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## ARE NEUTRAL SUNSPOT WINDS IMPORTANT FOR PENUMBRAL DYNAMICS AND THE FIRST IONIZATION POTENTIAL EFFECT?

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### ABSTRACT

The low ionization state in parts of a sunspot may play an important role in its evolution and dynamical state. The cool magnetic interior region of the sunspot develops a substantial neutral atomic and molecular hydrogen osmotic pressure which can drive a wind outward from the umbra. Ambipolar diffusion against the magnetically pinned ionized plasma component can also distort the umbral magnetic field into a filamentary penumbral structure. This may be important for explaining the development of the sunspot penumbra and the Evershed flow. This fractionation process may also be important for the “First Ionization Potential” (FIP) effect seen in the solar wind. In support of this mechanism we find evidence for such ionization fractionation in UV observations of molecular hydrogen in a sunspot umbra and penumbra.

*Subject headings:* Sun: magnetic fields, sunspots, solar wind

### 1. INTRODUCTION

Existing sunspot models fall short in explaining all their observational facts. One puzzling dynamical feature has been the outward Evershed flow (cf. Bray and Loughhead 1962). To account for this, Thomas and Weiss (1992) developed models based on flux-tube siphon flows. Jahn and Schmidt (1994) accounted for these flows by treating the penumbra in terms of convective interchange mitigated by whole flux tubes. Recently, high resolution observations of sunspot penumbrae, like those of Scharmer et al. (2002) and Rimmele (2004), have shown that fine structure in sunspot penumbra is more complex than either of these pictures directly accounts for. Our discussion here illustrates another physical concept that may help to explain the penumbral dynamics now being observed.

A region with a sharply bounded magnetic field in a partially ionized, thermally differentiated, plasma may generate dynamically important *cross-field* flows. We consider an idealized representation of the umbral magnetic field near the temperature minimum in a sunspot using a two-fluid model consisting of a dominant neutral and a tenuous ionized plasma component. As is observed in sunspot umbrae (prior to the appearance of penumbrae) there is a substantial temperature gradient between the inner (magnetized) and outer (ionized) plasma. In the Sun the cooler inner region is insulated from the hotter atmosphere (near the photospheric level) by the magnetic field, which prevents convective energy penetration from the external atmosphere, and by the relatively opaque  $H^-$ -rich photosphere which provides radiative isolation from the nearby hot gas. A consequence of this stratification is a strong horizontal gradient in the density of neutral and molecular hydrogen and the temperature between the magnetized and photospheric plasma. The diffusive (osmotic) pressure associated with this gradient and the resulting flow may have important consequences for the dynamics of a penumbral region, the outward Evershed flow, and the FIP effect in the solar wind.

### 2. A TWO COMPONENT PLASMA NEAR THE TEMPERATURE MINIMUM

At unity optical depth (i.e. reference height  $z = 0$  with positive height measured outward), and in a plasma with a temperature of about 4000K, as in Zwaan’s (1974) sunspot models, the ratio of the electronic partial pressure to the sum of neutral H and molecular  $H_2$  is about  $10^{-5}$ . More recent models (Maltby et al. 1986, Pizzo 1988, Collados et al. 1994) are not qualitatively different and suggest that umbral temperatures near  $z = 0$  may be closer to 3000K, perhaps with an even smaller ionization fraction. These and equilibrium one-dimensional sunspot models (cf. Fontenla et al. 1999) suggest that this low temperature “neutral zone” extends upward to about  $z = 500km$ .

Near  $z = 0$  realistic numerical models of the upper convection zone and photosphere (Stein and Nordlund 1998) show that temperature falls steeply with height due to vanishing  $H^-$  opacity as the plasma electron density begins to drop. This region is about 500km below the mean atmosphere temperature minimum. Beneath this rapid temperature drop the  $H^-$  opacity dominates visible and IR wavelengths. The sunspot temperature minimum region is a few hundred kilometers below the mean atmosphere temperature minimum, near the top of the convection zone. At this height the horizontal gradients in temperature and electron density between the magnetic umbra and the non-magnetic photosphere are large. A useful classical solution for the field and temperature geometry of an umbral flux tube is calculated by Pizzo (1986), yielding a Wilson depression of typically 500km and a core to exterior temperature gradient near the flux tube temperature minimum of  $\approx 5000K$ .

