (2.6) is then modified

$$\frac{\partial F^{rad}}{\partial r}+\frac{\partial(\rho C_p K S_\alpha)}{\partial r}+Q_{eff}=0 \qquad (2.10)$$

where

$$S_\alpha=\frac{\partial T}{\partial r}+\Gamma+\frac{I}{C_p}\frac{\partial \alpha}{\partial r} \qquad (2.11)$$

is the superadiabatic temperature gradient with ionization. The adiabatic temperature distribution (lapse rate) for an ionized medium is equivalent to $S_a = 0$, similar to the neutral, $S = 0$, adiabatic temperature gradient.

As pointed out earlier, we adapt the computer code of Endal and Twigg (1982) and integrate the stellar envelope equations governing temperature, density, radius, and optical depth using the envelope mass, $M - M_r$, as the independent variable. This computer code accounts for the latent energy associated with ionization. We modify the energy equation by adding an effective heat source, Q_{eff}, which represents vertical and horizontal advection. We shall now construct models of sunspots and faculae to ascertain the cooling and heating necessary to form these photospheric features.

3. SUNSPOT AND FACULAR MODELS

In this section we utilize the above described stellar envelope code, which includes vertical and horizontal advection. We provide three model solutions to illustrate: 1) the effect of vertical advection; 2) the effect of horizontal advection; and 3) the significance of the depth at which these processes occur.

Sunspots, in addition to possessing a cooler effective temperature than the undisturbed photosphere, consist of a local geometrical depression of order 500 km (Allen, 1973). This depression was discovered by Alexander Wilson in 1774 from the observed extensive flattening of sunspot geometries as they approached the solar limb. The Wilson depression is generally viewed as a manifestation of the sunspot magnetic field as it excludes material in accordance with the horizontal pressure balance. In our model, we consider the vertical momentum equation and view the Wilson depression to be associated with the reduced buoyancy of the cooler, denser material below the sunspot umbra as well. Our envelope code attempts not only to model a cooler photosphere, but additionally a depressed surface for the sunspot umbra. For faculae, as discussed in the introduction, the buoyancy is thought to result in an uplifted surface with a minimal photospheric temperature enhancement. This appears capable of giving rise to the observed continuum contrast behavior.

Boundary Conditions. Our envelope code solves the second order energy equation and the first order equation of vertical momentum balance (hydrostatic equilibrium). Thus three boundary conditions are needed. We assume that the active region disturbance does not extend below a certain depth. Thus at the lower boundary at 12,000 km depth the temperature and density are assumed to be undisturbed and the energy flux there is equal to the Sun's irradiance. In practice, the equations are integrated downward, starting from the top of the photosphere, and a "shooting" technique is used to satisfy the lower boundary conditions. For this purpose, we choose the temperature (and equivalently the surface irradiance), the density, and the height of the radiating surface at an optical depth of 2/3 which defines the top of the photosphere. We provide magnitudes for the vertical and horizontal advections to define Q_{eff}, and vary these rates until, for a given subsurface density, pressure, and temperature, we can match the 3 boundary conditions of the undisturbed convection zone at a depth of 12,000 km.

Vertical Advection. Our first sunspot model 1, shown in Figure 1, describes the effects of vertical advection in a superadiabatic environment. The surface irradiance is lowered to 0.5 (in units of the Sun's normal surface irradiance), corresponding to a photospheric temperature of 4,836 K, and a downflow velocity of 500 m s^{-1} is adopted. Numerous problems arise from this calculation. The temperature of the disturbed region remains lower than that of the background throughout the entire convection zone and, as a consequence, the densities and pressures are elevated above the background below 2000 km depth. In steady state, with vertical advection only, the flow heating cannot do both: lower the surface temperature to umbral values and return the temperature at deeper levels to background values. With vertical advection alone, our boundary conditions cannot be satisfied.

Vertical and Horizontal Advection. Considering both vertical and horizontal advection through an effective term, Q_{eff}, Figures 2-3 show our model 2 for sunspot and facula. Figure 2 presents the computed temperatures, optical depths, densities and pressures for models of a sunspot, a facula, and the undisturbed solar envelope in the top few thousand km. First, note that near the photosphere (t = 2/3), the three curves in each panel have similar shapes. They can be almost superposed by simply shifting them in altitudes. This supports the view that these active region features can be modelled simply by an altered geometry (e.g., hillock or well). Second, note that the sunspot cooling, together with hydrostatic equilibrium, provides for a reduced altitude of the umbral photosphere (t = 2/3), in accordance with the Wilson depression. Although the sunspot density in the upper layers is lower than the undisturbed material at these depths, the densities are larger for the corresponding optical depth. Unlike the previous case, at greater depths, the densities are minimally enhanced compared with the undisturbed material, and the pressures, densities, and other thermodynamic state variables are unchanged below a few thousand km depth. Figure 3 shows the normal radiative transport plus eddy heat conduction, basically the surface irradiance, F_0, plus the vertical and horizontal advection. The effective heating is equal to the sum of the last two terms. The additional horizontal advection enhances the superadiabatic gradient and allows a velocity of 50 m s^{-1}, at 1,000 km depth, to offset the eddy heat conduction and lower the surface irradiance to umbral values. The return to background temperatures, densities and pressures satisfies hydrostatic balance associated with a reasonable sunspot depression.

