MHD STREAMER STRUCTURE, SLOW SOLAR WIND, AND THE STREAMER BRIGHTNESS BOUNDARY

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ABSTRACT

Flow tubes adjacent to closed magnetic field lines on the boundaries of streamers can have spreading factors which change rapidly with height. Numerical models in this thin layer are subject to uncertainties. Here we use an analytic model of magnetically closed and adjacent open regions to analyze the spreading factor close to the closed field lines. The model is based on the one-temperature, isothermal flow model of Pneuman (1968), extended to calculate spreading factors and plasma beta, and to better explain streamer evolution with increasing temperature.

Key words: Streamers, Theory, MHD, Solar Wind

1. INTRODUCTION

Coronal streamers are bright because their density is higher than in adjacent regions of the corona. The boundary of streamers, the Òbrightness boundaryÓ is often sharp and is sometimes thought of as being the interface between open (to the interplanetary medium) and closed magnetic field lines. However, this probably is not the case since the brightness boundary is commonly observed to extend even to the outer limits of the LASCO/C3 field of view — 30 solar radii (R_S) whereas static closed field lines do not extend past ~5 R_S in any published model.

Recently, Suess et al. (1999a) found that Ulysses observes only slow wind just inside the brightness boundary. It is therefore more likely that the brightness boundary and the fast/slow wind boundary are identical. This is supported by several independent lines of evidence, including: (i) A sharp velocity boundary in UVCS Doppler dimming data that apparently coincides with the brightness boundary (Habbal et al., 1997; Woo and Habbal, 1999). (ii) The sharp boundary between fast and slow wind in the interplanetary medium (McComas et al, 1998). (iii) The coincidence between first ionization potential (FIP) abundance anomalies and the fast/slow wind boundary at Ulysses (Geiss et al., 1996). (iv) The coincidence between UVCS-observed abundance anomalies in the legs of streamers and FIP abundance anomalies (Raymond et al. 1998). Raymond et al. furthermore concluded that slow wind originates in very slow or transient (on intervals of ~a day) releases or solar wind in the bright legs of streamers, just inside the brightness boundary. This is required for the gravitational settling that they infer exists.

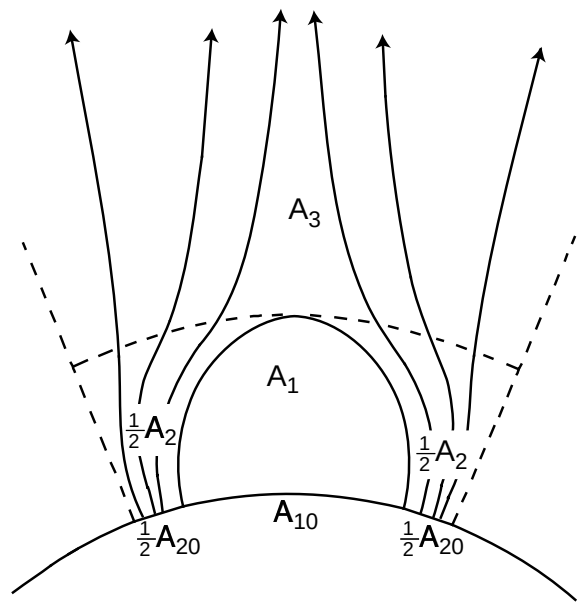
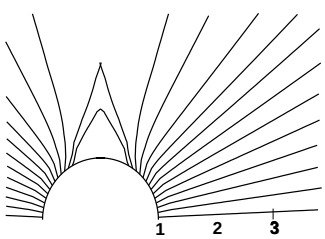


Fig. 1: Geometry assumed for the streamer model. A_1, A_2, and A_3 are described in the text.

Assuming the brightness and fast/slow wind boundaries are the same, it would be valuable to have a model of this region that can easily be used to analyze the different physical phenomena and questions that arise. In particular, we would like to be able to make a quantitative evaluation of the hypothesis by Noci et al. (1998) that slow wind arises because of the special properties of the geometric spreading factor along streamlines in complexes of otherwise closed streamer magnetic field regions. A 2d MHD model (V squez et al., 1999) has been used to find solutions like those proposed by Noci. Here we describe a simpler 1d model which promises to be able to do the same, but which we find cannot do so in its simplest form. Still, we are able to find new results on how streamer structure evolves under changing temperature and on the geometric spreading factor in the legs of streamers.