The cold umbra has a considerably lower electron density and its much lower  $H^-$  opacity allows this non-convective umbral plasma to radiate upward and to cool. The mean atmosphere models of Fontenla et al. 1999 also illustrate these differences. Estimates of the mean  $H^-$  density imply, at visible and near-IR wavelengths and near  $z = 0$ , that the photon free-path is short enough that the interior hot wall of the sunspot umbra is ra-

diatively isolated from the cool sunspot core (cf. Joshi, Punetha, and Pande, 1979).

In general we expect the umbral region of a sunspot, before the development of its penumbra, to be several thousand degrees cooler than the surrounding, relatively  $H^-$ -rich, photosphere. In a few-100km region below the temperature minimum the umbra is primarily neutral gas with an ionization fraction of  $10^{-5}$  or less and (from Fontenla et al. 1999 models) a hydrogen mass density that ranges from about  $10^{-7}$  to  $10^{-10}g/cm^3$ .

### 3. A NEUTRAL WIND AND LEAKY FLUX REGIONS

In hydrostatic and magnetic equilibrium we expect the gas and magnetic pressure within the umbra to equal the exterior pressure. In the neutral zone most of the umbral gas does not interact with the field so that only  $B$  contributes to the interior force balance. Under these conditions the neutral gas is free to “leak” from the high field umbral region into the surrounding hot photosphere. Since the neutral fluid density is low outside the umbra this osmotic pressure can be significant – essentially equal to the initial gas pressure in the magnetized region. The only impediment to this outward flow is the net collisional momentum transfer to the neutral atoms and molecules from the tenuous ionized component of the plasma which remains tightly coupled to the magnetic field.

The dynamics of a neutral and ionized fluid in a magnetic field (closely related to ambipolar diffusion), has been considered in the solar atmosphere before (cf. Fontenla et al. 1990, Schmieder et al. 1999, Chitre and Krishan 2001) but, to our knowledge, has not been applied to sunspots. Here we formulate the problem in terms of an ionized plasma of density  $\rho_i = \rho f$ , a neutral plasma  $\rho_n = \rho(1 - f)$ , the respective neutral and ionized plasma bulk velocity fields ( $\mathbf{v}_{i,n}$ ), pressures ( $p_{i,n}$ ), magnetic field ( $\mathbf{B}$ ), and collision rate between neutrals and ions ( $\gamma_{ni}$ ) and ions against neutrals ( $\gamma_{in}$ ). In this case the force density on each fluid component can be expressed as

$$\rho_i \frac{d\mathbf{v}_i}{dt} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \nabla p_i - \gamma_{in}(\mathbf{v}_i - \mathbf{v}_n)\rho_i \quad (1),$$

and

$$\rho_n \frac{d\mathbf{v}_n}{dt} = -\nabla p_n - \gamma_{ni}(\mathbf{v}_n - \mathbf{v}_i)\rho_n \quad (2).$$

In our idealized problem we consider a vertical  $B$  field ( $z$ -direction) that is non-zero to the left (at  $x < 0$ ) and zero at  $x > 0$ . The relative bulk separation velocity between ions and neutrals (“slip” velocity) is given by  $\mathbf{v}_i - \mathbf{v}_n$ . From equation (1) with no slip velocity we obtain simply  $-\delta B^2/8\pi = \delta p_i$  the magnetostatic pressure balance condition across the magnetic interface. We assume the ions are pinned to a fixed magnetic field. In equation (2), if we have  $\mathbf{v}_i = 0$  then in a steady-state we obtain  $dp_n/dx = -\gamma_{ni}\rho_n \mathbf{v}_n$ .

The momentum “drag” transfer to the neutral fluid is dominated by the ion collision rate which at low velocities, corresponding to Evershed flows of less than a few km/s, is independent of the slip velocity (Draine et al. 1983). In this case  $\gamma_{ni} \approx 1 \times 10^{-9}n_e [cm^3/s]$  where  $n_e$  is the ion number density and we’ve assumed ions and neutrals have similar masses. Initially the interior neutral gas pressure is, plausibly, comparable to the magnetic pressure ( $p_n \approx B^2/8\pi$ ) and we take  $l$  to describe

the magnetic boundary thickness. The neutral “wind” velocity across the magnetic boundary is then

$$v_n = 7 \times 10^{-17} \frac{B^2}{\rho^2 f l} [cm/s] \quad (3)$$

where  $f$  is the ionization fraction. Here magnetic field, density and boundary thickness are measured in Gauss and cgs units.

