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The source region of the fast solar wind

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Abstract. We discuss how the lower corona may be connected to the chromospheric network pattern through magnetic funnels at the boundaries of the chromospheric network. At the feet of these funnels are located thin ionizing layers. The steady-state flow and temperature structure in the funnels is analyzed on the basis of the continuity of downward electron heat flux from the coronal base and the upward advection of enthalpy and kinetic energy from below. The flow in such a funnel remains subsonic provided the downward heat flux from the lower corona is sufficiently large, otherwise it becomes choked or exhibits a critical supersonic-subsonic transition. The ionization layer, generated by electron impact, is very thin (~ 20 km) and is located at about 4.5 chromospheric pressure scale heights (i.e. ~ 700 km) below the base and its structure is similar to that of a classical constant pressure weak deflagration in which the flow is accelerated but remains subsonic. Although our model may shed some light on the structure of the connection between the fast solar wind and its origin in the chromosphere it cannot, by virtue of being steady, uniquely predict the mass flux of the wind.

Key words: Sun: corona – solar wind

1. Introduction

The heating and acceleration of the fast solar wind and its origin in the chromospheric network pattern is complicated by the different physics at work in different regions operating on widely differing length scales. We have attempted to simplify this complex problem by splitting it into three parts, consisting of: (1) the lower corona and solar wind [McKenzie at.al. (1995, 1997a)]; (2) the flow in magnetic funnels [Dowdy et.al. (1986)] at the boundary of the chromospheric network pattern [Gabriel (1976)]; and (3) the ionization layers at the feet of the funnels, arising from electron impact collisions driven by electron heat conduction from above [Axford and McKenzie (1993)] .

We provide a brief outline of the nature of the flow in the magnetic funnels and how it is connected to thin (~ 20 km) electron impact ionization layers. If the downward electron heat flux from the lower corona is sufficiently large it is possible to maintain subsonic flow throughout the funnel. Such a subsonic flow can be smoothly joined to an ionization layer in which the plasma is produced by ionizing electron impact collisions with neutral hydrogen and is accelerated within the layer, exiting at a subsonic speed in the fashion similar to that of a classical weak deflagration [Courant and Friedrichs (1963); Axford (1961)]. For temperatures appropriate to the lower corona ($\sim 10^6 K$)and chromosphere ($5 \cdot 10^3 K$) and with reasonable temperature gradients (but see later) the layer is situated at about 700 km below the coronal base where at the top the temperature is about $1.6 \cdot 10^5 K$ and the density is around $4 \cdot 10^{10}\text{cm}^{-3}$.

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2. Flow in a magnetic funnel

Here we outline how the lower corona is connected to the chromospheric network pattern through magnetic funnels . In our simple model the shape of the funnel is determined through a balance between the chromospheric gas pressure exterior to the funnel and magnetic pressure inside the funnel. Therefore the shape of the narrow funnel $A(z)$, using conservation of magnetic flux in the funnel, is given by

$$A(z) = A_0 \exp\left(\frac{z}{2H}\right), \tag{1}$$

where H is the chromospheric pressure scale height which is of O(150 km) for temperatures of $5 \cdot 10^3 K$, and the height z is directed upwards and we solve along the centre of the funnel. The flow and temperature structure in the funnel is analyzed on the basis of the conservation laws of mass and momentum for a single fluid ($T_p = T_e = T$), along with the energy equation expressing the conservation of downward electron heat conduction from the lower corona and the upward advection of the flux of enthalpy and kinetic energy in the funnel and in which radiative cooling can be neglected. These laws can be cast in terms of a "wind equation" for the upward flow speed (v) in the funnel, coupled with a temperature structure equation:

$$(1 - M^2)\frac{1}{v}\frac{dv}{dz} = \frac{1}{T}\frac{dT}{dz} - 1 + \left(\frac{T_n}{T_0}\right)\frac{1}{T}, \tag{2}$$

$$c_T A T^{5/2}\frac{dT}{dz} = 5(T-1) + c_T T_0' + M_0^2(v^2 - 1) + \left(\frac{2T_n}{T_0}\right)z, \tag{3}$$

