Osmotically Driven Neutral Sunspot Winds

J. R. Kuhn and H. Morgan

Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI, 96822, USA

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 umbra 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 wind can contribute to the development of the sunspot penumbra and the Evershed flow.

1. Introduction

As we have learned from this meeting, existing sunspot models fall short in explaining all their observational facts. In this era of realistic numerical simulations, and especially in light of this tribute to Bob Stein’s contributions, it is apropos to argue here for some additional physics these models may not include. Despite the lively debate at this meeting over the mechanisms of the Evershed flow (cf. Bray & Loughhead 1962), it is not completely explained. Note that neither the Thomas & Weiss (1992) models based on flux-tube siphon flows, nor Jahn & Schmidt (1994) account for all of the features of the complex flow patterns now seen in high resolution solar penumbral imagery like those of Scharmer et al. (2002) and Rimmele (2004). Our discussion here illustrates another physical concept that must exist at some amplitude within the umbra and penumbra and which, we believe, contributes to the evolution and dynamics of a sunspot.

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 a penumbra) 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 surrounding 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) pres-
sure associated with this gradient and the resulting flow may have important consequences for the dynamics of a penumbral region.

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 4000 K, 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, Collados et al. 1994, Fontenla et al. 1999 – FWFAK) are not qualitatively different and suggest that umbral temperatures near $z = 0$ may be closer to 3000 K, perhaps with an even smaller ionization fraction. From the FWFAK atmosphere models we note a 300 km region above $z = 0$ where the umbral neutral H density is larger than the surrounding photosphere by as much as an order of magnitude. Comparison with Zwaan’s (1974) models also indicates that the H$_2$ number density can be about 30% of the H density and $10^2$ times larger than the surrounding photosphere. We designate this 300 km region of the umbra the “neutral zone.”

The cold umbra has a considerably lower electron density so that its lower H$^-$ opacity allows this non-convective plasma to radiate upward and to cool. The horizontal H$^-$ density also increases sharply outward through the magnetic boundary so that the hot photosphere is effectively radiatively isolated from the cool umbral interior.

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. As the umbra forms and cools 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 – approaching the initial gas pressure in the magnetized region. The only impediment to this outward flow is the 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. Since the neutral and molecular hydrogen are quickly ionized when the flow penetrates the boundary there is no “back filling” neutral density to diminish the osmotic/diffusion flow once it begins.

The dynamics of a neutral and ionized fluid in a magnetic field, have been considered in the solar atmosphere before (cf. Fontenla et al. 1990, Arge & Mullan 1998, Schmieder et al. 1999, Chitre & Krishan 2001). Arge & Mullan (1998) have even described a model for the FIP effect based on an ambipolar model. To our knowledge the neutral osmotic wind effect in strong-field photospheric regions we describe here has not been previously considered.

We formulate our 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 ($v_{i,n}$), pressures ($p_{i,n}$), magnetic field ($B$), 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

\[
\rho_i \frac{d\mathbf{v}_i}{dt} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \nabla p_i - \gamma_{in}(\mathbf{v}_i - \mathbf{v}_n)\rho_i
\]

(1),

and

\[
\rho_n \frac{d\mathbf{v}_n}{dt} = -\nabla p_n - \gamma_{ni}(\mathbf{v}_n - \mathbf{v}_i)\rho_n
\]

(2).

In our idealized problem we consider a vertical B field (z-direction) that is non-zero to the left \((x < 0)\) and zero at \(x > 0\). The relative bulk separation velocity between ions and neutrals (the “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 the 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 flows of less than about ten km/s, is independent of the slip velocity (Draine et al. 1983). In this case \(\gamma_{ni} \approx 1 \times 10^{-9}n_e [s^{-1}]\) where we take \(n_e\) as an estimate of the ion number density and we have assumed ions and neutrals have similar masses. Initially the interior neutral gas pressure is, plausibly, comparable to the magnetic pressure so that \(p_n \approx B^2/8\pi\). We let \(l\) describe the magnetic boundary thickness. The neutral H “wind” velocity across the magnetic boundary is then

\[
v_n = 2.4 \times 10^{31} \frac{B^2}{n_H n_e l} [\text{cm/s}]
\]

(3)

where \(n_H\) is the neutral H number density. Here magnetic field, density and boundary thickness are measured in Gauss and cgs units.

While the initial ion velocity is zero, the neutral wind from Equation (2) creates a non-zero third term on the RHS of Equation (1) which implies a positive acceleration of the ionic fluid. This ionic wind drags the ions and the magnetic field outward away from the umbra once \(v_n > 0\).

The neutral wind velocity depends sensitively on the thermal and magnetic boundary. The magnetic boundary thickness may be quite small since the exterior convection zone concentrates stray flux into the downdraft regions immediately surrounding the umbra (where there is no convective flow). Scharmer et al. (2002) achieved a spatial resolution of <90 km but did not resolve the magnetic penumbral boundary structure.

