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Steady Flows in Quiescent Prominences

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The normal polarity prominence model of Hood & Anzer has been modified to include the effect of a steady flow along the magnetic field lines. We consider two isothermal regions that model the hot corona and the cool prominence, considered as a vertical sheet of dense material with infinite length and height but finite width. The magnetic field, pressure and density are assumed to be exponentially decaying in the vertical direction (the velocity is independent of the height in our model) and equations for the horizontal behaviour are determined. Invariance along the prominence direction is assumed, but the magnetic and velocity vectors retain all their components.

The introduction of a field aligned flow results in the coronal magnetic field no longer being force free and a pressure deficit allows a siphon flow to occur. Substantial coronal velocities are possible but only sub-sonic (and hence in the low plasma β corona sub-Alfvénic) flows are considered and these are consistent with observations.

Finally, we propose a simple model for the steady supply of material into a prominence to balance the observed draining motions.

1. INTRODUCTION

Solar prominences have interested theorists and observers for many decades. There are several problems related to the formation, support and eventual eruption that have still to be fully resolved. Among them there is the question of the source of the prominence mass. Two models have been basically discussed in the literature: one is concerned with the condensation of material from the surrounding corona, whereas for the other the mass source is the below chromosphere, with the material being ejected or siphoned into the prominence. The siphon mechanism to transfer material from the solar surface into a prescribed gravitational dip in a magnetic coronal arcade, such as described in the classical static model by Kippenhahn & Schlüter (1957) (from now on KS), has been shown to be possible by several authors, starting from Pikel'ner (1971).

In the present paper the problem of a steady supply of material from the solar surface into a quiescent prominence is treated, following the idea by Priest & Smith (1979) who suggested, in a cartoon, how a fully formed prominence could be supplied by material through a siphon mechanism with the prominence acting as a sink of material. They assumed that a Rayleigh-Taylor instability allows the plasma to dribble across the magnetic field lines resulting in the observed slow down flow. However, in this paper the possibility of the presence of a steady flow along the field lines from the corona into the prominence will be fully demonstrated by solving the complete set of the ideal MHD equations. The structure of the magnetic arcade will result from the solution, that means that in our model the flow plays an active role and is *not* just super-imposed over a static model, as done by the majority of the other authors.

The steady flow model for normal polarity (that is when the magnetic field passes through the prominence in the same direction as suggested by the underlying photospheric field), quiescent prominences proposed in the present paper is a generalization of the static model by Hood & Anzer (1990), from now on referred to as HA.

2. THE MODEL

Consider an ideal, isothermal plasma in a uniform gravitational field (along the z axis) with a steady mass flow that, for the sake of simplicity, is parallel to the field lines. Furthermore, assume that all the physical quantities are independent of y (in cartesian coordinates), that is $\partial/\partial y \equiv 0$. Now, write the magnetic field and pressure in the form

$$\vec{B} = B_0(X(kx), Y(kx), Z(kx))\, \mathrm{e}^{-kz},$$

$$p = (B_0^2/4\pi)P(kx)\, \mathrm{e}^{-2kz},$$

where B_0 and k are dimensional constants. Using the basic MHD equations together with the symmetry assumption the following form for the velocity is found

$$\vec{v} = c\,\lambda \frac{X}{P}(X, Y, Z),$$

with the functions $Y(kx)$ and $Z(kx)$ given by

$$Y = \alpha X/(1 - \lambda^2 X^2/P), \qquad Z = X'.$$

In an isothermal atmosphere the density is simply $\rho = p/c^2$, where $c^2 = \mathcal{R}T/\mu$ is the square of the (constant) sound velocity. For all the mathematical demonstrations the reader is implicitly referred to Del Zanna & Chiuderi (1995), where a general treatment of symmetric MHD equilibria is presented, and to Del Zanna & Hood (1995), from now on DH, where this prominence model is discussed in more detail.

After some lengthy calculations, the governing equations are found to be

$$Z' = \frac{\gamma P - X^2 - Y^2 + (1+q)M_{\mathrm{A}}^2 Z^2}{X(1 - M_{\mathrm{A}}^2)},$$

$$P' = -qPZ/X,$$

where the function q is defined as

$$q = \frac{\gamma + M^2 - 2M_{\mathrm{A}}^6/\lambda^2}{1 - M^2 - M_{\mathrm{A}}^2 + M_{\mathrm{A}}^6/\lambda^2}.$$