Let us consider the magnitude of the advection terms to understand their relevance to the sunspot cooling problem. The chosen cooling associated with vertical advection peaked between 1,000 and 2,000 km depth. For densities of order 10^{-5} gm cm^{-3}, one requires 50 m s^{-1} vertical velocities to achieve the peaked 800 gm cm^{-3} s^{-1} Q_{eff} cooling in this model. The horizontal advection is easily achieved with similar velocities. For example, one observes that at the same depth, e.g. 2,000 km, the sunspot is cooler than its unperturbed surroundings by 1000 K. Even if we assume that the horizontal scale of this perturbation is 100,000 km wide, a horizontal temperature gradient of order 10^{-7} K cm^{-1} results. This allows horizontal velocities of 10 m s^{-1} to provide the heating necessary to return the cooled gases to their normal environment.

For faculae, the flow heating results in an uplifted photosphere related to the model of Schatten et al. (1986). Some important differences arise, too. For example, the isopicnic or equal density surfaces are spread out vertically near the photosphere, in addition to being uplifted. This will be the subject of a future paper. Our number 2 model is based on rough estimates of the photospheric boundary conditions, with the normal spot and facular surface irradiance and temperatures at t = 2/3 being: L_n = 1.0, L_s= 0.5, L_f = 1.1 (in units of the Sun's normal surface irradiance); T_n = 5,750, T_s = 4836, and T_f = 5,897 K, respectively. The flow velocities are near 50 m s^{-1} for downflow in the sunspot and near 20 m s^{-1} for upflow in the facula.

Surface elevation changes are associated with the depth of the cooling and heating terms, through the principle geophysicists refer to as "isostasy" - vertical hydrostatic equilibrium. A 600 km sunspot well and a 150 km facula hillock are calculated in this model. The sunspot value is close to the typically quoted 500 km Wilson depression (Allen, 1973). The value for the facula is comparable to the height required to explain facular contrasts in the Schatten et al. (1986) hillock model. The contrast modelling suggested a conical uplifted form with a base angle of 15°. The diameter for faculae is typically 1.6" = 1,200 km (Allen, 1973). This provides an altitude for the tip of the facular cone of 160 km, comparable to the present value of 150 km.

Advection at Greater Depth. Sunspot cooling has been discussed by Parker (1987) as occurring at a depth below 10,000 km. The association of the cooling depth with the hydrogen ionization layer near 2,000 km is an important aspect of the Schatten and Mayr (1985) sunspot model. To illustrate the significance of the cooling/heating depth, we have run another model where we have supplied the effective heating near 6,000 km depth. The surface irradiances for sunspot and facula were kept the same. Figure 4 shows the same physical parameters as in Figure 2 plotted versus depth. For a cooling region located near 6,000 km, a Wilson depression of 2,800 km results which is much larger than observed. For the facula, an uplift of 700 km results. Cooling regions significantly deeper than the hydrogen ionization layer, if they offset a significant fraction of the surface irradiance, provide too large a Wilson depression to be consistent with observations.

Because our computer model is one dimensional, a number of questions arise that bear on the three dimensional nature of the dynamics. For example, balancing only the vertical momentum equation leaves open what happens to the horizontal component. As our Figure 2 shows, there is no horizontal momentum balance, particularly near the upper levels. The spots have a reduced pressure and the faculae an enhanced pressure. Horizontal pressure gradients can be balanced by magnetic fields and/or flow motions. As pointed out by Meyer et al. (1974), an inflow pattern arising from reduced sunspot pressures can help stabilize sunspot fields against expansion.

For the faculae, the enhanced pressure would result in an outflow of material. The outflow would be greatest in the solar atmosphere above the photosphere, where pressure gradients are largest. There is observational evidence supporting this, in that plage have greater contrast in the chromosphere than faculae have in the photosphere. Additionally, the chromospheric manifestation of the facula (plage) covers a wider area than its photospheric manifestation, supporting the view of an outward expansion of the gases.

4. FIELD INHIBITION AND FLOW

Our model results show that appropriately chosen cooling and heating rates can reproduce the surface manifestations of sunspots (Wilson depression and 1000 K temperature reduction) and faculae (150 km hillocks associated with small temperature enhancements). However, our model has the weakness that it is 1-D in the vertical, along field lines, where the field exerts no influence. In a more realistic, 3-D model, the magnetic field can play an important role for the sunspot development. Biermann's field inhibition mechanism has a very attractive feature: sunspots and faculae are observed to be associated with magnetic fields. Notwithstanding some of the difficulties with the Biermann mechanism we examine here its positive aspects which may complement the advection view.

