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LETTER

Letter to the Editor

Energy considerations for solar prominences with mass inflow

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Abstract. In this Letter we study the inflow of enthalpy and ionisation energy into solar prominences. We use 1D stationary slab models for the prominence to calculate this inflow. We compare the resulting energy gain with the integrated radiative losses obtained for such slab models. We find that for reasonable inflow velocities many of our models can be in energy equilibrium; only the very massive prominences will either require some additional heating or they have to cool down to low central temperatures. We also discuss the possibility or heating the prominence by vertical downflows.

Key words: book reviews – radiative transfer – Sun: prominences – Sun: transition region

1. Introduction

Quiescent solar prominences require both a support mechanism to keep the heavy dense material high up in the corona and an energy supply which can compensate the radiative cooling. These questions were addressed in a recent paper by Anzer & Heinzel (1999, referred to as AH) who constructed slab models which were in mechanical equilibrium. They studied the radiative properties of these models and their energy balance. They used one–dimensional slab models and subdivided the prominence into two distinct regions: an inner cool region which is optically thick and a prominence-corona transition region (PCTR) which can be treated in the optically thin approximation. For the modelling of the inner region an ad-hoc temperature profile was assumed and on this basis the full radiative transfer problem was solved. From this the net radiative losses occurring in the prominence could be calculated. The energy equilibrium then requires that at each position in the prominence these losses have to be balanced by the appropriate local heating. This heating mechanism was not specified in AH, but the need for efficient heating of the central parts of the prominence became quite evident. In the present Letter we study this aspect and in particular we shall answer the question whether this heating can be provided by the inflow of enthalpy and ionisation energy into the prominence. This type of heating was discussed recently for the case of the chromosphere – corona transition region by Chae et al. (1997). These authors found that the predominant redshifts could be explained by downflows of about 7 km s^{-1} at a height where the temperature amounts to 10^5 K (note: the velocity scales roughly as the temperature *T*). Since the transition region between the interior of the prominence and the surrounding corona (PCTR) has similar properties, we expect that this heating mechanism can also work in prominences provided that large enough inflows occur (Poland, private communication). This is also consistent with the siphon mechanism suggested by Pikel'ner (1971).

In this paper we shall not study the optically thin hot parts of the transition region. Energy equilibria for these regions were already given in AH. In this region it is fairly easy to achieve an energy balance. The only problem there is to match the curve for the differential emission measure with the observations (Engvold et al. 1987, and Chiuderi & Chiuderi Drago, 1991). In this paper we take the same 1D slab models as in AH. In Sect. 2 we give the equations describing our model, in Sect. 3 we present the results, in Sect. 4 we discuss the effects of vertical downflows and Sect. 5 gives a discussion of these new results.

2. Formulation of the problem

Here we use the same 1D slab geometry as in AH and also denote the different models in the same way (see Table 1 in AH). We also chose the temperature $T_1 = 30000$ K in order to separate the inner and outer regions of our prominence models. We assume a steady inflow of hot plasma through this boundary. This flow has to stream along the magnetic field lines, resulting in an inflow of enthalpy and ionisation energy through this boundary. The formula which allows us to calculate this flow is adopted from that given by Chae et al. (1997):

$$F = \left(\frac{5}{2}p + I\right) v \frac{B_x}{B} \quad (1)$$

where F is the flux in x – direction, I is the ionisation energy, v the flow velocity along the field at the boundary and $\mathbf{B} = (B_x, 0, B_z)$ the field vector at this boundary. The mass flow is

$$\dot{M} = \rho v \frac{B_x}{B}. \quad (2)$$

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We also have

$$I = n_H i E_{\rm ion} \quad (3)$$

$$p = (1.1 + i) n_H kT \quad (4)$$

$$\rho = 1.4 m_H n_H \quad (5)$$

where n_H is the total hydrogen density (i.e. neutral plus ionised particles), i the ionisation degree, $E_{\rm ion}$ the hydrogen ionisation energy per atom amounting to 2.2×10^{-11} erg, p the gas pressure and ρ the density. As in AH we have taken a hydrogen plasma with 10% helium added and we have neglected the effects due to helium ionisation. With these definitions Eq. (1) can be rewritten as:

$$F = \left[\frac{5}{2}(1.1 + i)kT + iE_{\rm ion}\right] n_H v \frac{B_x}{B}. \quad (6)$$

The amount of energy which is available for heating is the difference of this flow at the surface and the flow near the center. Since mass conservation of the flow in a steady state gives

$$n_H v \frac{B_x}{B} = const \quad (7)$$

we then obtain

$$\Delta F = \left\{\frac{5}{2}k\Delta\left[(1.1 + i)T\right] + E_{\rm ion}\Delta i\right\} n_H v \frac{B_x}{B}. \quad (8)$$