In these equations α, λ and γ are dimensionless parameters ($\gamma = 2[1/(2kH) - 1]$, where $H = c^2/g = \mathcal{R}T/\mu g$ is the pressure scale height), whereas M and M_A are respectively the Mach number $|\vec{v}|/c$ and the Alfvénic Mach number $|\vec{v}|/(|\vec{B}|/\sqrt{4\pi\rho})$. The last equation simply reduces to $q = \gamma$ in the static case $\lambda = 0$ (the term $2M_A^6/\lambda^2$ is proportional to λ^4). Note that this result is exactly the same as in Tsinganos et al. (1993), but its validity has been extended here to the more general case $B_y \neq 0$ and $v_y \neq 0$. Needless to say, in the dynamic case $\lambda \neq 0$, the two equations must be solved numerically, whatever the value of γ. This is a simple initial value problem for the set of unknown functions $P(kx), X(kx)$ and $Z(kx)$, for any given values of the parameters γ, α and λ.

In our attempt to build a prominence model, consider a vertical sheet of cool material of infinite height and length but finite width, surrounded by the hot coronal region. The main assumption in the HA model consists in considering both the prominence and the surrounding corona as isothermal regions with different constant temperatures, namely $T_{\rm cool}$ and $T_{\rm hot}$, with $T_{\rm cool} \ll T_{\rm hot}$. The transition zone between these two regions is then assumed to be so narrow that, taking as plane of symmetry the $y - z$ plane and considering for simplicity only the region $x > 0$, the scale height profile can be assumed to be

$$H(x) = H_{\rm cool}, \ (0 < x < x_{\rm prom}); \qquad H(x) = H_{\rm hot}, \ (x > x_{\rm prom}),$$

where $x_{\rm prom}$ is the prominence half width and where $H_{\rm cool} = \mathcal{R}T_{\rm cool}/\mu_{\rm cool}g$, $H_{\rm hot} = \mathcal{R}T_{\rm hot}/\mu_{\rm hot}g$. As in HA, the value $2H_{\rm hot}$ is assumed here for the characteristic length k^{-1}.

In the prominence and coronal isothermal regions the theory developed above is applied. Therefore, the numerical integration starts from the centre of the prominence $x = 0$ and goes on with $H = H_{\rm cool}$ and $\gamma = 2(H_{\rm hot}/H_{\rm cool} - 1) \gg 1$ until $x_{\rm prom}$. Then the jump conditions (e.g. Priest 1982) are applied and the new initial values and parameters are derived. In the corona $kH = 1/2$, $\gamma = 0$ and the integration is continued until $x_{\rm edge}$, the foot point of the arcade where $B_x = 0$ ($X = 0$). Note that in the dynamic case, even if $\gamma = 0$, the function q is not zero and no analytic solution can be found.

In order to obtain a solution for which the field lines show a central dip, supporting the dense material of the prominence against gravity, the conditions $X(0) = 1, X'(0) = 0, X''(0) > 0$ are assumed. Moreover, other three quantities are required to derive the values of $\alpha_{\rm cool}$ and $\lambda_{\rm cool}$. Suitable choices are P_0, Y_0 and M_0, respectively the values of pressure, magnetic field component along the prominence axis and Mach number at $x = 0$, with the other parameters are given by $\lambda_{\rm cool} = M_0P_0/(1 + Y_0^2)^{1/2}$ and $\alpha_{\rm cool} = Y_0[1 - M_0^2P_0/(1 + Y_0^2)]$.

3. RESULTS

As values of the parameters of our model we choose the same as in HA, so that the limit to the static case may be easily checked in order to compare the results. Therefore we take, for the prominence region, the temperature and the mean molecular weight respectively as $T_{\rm cool} = 6 \times 10^3$ K and $\mu_{\rm cool} = 1$, giving a pressure scale height $H_{\rm cool} = 180$ km. The normal and longitudinal field components at $x = 0, z = 0$ as $B_x = 5$ G and $B_y = 12$ G, yielding $B_0 = 5$ G and $\alpha_{\rm cool} = 2.4$ (in the limit $\lambda_{\rm cool} = 0$), with a correspondent angle of $\theta \simeq 22.6°$ between the field and the prominence. The average number density is taken to be $\overline{n}_{\rm cool} = 2 \times 10^{17}\,{\rm m}^{-3}$; considering this value as the half of the central density, we take the central pressure as $p(0,0) = 2k_{\rm B}T_{\rm cool}\overline{n}_{\rm cool} = 0.0332$ pascals, to be nondimensionalized against $B_0^2/4\pi \simeq 0.2$ pascals. The width of the prominence is $2x_{\rm prom} = 3\,000\,{\rm km}$. In the corona we choose $T_{\rm hot} = 10^6\,{\rm K}$ and $\mu_{\rm hot} = 0.5$, with a corresponding scale height of $H_{\rm hot} = 6 \times 10^4\,{\rm km}$, so that $k^{-1} = 1.2 \times 10^5\,{\rm km}$.