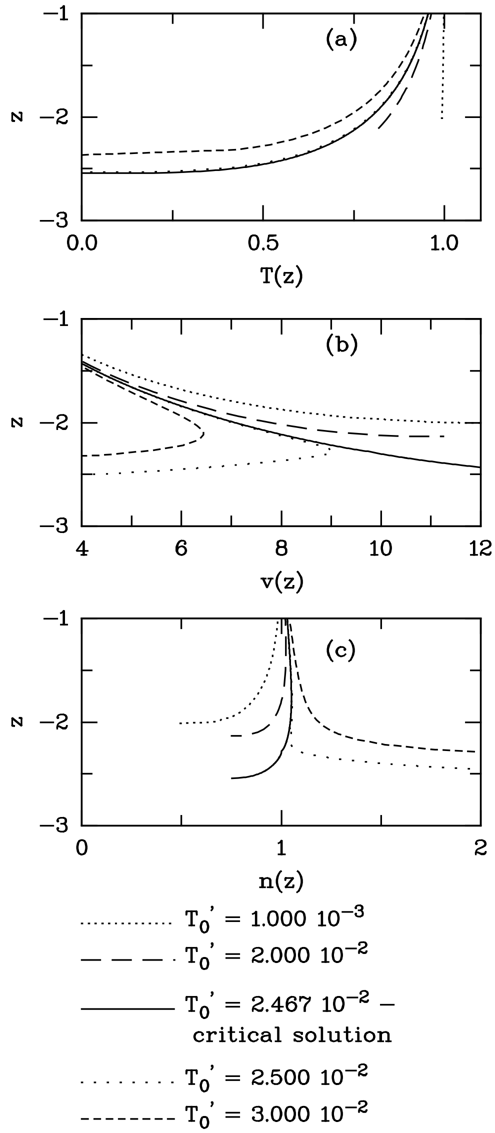

Fig. 1a–c. The structure of the funnel flow showing distributions of $T(z)$, (**a**), $v(z)$, (**b**) and $n(z)$, (**c**) with funnel depth z (normalized to $2H$) for different temperature gradients T_0' at the base of the corona and a base Mach number of 1/12 corresponding to a speed of $\sim$ 10 km/sec. Note that the family of $v(z)$ curves exhibits a saddle point topology (in which the critical curves permit smooth supersonic-subsonic (and vice versa) transitions). The flow remains subsonic provided $T_0' > 2.467 \cdot 10^{-2}$, with the density increasing downward accompanied by a dramatic decrease of the temperature at the bottom of the funnel (see the curves for T_0' = 2.5 and $3 \cdot 10^{-2}$).