The Biermann mechanism can serve to initiate the disturbance, and the flow circulation may be the consequence. Strong magnetic fields can disrupt the convection locally, effectively blocking the heat flux from the interior and thereby starving the sunspot umbra of energy. As a result, the temperature would decrease. With reduced temperature and concomitantly lower density and pressure compared to the surroundings, a circulation would be induced which transports the energy away from the sunspot to form faculae. This circulation can also carry along some magnetic field which is observed in facular regions. Moreover, the magnetic field inhibits cross field motions and thus can reduce the diffusion coefficient by breaking up/inhibiting the eddies. The energy flux would then be suppressed as in the Biermann mechanism. In contrast to the original Biermann mechanism, however, flows would carry away the blocked energy, thereby supplying the energy that goes into the faculae. Biermann's mechanism would also tend to reduce the calculated flow velocities. This in turn would slow down the motions required to offset the eddy heat transport, and smaller flow velocities would be needed than those computed in our 1-D model.

In our picture, faculae can then be viewed as evidence for the disbursement of heat below sunspots. The ejection and disbursement of faculae from the vicinity of sunspots into the surrounding active region can be understood as a result of the "aerodynamic lift force", $-\rho V \cdot \nabla V$. Considering downflows below the sunspot and weaker upflows surrounding the active region, this aerodynamic force is directed inward near the sunspot (stabilizing the spot) and outward in the facular regions (disbursing faculae) where the flow is upward.

How does this compare with the earlier views of these structures? Meyer et al. (1974) had downflows surrounding the sunspot in the early growth stages of sunspot development and upflow patterns in the decay stage. The flows were only utilized for stability, not cooling. In the present view, the upflows do not immediately surround the sunspot but rather occur on fibril fields "peeled off" sunspot structures moving to a considerable distance from the sunspot ($\approx$ 50,000 km away) in the region where faculae exist on the outskirts of the active region. Since faculae do follow sunspot development, we note that the Meyer et al. view is remarkably similar to our picture. However, these authors had not identified faculae with the upflow pattern which sheds the suppressed sunspot energy.

5. DISCUSSION AND SUMMARY

Sunspots and faculae have been modeled using a modified stellar envelope code. Downflow velocities of 50 m/sec can achieve a 1,000 K drop in the surface temperature of the photosphere and reduce the surface irradiance to half its value. Concurrently, a 600 km Wilson depression forms associated with the enhanced density of the cooler gases. Similar upflow velocities provide for slightly enhanced temperatures and 150 km uplifted surfaces for faculae. The calculations show that, to first approximation, sunspot and facular structures (in density, temperature and pressure) can be obtained by simply vertically shifting the undisturbed photospheric material to form wells and hillock geometries, respectively. However, the chromospheric manifestations of these features can be quite different owing to the influence of the magnetic field and flow.

Schatten and Mayr calculated flow velocities of about 2 m/sec and particle fluxes of 2×10^{21} particles cm^{-2} s^{-1}. In the present model, the required flow velocities are larger. However, the cooling in the present model occurs in a shallower layer, at 1,000 km depth, where the density is lower, providing a particle flux of 5×10^{21} particle cm^{-2} s^{-1} which is comparable to the Schatten and Mayr value. We note that Zirin and Wang (1989) measured proper motions of 500 m/sec from bright features seen in the penumbral region of sunspots, which also supports the inflow pattern.

As pointed out before, or model is only 1-D and thus cannot include a magnetic field nor replicate the fluxtube size/brightness relationship discussed by Spruit and Zwaan (1980) and modeled by Spruit (1977) and others using the well model geometries. Thus the hillock model does not have some of the "richness" of support enjoyed by the well geometry. Nevertheless, the contrast behavior of faculae appears to fit the hillock geometry.

Biermann's magnetic field inhibition mechanism has an attractive feature: strong magnetic fields are always observed with sunspots. The fate of this energy in the Biermann mechanism, however, is still not clear. Allowing the eddy heat flux to be disbursed by subsurface magnetic fields into the surrounding faculae provides a way to connect faculae to sunspots. As the eddy heat flux is transported upward, it encounters the surrounding sheath of magnetic field structure associated with a sunspot. If this field acts like a conduit for energy transport along the field but as a barrier to heat transport across it, the eddy heat flux cannot enter the core of the sunspot but rather would be disbursed to the faculae surrounding a sunspot. The faculae would be connected to the material below sunspots by subsurface magnetic fields. This view may be referred to as a "field inhibition/transport" model as the field plays a dual role. It inhibits heat transport into the sunspot as in the Biermann mechanism, yet it augments heat transport into the surrounding faculae and plage structures through flow. Faculae thus appear essential for sunspot stability by allowing the Sun to shed the luminosity that would otherwise accumulate below the sunspot. The present modelling effort provides for uplifted facular structures - hillocks, as Schatten and Mayr (1985) suggested and as Schatten et al. (1986) utilized to model facular contrasts.

A crucial test for the flow model would be to observe Doppler shifts in the vicinity of active regions. Cyclonic motions (counterclockwise in the northern hemisphere) around sunspots are expected from the dynamical model. High resolution photographs of faculae may distinguish between the hillock and well geometries; a dark core representing the well bottom would support the well model and exclude the hillock geometry.

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