The values of the parameters for our model are then

$$kH_{\rm cool} = 0.0015,\ kx_{\rm prom} = 0.0125,\ P_0 = 0.167,\ Y_0 = 2.4,$$

that is exactly the same as in HA, to which a value for M_0 has to be added in order to fix the velocity field magnitude. The equations are integrated for four different values of M_0, namely

$$M_0 = (0.0,\ 0.5,\ 0.8,\ 1.0) \times 10^{-3},$$

and the results are shown in Fig. 1. For more plots and discussions the reader is referred to DH.

4. A SIMPLE MODEL FOR THE PROMINENCE MASS SUPPLY

Now we want to investigate a symmetric converging flow into the prominence, as suggested, in a simple cartoon, by Priest & Smith (1979) as a possible explanation for the steady replenishment of the prominence mass. As neither the governing equations of our model nor the matching conditions at the interfaces between the prominence and the corona depend on the actual direction of the flow, the only problem to solve is basically the question of the mass conservation inside the prominence. Again, following the idea by Priest & Smith, we assume that the material sucked into the prominence neutralizes cooling down and then dribbles down to the solar surface.

Using the relations derived for our model, it is possible to calculate characteristic quantities like the time scale τ of the replenishment process and the down flow velocity, simply derived by imposing the conservation of the total mass of the prominence. Consider a prominence with a finite height extending from $z = 0$ to $z = z_{\rm prom} = 50\,000$ km. The mass and the mass entering per unit time, as functions of z and per unit length, are respectively given by $2\int_0^{x_{\rm prom}}\int_0^z \rho\,{\rm d}x\,{\rm d}z$ and $2\int_0^z(\rho v_x)_{x_{\rm prom}}\,{\rm d}z$, yielding

$$m(z) \simeq \frac{B_0^2 P_0 x_{\rm prom}}{8\pi k c_{\rm cool}^2}(1 - {\rm e}^{-2kz})$$

and

$$\dot{m}(z) \simeq \frac{B_0^2 M_0 P_0}{4\pi k c_{\rm cool}\sqrt{1+Y_0^2}}(1 - {\rm e}^{-2kz}),$$

where we have approximated $\int_0^{x_{\rm prom}} P{\rm d}x \simeq (1/2)P_0 x_{\rm prom}$ and $X(kx_{\rm prom}) \simeq 1$. The characteristic time scale τ is independent of the height:

$$\tau = \frac{m}{\dot{m}} \simeq \frac{x_{\rm prom}\sqrt{1+Y_0^2}}{2c_{\rm cool}M_0}.$$