The model is based on the analysis of Pneuman (1968). Fig. 1 shows the geometry, assumed to be axisymmetric about the Sun and symmetric across the neutral line down the center of the streamer. A_{10} is the area of the base of the closed field lines in the streamer and A_{20} is the sum of the open, outflow areas on either side of the streamer. $A_1(r)$ and $A_2(r)$ are the areas of the regions 1 and 2 at constant height above the base at r_0. $A_3(r)$ is the area above the streamer. The dashed lines marking the outer boundaries of region 2 are assumed, in this example, to be radial so $A_3(r) \propto r^2$. We assume approximately radial flow and consider average values of the variables over the cross sections A_1 A_2, and A_3. This reduces the problem to 1d. We also assume that the gas is isothermal in regions 1 and 2 (a *two-temperature* model) and here we will consider only the simpler *one-temperature* model in which $T_1=T_2$. This closely follows Pneuman's analysis, although we extend his results and conclusions.

The assumption of hydrostatic equilibrium inside region 1 is based on the knowledge that β (the ratio of thermal



to magnetic pressure) is greater than unity in streamers above some low height of generally no more than 1.1-1.2 R_S (Suess et al., 1999b), which defines r_0 in the model. The closed field lines in the streamer are thus confined by the pressure from the magnetic field and plasma on adjacent open field lines pressing on the boundaries of the streamer (Suess and Smith, 1996). Empirical results from SOHO/UVCS and YOKHOH/SXT (Li et al., 1998; V squez et al., 1999) have empirically verified that β>1, but MHD models have long predicted this as a general property (Suess et al., 1999b). Because this is such an important and fundamental point for the viability of this analytic model, we show in Fig. 2 a typical numerical result for β. This model qualitatively reproduces the empirical bimodal (sharply divided fast and slow) solar wind (Phillips et al., 1995) and exhibits the property that the streamer is mainly confined by coronal hole field pressing on the streamer boundaries. β>1 throughout the streamer in this example.

2. ANALYSIS

The equations describing conditions in Fig. 1 are: (1) Hydrostatic pressure balance in region 1, with mean ion molecular weight μ and base radius (height) r_o.. We use μ=0.69 (20% alpha particles!) to compare with Pneuman (1968), who used the same value. (2) Radial momentum equation for isothermal Parker wind flow with an arbitrary geometric spreading factor in region 2. (3) Conservation of mass flux in region 2. (4) Conservation of magnetic flux in region 2 (B_{2o} and A_{2o} are the reference height magnetic field strength and cross-sectional area at r_o). (5) Conservation of total area $A_1(r)+A_2(r)$. (6) Pressure balance on the interface between regions 1 and 2.

$$N_1 = N_{10} \exp\left\{-\frac{\mu G M_8 m_p}{r_o k T_1}\left(1-\frac{r_o}{r}\right)\right\} \quad (1)$$

$$m_p N_2\left(V_2 \frac{dV_2}{dr} + \frac{GM_8}{r^2}\right) = -\frac{kT_2}{\mu}\frac{dN_2}{dr} \quad (2)$$

$$N_2 V_2 A_2 = N_{2o} V_{2o} A_{2o} \quad (3)$$

$$B_2 A_2 = B_{2o} A_{2o} \quad (4)$$

$$A_1 + A_2 = \frac{r^2}{r_o^2}\left(A_{1o} + A_{2o}\right) \quad (5)$$

$$2kN_1T_1 = 2kN_2T_2 + \frac{1}{8\pi}B_2^2 \quad (6)$$

$p_2=2N_2kT_s$ and the dimensionless parameters are

$\psi=(\mu GM\ m_p)/(r_o kT_1)$	
$\tau=T_1/T_2$	Temperature Ratio
$R=A_{2o}/A_{1o}$	Area Ratio
$\beta=2N_{2o}kT_2/(B_{2o}^2/(8\pi))$	Plasma β
$N=N_{1o}/N_{2o}$	Density Ratio

(2) can be integrated and the equations solved analytically, with the requirement that the solution for V_2 pass through the critical point smoothly from subsonic flow close to the Sun to supersonic flow far from the Sun. In practice, the solution is generally more easily found by numerical integration of (2) in regions 2 and 3. A more detailed discussion of the solution will be given elsewhere, in a report on the *two-temperature* model ($\tau\neq1$). The reader is referred to Pneuman (1968) for details on how the *one-temperature* solution (τ=1) is found. Here we report on the following properties from the *one-temperature* model: the height of the top of

First, it predicts how a streamer evolves under continuously increasing temperature. There is an absolute maximum temperature of ~3.5×10^6 K beyond which isothermal streamers do not exist on the Sun, under the assumption that $\beta>1$ in region 1. Branching solutions between fast and slow wind, for increasing spreading factors, are not obtained in this simple model. In V squez et al.Õ (1999) model, the spreading factor behavior, which is reproduced schematically here in Fig. 10, occurs where $\beta<1$ and where the kinetic energy is also less than the magnetic field energy density. Therefore, simply adding the region 4 described above will probably recover this behavior.

Finally, it appears that the radial dashed line in Fig. 1, bounding region 2, can now be interpreted as the brightness boundary, as opposed to being in the center of a coronal hole as supposed by Pneuman (1968).

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