The neutral wind velocity depends sensitively on the thermal and magnetic boundary thickness. The magnetic boundary thickness may be quite small since the exterior convection zone concentrates stray flux into the downdraft regions immediately surrounding the umbra (wherein there is no convective flow). Observations from Scharmer et al. (2002) achieve a spatial resolution of 90km but do not resolve the magnetic penumbral fine structure. The thermal stratification is dominated by  $H^-$  opacity and, based on the molecular models of sunspots by Joshi et al. (1979), near unity optical depth (at 500nm) the radiation length ( $1/\kappa\rho$ ) can be less than 10km. Thus the flux concentrating effect of surrounding convection and the strong temperature dependence of  $H^-$  opacity suggests to us that the magnetic/thermal boundary may be quite sharp. Lacking observational constraints we assume here a value of 10km, but these estimates may change if we learn more from the next generation of high resolution observations. With  $l = 10km$  in the deep neutral zone,  $\rho = 10^{-7}g/cm$ ,  $B = 3kG$ , and  $f = 10^{-5}$  then  $v_n \approx 63m/s$ . We note that the neutral wind velocity scales approximately as  $p/\rho^2$  so it is a steep function of vertical position in the atmosphere, increasing approximately exponentially with height in the neutral zone until the temperature and ionization fraction are large enough to quench the osmotic flow.

Unlike ordinary diffusion flows, the neutral wind escaping from the umbra is quickly ionized when it penetrates the magnetic interface. Consequently there is no “back-filling” neutral concentration at  $x > 0$  to suppress the flow, although it halts immediately beyond the magnetic boundary in the radiative/convective exterior where it mixes with the turbulent plasma.

### 4. PENUMBRA DYNAMICS

Penumbrae develop from large pores and umbral regions. These filamentary (but sharply defined) structures emanate from the umbra over a typical timescale of about a day and with a typical radial extent of about 7500km (cf. Bray and Loughhead, 1965). According to Zwaan (1992) the penumbra seems to develop at the expense of the umbral magnetic flux. If there is a characteristic velocity with which the penumbra evolves it is not fast, perhaps 50-100 m/s. Interestingly, this is the velocity scale of the neutral wind in the deeper neutral zone. We note that the observed scale of the outward velocity of the Evershed flow in the penumbra is typically 1km/s or larger (cf. Thomas and Weiss, 1992).

The neutral wind creates a non-zero third term on the RHS of Eq. 1 which implies a positive acceleration of the ionic fluid. Thus this wind drags the ions and the magnetic field outward away from the umbra.

The steady-state solution to Eqns. (1) and (2) is  $\delta p_n + \delta p_i = -B^2/8\pi$ . The magnetized region is carried outward until the total neutral and ionic pressure difference across the magnetic interface balances the magnetic

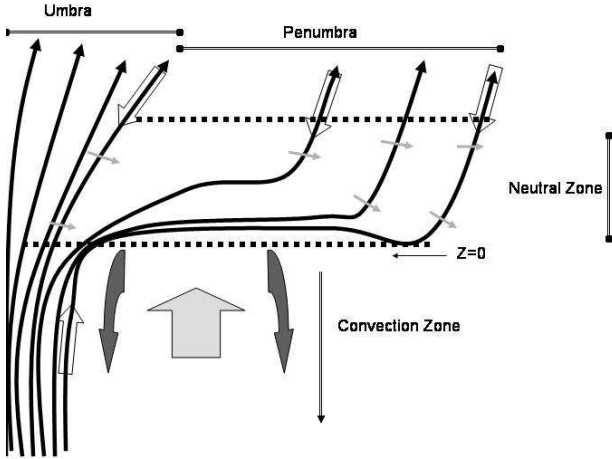


FIG. 1.— An umbral region (left) with a primarily vertical B field (dark lines) has its magnetic field advected into the “neutral zone” by the cross-field neutral wind (short grey arrows). Entrained ionized and neutral plasma flows along field lines from above and below to replenish the low temperature sunspot plasma. Transparent arrows indicate deep upflows and possible reverse Evershed flows corresponding to the upper level downflows.