From the models of AH one sees that $i \approx 1$ at the surface and $i \approx 0.3$ near the center.Taking a central value of $i = 0$, we obtain an upper limit of ΔF

$$\Delta F \approx \left[\frac{5}{2}k(2.1T_1 - 1.1T_c) + E_{\rm ion}\right] n_H v \frac{B_x}{B}, \quad (9)$$

where T_c is the central temperature of the prominence. It is interesting to note that for these parameters the enthalpy contribution is about 1.9×10^{-11} erg compared to the ionisation energy of 2.2×10^{-11} erg.

Our non–LTE radiative transfer models were calculated under the assumption of magneto–hydrostatic equilibrium. But the present considerations require a non–vanishing inflow velocity. Therefore, using the AH – type models is not entirely self–consistent. But the flow velocities are subsonic in the hot ($T = 10^6$K) corona, therefore from Eq. (7) and from the fact that the gas pressure has to increase towards the cooler region we find that the flows are highly subsonic inside the prominence. This then means that dynamic contributions to the pressure term can be completely neglected and our equilibrium models are good approximations.

The question of the gradual mass increase in the prominence resulting from this inflow will be discussed later.

3. Results

We have calculated for all the models presented in AH the total radiative losses, $L_{\rm tot}$, given by

$$L_{\rm tot} = 2\int_0^{x_1} L dx \quad (10)$$

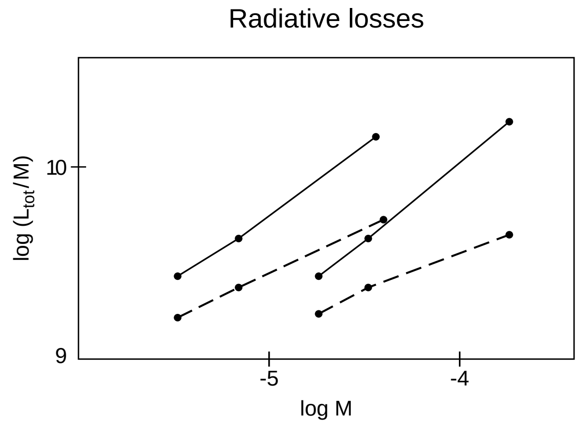

Fig. 1. Variation of the specific luminosity $L_{\rm tot}$/M as a function of column mass M, for thin slab models (left) and thick slab models (right). Solid curves are for T_c = 8000 K, dashed curves for T_c = 6500 K.

where L is the local net radiative loss function as calculated by AH and x_1 is the position of the outer boundary with $T(x_1) = T_1$. The total heating from inflow amounts to

$$F_{\rm tot} = 2\Delta F \quad (11)$$

because one has inflow from both sides of the prominence. We take $T_1 = 30000$ K and T_c is either 6500 K or 8000 K, depending on the model. For the inflow we take $n_H v = 5 \times 10^{14}$ cm^{-2} s^{-1}, which corresponds to a coronal density of $n_H = 10^8$ cm^{-3} and a flow velocity in the corona of $v = 5 \times 10^6$ cm s^{-1} at $T = 10^6$ K. This then scales to $n_H = 3 \times 10^9$ cm $^{-3}$ and $v = 1.7 \times 10^5$ cm s^{-1} at T = 30000 K. Our value for the coronal inflow velocity is rather large (i.e. 1/2 of the local sound velocity), therefore the resulting estimates for the heating can be considered as upper limits. The value of the ratio B_x/B amounts to about 0.8 for the thick slab models of AH and 0.3 for the thin slabs. The relevant quantities for all our models are summarized in Table 1. The models are denoted in the same way as in AH: M1 to M3 refers to geometrically thick slabs, M4 to M6 to geometrically thin slabs; T6 stands for T_c = 6500 K and T8 for T_c = 8000 K. *M* is the total column mass in g cm^{-2}, *D* the slab thickness in km, $L_{\rm tot}$ the integrated radiative losses, F_{tot} the heating by inflow, both in erg cm^{-2}s^{-1}, and $L_{\rm tot}/M$ the radiative losses per unit mass, in erg g^{-1}s^{-1}.

From our table we see that only the low mass models M3T6, M6T6 and M6T8 are in energy equilibrium. The models M3T8 and M5T6 are close to an equilibrium. All other models cannot be balanced by the inflow of enthalpy and ionisation energy and will therefore require some additional heating mechanism. This implies that an energy equilibrium by an inflow mechanism can be achieved only for sufficiently cool and very tenuous prominences.