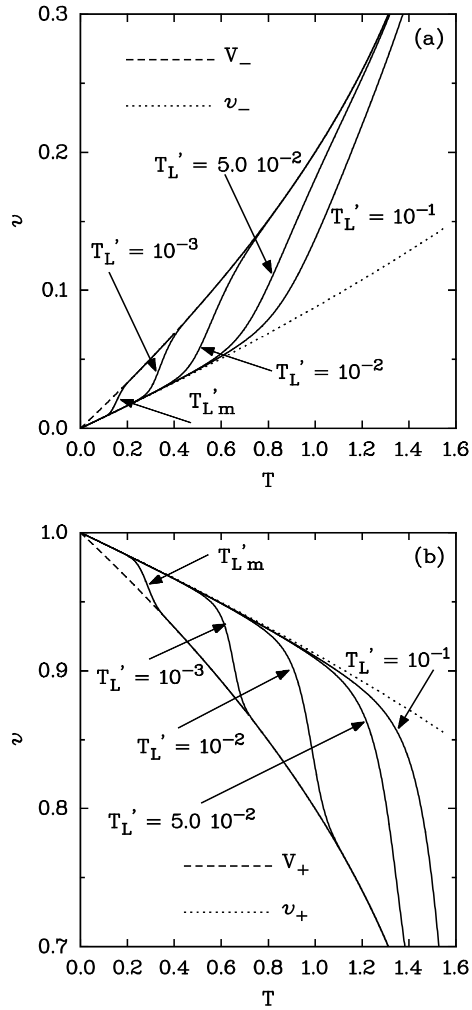

Fig. 2a and b. Solutions of the structure equation for the ionization layer in the (v, T) plane for different temperature gradients T_L' at the top of the layer: **a** weak deflagrations in which the ionized plasma is accelerated from a subsonic speed v_- to a greater subsonic V_-; **b** weak detonations in which the supersonic flow is decelerated from v_+ to V_+ (see Eqs. 11c and 11d).

where z is normalized to $2H$, A to A_0, v to v_0 at the base, M is the Mach number $v/(2kT/m)^{1/2}$, T has been normalized to the temperature at the base of the lower corona $T_0 \sim 10^6 K$, $T_n = 5 \cdot 10^3 K$ is the temperature of the chromosphere, T_0' is the downward temperature gradient at top of the funnel, and the ratio of the thermal length scale to that of the funnel $c_T = 10^{-6} T_0^{3/2}/(nv)_0 k2H$ is large (of O($2.4 \cdot 10^3$)). Because the depth ($z < 0$) is normalized with respect to $2H$ the area factor $A = e^z$. The family of solutions for the speed $v(z)$, density $n(z)$ and temperature $T(z)$ corresponding to a given particle flux in the lower corona ($\sim 4 \cdot 10^{14} \mathrm{cm}^{-2}\mathrm{s}^{-1}$) and different downward heat fluxes (measured in terms of T_0') are depicted in Figs. 1a-c in which z = 0 denotes the coronal base.

Note that gravitational stratification is negligible since $T_n/T_0 \sim 5 \cdot 10^{-3}$. If the downward heat flux is too weak ($T_0' < 2.467 \cdot 10^{-2}$ in normalized units) the flow speed goes sonic at a certain depth z and hence becomes choked. This arises because in the upper section of the funnel the pressure and the temperature are almost constant, and therefore so also is the density, whereas the flow speed must increase exponentially downwards into the funnel with a scale height $2H$ ($\sim$ 300 km) to conserve the particle flux. Therefore there is a critical downward heat flux (T_0' = $2.467 \cdot 10^{-2}$), which permits a smooth supersonic-subsonic flow, and for heat fluxes greater than this critical one the flow remains subsonic throughout the funnel, exhibiting a maximum at a depth which decreases with increasing T_0'. These subsonic flows are characterized by densities which decrease with increasing height and are accompanied by very rapidly decreasing temperatures below a certain depth. At the bottom of such subsonic funnel flows are located thin ionization layers, generated by electron impact on neutral hydrogen below.

3. Structure of electron impact ionization layer

Here we model the structure of an ionization layer, located at the foot of a magnetic subsonic flow pattern, which can be characterized as a weak deflagration, bearing in mind that our description is equally valid for a supersonic flow undergoing a weak detonation. Because the thickness of the ionization layer ($\sim$ few tens of km) is very much less than the scale height of the funnel $2H$ (300 km), the area variation of the funnel and gravity can be neglected. In the simplest case in which we assume collisions are sufficiently frequent to maintain equal speeds for protons and hydrogen atoms as well as equal temperatures $T_n = T_p = T_e = T$, the equations governing the structure may be written:
Plasma Production:

$$\frac{d(nv)}{dz} = \beta(T)Nn \tag{4}$$

Continuity:

$$m(N+n)v = \mathscr{J} \tag{5}$$

Total Momentum:

$$m(N+n)v^2 + (N+n)kT + nkT = \mathscr{M} \qquad \text{(const)} \tag{6}$$

Electron Energy :

$$\frac{d}{dz}\left[nv5kT - \kappa\frac{dT}{dz}\right] = -\beta(T)NnE_i \tag{7}$$

Energy Flux:

$$nv(E_i + 5kT) - \kappa\frac{dT}{dz} = -\mathscr{E} \qquad \text{(const).} \tag{8}$$