pressure. Note, that as long as the magnetized plasma remains thermally isolated from the exterior (with a large neutral component) and the external ionized pressure doesn’t increase then there can be *no time-independent solution*. In a real penumbra equilibrium should occur when: 1) the neutral pressure is sufficiently small, either because the penumbral filament is no longer effectively thermally isolated from the hot photosphere, or 2) the neutral wind successfully evacuates the interior field region, or 3) the magnetic field is small enough.

#### 5. SOME FEATURES AND EXPECTATIONS OF A NEUTRAL WIND SUNSPOT MODEL

While our description is far from a complete model it has some attractive features which warrant further study:

In this picture a penumbral filament (“flux region”) is advected from the umbra into the photosphere by a vertically localized horizontal outward flow. The penumbra forms near the top of the convectively unstable exterior. Figure 1 shows a cartoon representation of this.

The neutral wind is driven by the umbra/photosphere and moving penumbra/photosphere interface. We therefore expect the flow along a penumbral filament to include the effects of: 1) the continuous cross-field leakage of neutral gas all along the length of the filament/photosphere interface, and 2) a parallel ionized and neutral outward flow channeled along the field lines of the horizontally elongated penumbral flux region.

The neutral plasma which evacuates the umbral and penumbral flux regions may be replaced by mass upflows from below and by downflows from the flux regions that connect with the hotter upper regions of the chromosphere and transition region/corona. These downflows might be the siphon-like reverse Evershed flows observed in the chromosphere and above (cf. Georgakilas and Christophoulou, 2003).

Although the magnetic interface-driven neutral flow is 10-100m/s the observed outward Evershed flow can be one or two orders of magnitude larger. How can such a large velocity be a consequence of the osmotic flow? The partially ionized plasma flow in the penumbra will be

channeled by the nearly horizontal magnetic field. Unlike the umbra, the penumbra is filamentary so that the neutral outflow exists along the length of the filament. Thus, within the filament the parallel flow velocity along the field lines must be larger than the wind velocity by a factor of approximately the ratio of the effective area of the filament to its cross-section. In detail this is difficult to estimate but from the Scharmer et al. (2002) high resolution images the length-to-diameter ratio of the filaments can easily be 10, yielding channeled flow velocities that are two orders of magnitude larger than the interface neutral wind velocity.

#### 6. IONIC FRACTIONIZATION, FIP EFFECT

An unusual feature of this model is that it tends to predict a larger charged-species concentration in the umbra than in the penumbra. Conversely we expect a larger concentration of neutrals in the penumbra as they are siphoned from the umbra. For many molecular and atomic species this tendency can be masked by local ionization equilibrium effects caused by the temperature difference between the umbra and penumbra, but in general we expect elements with a *lower* first ionization potential to have a *higher* density in the strong field region. This can have interesting consequences for the solar wind FIP effect if the wind acceleration mechanism is related to strong B-field regions deep in the chromosphere or even the photosphere. We note that wind observations show that low first ionization elements are most strongly enhanced (a factor of 3-5) in low latitude, active-region, slow solar winds (McKenzie and Feldman, 1992). These are precisely where we expect underlying sunspots to cause enhanced ionized species abundances in the strong field regions.

#### 7. EVIDENCE OF IONIC FRACTIONIZATION IN SUNSPOTS

It may be possible to detect a superabundance of neutral atoms or molecules in the penumbra, although this may be masked by the effects of the relatively short vertical optical path through the penumbra (as compared to the umbra – see Fig. 1) and by the details of the line formation and strong temperature dependence of the molecular dissociation equilibrium abundances. While there are few observations of molecular hydrogen, interpreting its spectra may be more straightforward because it is seen in emission in the far ultraviolet part of the spectrum. These lines are likely to be optically thin and it has a monotonically increasing molecular density with decreasing temperature in the photosphere (cf. Aller 1963).