The length scale that determines the magnetic/thermal boundary thickness is likely to be set by the \(\Pi^-\) radiation absorption length \((1/\kappa_{H^-}\rho_{H^-})\). According to Joshi et al. (1979), near unity optical depth, this length can be less than ten km. In combination with the flux concentrating effect of the surrounding convection we suggest that the boundary thickness can be quite thin. Lacking observational constraints, we adopt \(l = \text{ten km}\) in our calculations below – but note that this is an important unresolved observational issue for the model. From FWFAK’s models we find, near the top of the neutral zone, that \(n_H = 1.5 \times 10^{16}\) and \(n_e = 2 \times 10^{11}\text{cm}^{-3}\) so that from Equation (3), with \(B = 3\text{kG}\), we obtain \(v_n \approx 720 \text{m/s}\).
The magnetized ionic and neutral fluid which is driven toward the boundary must rapidly decelerate when it penetrates the ionized region. Ionization equilibrium calculations by Carlsson and Stein (1999) suggest that hydrogen in the convection zone will be ionized in less than a minute. Thus, we expect the advected magnetic field to accumulate in this boundary region. As the boundary advances outward due to the ambipolar neutral wind, it pushes accumulated flux ahead of it. Thus, the boundary remains sharply defined which sustains the osmotic flow in radially oriented filaments.

4. Penumbra Dynamics

Penumbrae develop from large pores and umbral regions. Observationally these filamentary structures emanate from the umbra over a typical timescale of about a day and with a typical radial extent of about 7500 km (cf. Bray & Loughhead, 1965). According to Zwaan (1992) penumbrae seem to develop at the expense of the umbral magnetic flux. The characteristic velocity with which a penumbra evolves is not fast, about 50 – 100 m/s. Interestingly, this is the velocity scale of the neutral wind in the deeper neutral zone.

The formal steady-state solution to Equations (1) and (2) is \( \delta p_n + \delta p_i = -\frac{B^2}{8\pi} \) when the ion-neutral collision rate has the same numerical form as \( \gamma_{ni} \). The magnetized region is carried outward until the total neutral and ionic pressure difference across the magnetic interface balances the magnetic 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 static 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.

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 simple graphic representation of this.

The neutral wind is driven by the umbra/photosphere and moving penum-bra/photosphere interface. We therefore expect the horizontal 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) an 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 along the field lines 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 & Christopoulou, 2003).

While the magnetic interface-driven neutral flow is < 1 km/s the observed outward Evershed flow can be an order of magnitude larger (cf. Thomas & Weiss 1992). How can such a large velocity be a consequence of the osmotic flow? The partially ionized plasma flow in the penumbra must be channeled by the
nearly horizontal magnetic field. Unlike the umbra, the penumbra is filamentary and the neutral cross-field outflow exists along the length of the filament. Thus, within the penumbral filament the parallel flow velocity along the field lines must be larger than the cross-field velocity by a factor of approximately the ratio of the boundary area of the filament to its cross-section. From the Scharmer et al. (2002) high resolution images the length-to-diameter ratio of the filaments can easily be ten. Thus, the channeled flow velocities can be of order 10 km/s in developed sunspots – consistent with Evershed flow observations.

5. Detecting Ionic Fractionization

It should be possible to detect the relative superabundance of neutral atoms or molecules in the penumbra, although this is complicated by the effects of the relatively short vertical optical path through the penumbra (as compared to the umbra – see Figure 1) and by the details of the line formation and strong temperature dependence of the molecular dissociation equilibrium abundances. Since \( \text{H}_2 \) is formed in the critical sunspot neutral region and is an important dynamical component of the neutral wind it offers a good observational test of our model. Unfortunately there are few observations of molecular hydrogen, although interpreting its spectra may be more straightforward than other molecules.

Jordan et al. (1978) discovered and analyzed many \( \text{H}_2 \) UV emission lines to conclude that they were due to florescence from hotter transition region UV line radiation illuminating the molecular hydrogen from above. Aller (1963) also showed that the density of \( \text{H}_2 \) decreases monotonically with increasing temperature in this regime. Thus, we do not expect the cooler umbra to exhibit weaker \( \text{H}_2 \) line emission than the penumbra unless the \( \text{H}_2 \) density is lower in the umbra.

Molecular hydrogen has 8 prominent Werner band transitions (1-0 to 1-7) which emit within the wavelength range of SUMER (Wilhelm et al. 1995). 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 observations. The line intensity has been integrated over the wavelength range of each line in each spatial bin. Figure 2 shows the SUMER observations in context with an inset image of the sunspot as observed by the Michelson Doppler Imager (Scherrer et al. 1995). 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. Although a complete UV line synthesis calculation is beyond the scope of this paper the clear decrease in umbral emission line intensity is good evidence that the neutral H$_2$ density is lower there.

6. Conclusions

Cool sunspot umbra should develop a significant osmotic pressure which drives a neutral wind outward into the surrounding photosphere and penumbra. Average cross-field velocities can be 0.20 km/s and the ambipolar wind will carry some of the umbral magnetic flux with it. Once the penumbra develops, the channelled horizontal flow velocity can be several km/s. The neutral wind tends to evacuate the high-field umbral region of neutral atomic and molecular gas. Upflows from
below and a reverse Evershed flow from the chromosphere must replenish this mass. While other mechanisms may ultimately control the penumbral Evershed flow, it seems difficult to avoid a neutral wind contribution in this weakly ionized region where there is a sharp magnetic and temperature boundary. Observations of molecular H$_2$ in sunspots tend to confirm that neutral gas has been evacuated from the umbra and clearly show the steep gradient in molecular hydrogen between the penumbra and sunspot exterior.

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