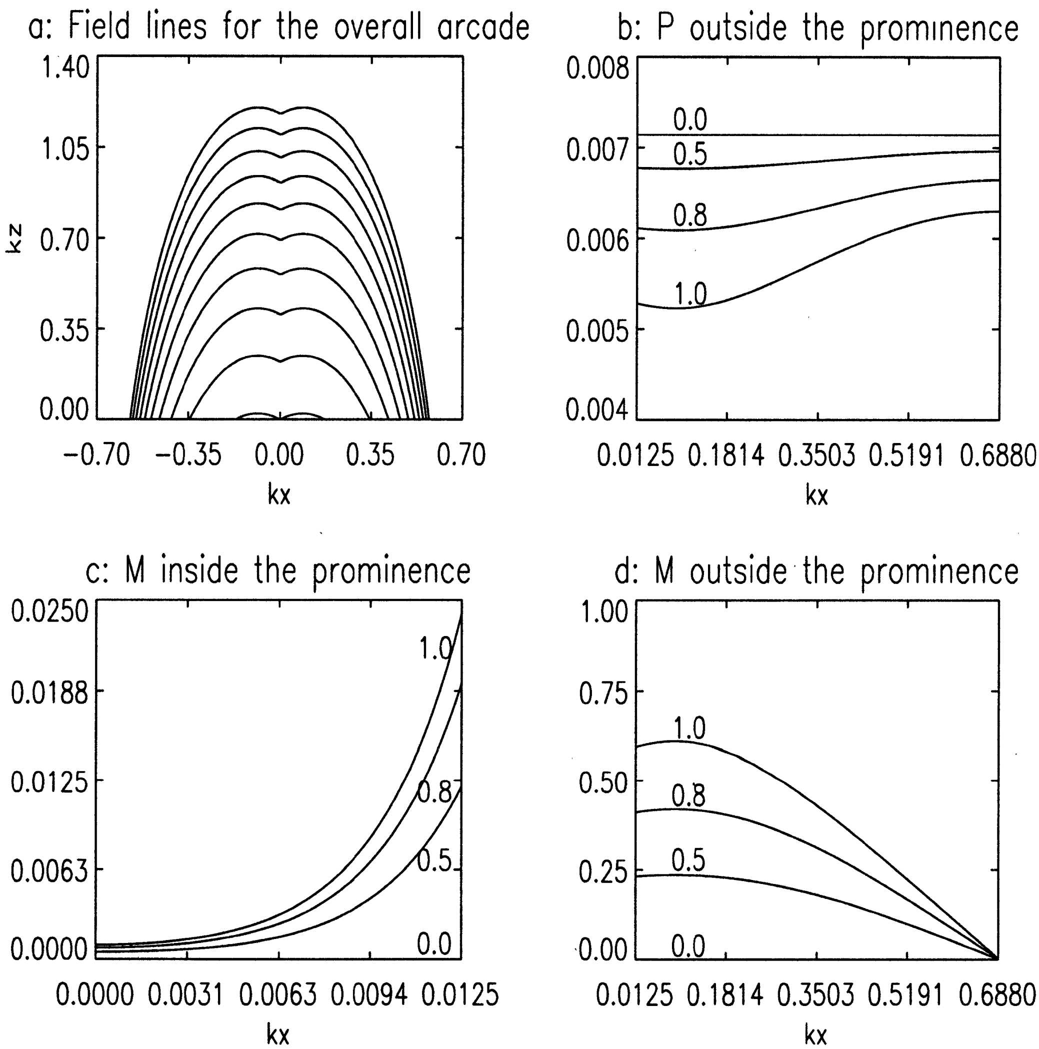

FIGURE 1. In this picture are shown: (a) the projections of the overall magnetic arcade, (b) the non-dimensional pressure in the coronal region, (c) the Mach number inside the prominence and (d) the Mach number outside the prominence. These are plotted for the four values of the initial Mach number M_0, in units of 10^{-3}. As we can see, the presence of the flow does not affect the magnetic structure of the arcade, which shows the classical dip for the support of the dense material. On the other hand, the coronal pressure is no longer constant and has a minimum at the same place as the maximum of the Mach number. For comparison, the sound speed in the prominence is $c_{\rm cool} \simeq 7\,{\rm Km\ s^{-1}}$ and in the corona $c_{\rm hot} \simeq 130\,{\rm Km\ s^{-1}}$. Therefore, if in the prominence region the velocity varies between $1 - 10^2\,{\rm m\ s^{-1}}$, that is essentially a static situation, the resulting coronal velocities can be as high as $\simeq 100\,{\rm Km\ s^{-1}}$.

With the values of the parameters given in Sect. 3 and choosing $M_0 = 10^{-3}$ we find $\tau \simeq 6.4$ days. Since the largest initial Mach number has been chosen, the time scale can be greater, in good agreement with the observed average life time of quiescent prominences ($\simeq$ 1 month). Therefore, this result leads to the suggestion that the existence of a quiescent prominence can be explained by a supply of chromospheric material siphoned into the prominence along the magnetic arcade field lines. Once this replenishment ends the prominence might disappear in a slow down flow towards the solar surface. Obviously, the possibility of a final eruption is not taken into account in this simple model.

The down flow speed $\dot{m}(z)/2\int_0^{x_{\rm prom}} \rho\, dx$ is a function of z:

$$v_{\rm d}(z) \simeq \frac{c_{\rm cool} M_0}{k x_{\rm prom}\sqrt{1+Y_0^2}}\,[\,1 - {\rm e}^{-2k\,(z_{\rm prom}-z)}\,],$$

and the maximum velocity, at the chromosphere, is $v_{\rm d} \simeq 0.12\ {\rm kms}^{-1}$. This value is rather small and confirms the result of an almost static situation inside the prominence region ($v_{\rm d}$ has the same order of magnitude of the entering velocity, as may be seen in Fig. 1c).

5. CONCLUSIONS

In this paper an extention to the dynamic case of the static Hood-Anzer model for quiescent prominences has been proposed. The possibility of a flow along the field lines of the magnetic arcade supporting the prominence has been demonstrated by solving the full set of MHD equations. As in the static model, the prominence and the surrounding coronal regions are considered isothermal with different temperatures. The results suggest that a pressure deficit around the prominence drives a siphon flow and its velocity lies in the range of the observed speeds. Finally, a simple model for the steady prominence mass supply has been proposed in order to explain the observed draining motion.

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