The last equation is not independent since it follows from Eqs. (4) and (7). There are three constants of the motion namely $\mathscr{J}$ (mass flux), $\mathscr{M}$ (momentum flux), and $\mathscr{E}$ (electron energy flux). E_i is the ionization energy ($\sim$13.6 eV) for electron impact ionization of hydrogen and $\beta(T)$ is the rate of ionization given by Allen (1976),

$$\beta(T) = 2\cdot10^{-10}T^{1/2}e^{-T_i/T} \qquad (\text{cm}^3\text{s}^{-1}) \tag{9}$$

$$T_i \approx 1.6\cdot10^5\ \text{K}.$$

It is convenient to analyze the structure in the (v,T) phase plane accomplished by dividing Eq.(4) by Eq.(8) to obtain

$$\frac{d(nv)}{dT} = \frac{\kappa\beta Nn}{nv(E_i + \frac{5}{2}kT) + \mathscr{E}} \tag{10}$$

in which n and N may be expressed in terms of v and T by using Eqs. (5) and (6):

$$nv = \frac{\mathscr{J}}{v_a^2}(v_- - v)(v - v_+) \tag{11a}$$

$$Nv = \frac{\mathscr{J}}{v_a^2}(v - V_-)(v - V_+) \tag{11b}$$

$$v_\pm \equiv \frac{1}{2}\left(\frac{\mathscr{M}}{\mathscr{J}}\right)\left(1 \pm \sqrt{1 - 4v_a^2/(\mathscr{M}/\mathscr{J})^2}\right) \tag{11c}$$

$$V_\pm \equiv \frac{1}{2}\left(\frac{\mathscr{M}}{\mathscr{J}}\right)\left(1 \pm \sqrt{1 - 8v_a^2/(\mathscr{M}/\mathscr{J})^2}\right) \tag{11d}$$

$$v_a^2 \equiv \frac{kT}{m} \tag{11e}$$

In subsonic flow the plasma is produced at the bottom of the layer with speed $v_-(n = 0)$, is accelerated and then exits at the top of the layer with speed $V_-(N = 0)$. Conversely in supersonic flow the plasma enters with speed $v_+(n = 0)$, is decelerated and exits with speed $V_+(N = 0)$. The solutions of the structure Eq. (10), illustrating the behaviour in the (v,T) plane for the cases of weak deflagrations and detonations, are shown in Fig. 2 for various values of the temperature gradient T_L' (or downward heat flux) at the top of the layer. In the deeper regions of the layer photoionization may become important but this is analyzed elsewhere [McKenzie at.al. (1997a)].

4. Matching the magnetic funnel to the ionization layer

The funnel flow can be matched to the ionization layer structure by requiring that the temperature and the speed as well as their gradients be continuous at the layer depth $z = z_L$. The continuity of T and v is guaranted in the sense that they simply define the values at the top of the layer. The match of the temperature gradient in the funnel (Eq. 3) with that at the top of the layer (Eq.8) provides a relation between T_0' and the depth of the layer z_L. The continuity of dv/dz at the top of the layer (where $v = V_-$) with that of the wind equation for the funnel (Eq. 2) yields a further relation between T, T_0' and z_L. At the bottom of the funnel, if we choose say $T = 1.6\cdot10^5K$, $T_0' = 2.47\cdot10^{-2}$, we find from these continuity relations that the layer is located at $z_L = 2.3\cdot(2H) \approx 700$ km below the base where the number density is around $4\cdot10^{10}\text{cm}^{-3}$.

5. Summary

We believe this simplified model is the first to illustrate the possible complex nature of the connection between the fast solar wind and its origin in the chromospheric network. The model contains a number of parameters, for example the coronal and chromospheric temperatures, but more important are the downward electron heat flux and the emanating particle flux of the wind, as well as the location of the ionization layer, all of which are interrelated. By providing relationships between these parameters this model contains an element of self regulation but, by virtue of being steady, it cannot uniquely predict the solar wind particle flux.

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