According to Zwaan (1974),  $H_2$  can account for 10% or more of the atomic H partial pressure in the sunspot neutral zone. Molecular hydrogen has 8 prominent Werner band transmissions (1-0 to 1-7) which emit lines within the wavelength range of SUMER. These are listed by Bartoe et al. (1979). A previous analysis of the  $H_2$  lines in this sunspot were made by Schuhle et al. (1999). In the SUMER data, the 1-0, 1-1 and 1-7 Werner band lines are heavily blended with emission lines of various ions and the 1-2 line has a very low intensity. These are disregarded for this study. The remaining four Werner band lines (1-3 to 1-6) have theoretical central wavelengths of 1119.08, 1163.81, 1208.94 and 1254.12Å respectively. The lines are easily identified in the SUMER sunspot ob-

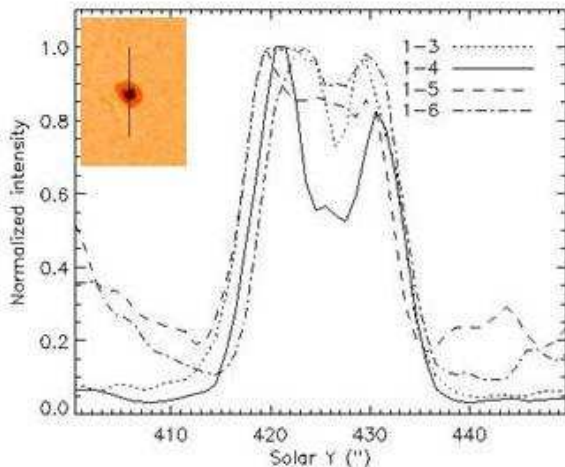


FIG. 2.— Inset - MDI/SOHO intensity image showing the leading sunspot of active region NOAA 8487 observed on 1999 March 18. The vertical black line shows the position of the SUMER slit across the sunspot. Intensities of several ultraviolet  $H_2$  spectral lines across the sunspot as measured by the SUMER/SOHO instrument on 1999 March 18. The legend refers to the Werner band of each line. For clarity, the intensities are spatially smoothed with a narrow Gaussian of FWHM 3 spatial bins ( $\sim 3''$ ) and are normalized to unity.

servations. The line intensity has been integrated over the wavelength range of each line in each spatial bin. Figure 3 shows the SUMER observations in context with an inset image of the sunspot as observed by the Michelson Doppler Imager (MDI). This figure shows the normalized intensity of the four Werner bands across the region of the SUMER FOV containing the sunspot. Differences between the spatial profiles of the bands may be due to blends or temporal changes within the sunspot, although these four observations were all made within one hour. All four bands show their highest intensity within the sunspot penumbra and a sharp decrease in intensity at the photosphere. The striking decrement in  $H_2$  intensity in the umbra is obvious. This is most prominent in the 1-4 band line.

Jordan et al. (1978) discovered and analyzed many  $H_2$  UV emission lines to conclude that they were due to fluorescence from hotter transition region UV line radiation illuminating the molecular hydrogen from above. A fully self-consistent line-formation model of these Werner band measurements is beyond the scope of this letter but it is important to note that Jordan et al. (1978) concluded that these UV lines should be optically thin. Because the equilibrium number density of molecular hydrogen monotonically rises with decreasing temperature (cf. Aller 1963) it is quite possible that the weaker  $H_2$  line intensity from the cooler umbra is due to a significantly lower umbral than penumbral  $H_2$  number density.

## 8. CONCLUSIONS

The radiatively isolated, cool, sunspot umbra should develop a significant osmotic pressure which drives a neutral wind outward into the surrounding photosphere and penumbra. Typical velocities can be 10-100 m/s and given expected umbral ionization fractions these velocities will carry some of the umbral magnetic flux with them. This neutral wind tends to evacuate the high-field umbral region of its neutral atomic and molecular gas. A likely consequence of this is upflows from below and a reverse Evershed flow from the chromosphere above in order to maintain mass conservation. It seems difficult to avoid such a neutral wind in a partially ionized region where there is a common magnetic and temperature boundary. Observations of molecular  $H_2$  in sunspots tend to confirm that neutral gas is superabundant in the penumbra in comparison to the umbra. If the slow solar wind ultimately originates from high field regions near the photosphere this neutral wind might also lead to a low first ionization potential (FIP) element enhancement in the solar wind.

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