We have also calculated the ratio between total radiative losses and column mass. These ratios as calculated in Table 1 are shown in Fig. 1 as a function of column mass for two different values of the central temperature. The two curves to the left are for thin slabs, the ones to the right for thick slabs. The ratio

Table 1. Summary of physical quantities, the different models are denoted in the same way as in AH.

Model	$M(\mathrm{g\,cm^{-2}})$	D(km)	$L_{\rm tot}$ (erg cm$^{-2}s^{-1}$)	$F_{\rm tot}$ (erg cm$^{-2}s^{-1}$)	$L_{\rm tot}/M$ (erg g$^{-1}s^{-1}$)
M1T6	1.8-4	2000	7.9+5	3.2+4	4.4+9
M1T8	1.8-4	2500	3.0+6	3.2+4	1.7+10
M2T6	3.3-5	2000	7.6+4	3.2+4	2.3+9
M2T8	3.3-5	2500	1.4+5	3.2+4	4.2+9
M3T6	1.8-5	2000	3.1+4	3.2+4	1.7+9
M3T8	1.8-5	2500	4.7+4	3.2+4	2.6+9
M4T6	3.6-5	400	2.0+5	1.2+4	5.6+9
M4T8	3.6-5	500	5.5+5	1.2+4	1.5+10
M5T6	6.7-6	400	1.6+4	1.2+4	2.4+9
M5T8	6.7-6	500	2.8+4	1.2+4	4.2+9
M6T6	3.3-6	400	5.4+3	1.2+4	1.6+9
M6T8	3.3-6	500	8.5+3	1.2+4	2.6+9

changes by a factor of 10 for the range of column masses taken in our models. The fact that the most massive prominences also have the largest specific losses can be explained by realising that the optically thin contributions to the radiative losses are proportional to the square of the particle density. Table 1 and Fig. 1 also show that models which have the same mean gas pressure, but different column masses (e.g. models M1 and M4, etc.) have approximately the same value for the ratio $L_{\rm tot}/M$.

4. Vertical flows

Our models give not only an inflow of energy but they also produce an inflow of mass at a rate of

$$\dot{M}_{\rm tot} = 2\times 1.4 m_H n_H v\frac{B_x}{B} = 2\times 10^{-9}\frac{B_x}{B}(\mathrm{g\,cm^{-2}s^{-1}}) \quad (12)$$

For our models M1 to M3 this gives $\dot{M}_{\rm tot} = 1.5\times 10^{-9}$ g cm^{-2}s^{-1}. If this mass is accumulated inside the prominence it would grow very rapidly, its mass would be doubled wihtin 10^5s for model M1, within 2×10^4s for model M2 and 10^4s for model M3. Since such a rapid steady growth of the prominence as a whole is not observed prominence material has to leave the prominence at a similar rate. (Note: prominence fine structures can form and disappear on slower time scales, but the quiescent prominence as a whole will be rather stationary). Mass losses of the required magnitude could be achieved by a systematic downflow of cool material in the center of the prominence. However this downflow cannot be modelled in our 1D slab configuration. For this reason will shall give here only some order of magnitude estimates for the flow. If we assume that the prominence extends over a height h and that the vertical outflow at the bottom is v_z, whereas there is no inflow at the top then the condition of mass conservation gives

$$d n_c v_z = 2 h n_H v\frac{B_x}{B}, \quad (13)$$

where d is the width of the downflow region, n_c its hydrogen density.

Such systematic downflows can provide additional energy at a rate of $\rho v_z g$, as has been proposed by Heasley & Mihalas (1976) and this could lead to an additional heating of the central parts of prominences. The mean heating rate will be given by

$$H_{\rm ver} = 1.4 m_H n_H v\frac{B_x}{B} g h \quad (14)$$

For $h = 3\times 10^9$ cm we then get

$$H_{\rm ver} = 1.6\times 10^{-10} n_H v\frac{B_x}{B}. \quad (15)$$

The heating by enthalpy and ionisation energy inflow from both sides amounts to $F_{\rm tot} = 8\times 10^{-11} n_H v B_x/B$. These numbers show that for the parameters chosen the gravitational energy release is twice as large as the enthalpy and ionisation energy flow. Therefore such a mechanism could be an important heat source for the central parts of prominences. There are, however, some basic problems with this scenario. Since the magnetic field in prominences is predominantly horizontal this downflow has to occur perpendicular to the field. Even for ionisation degrees as low as 0.2 the flow of neutral atoms across the field lines will be only of the order of 10^4 cm s^{-1} (Mercier & Heyvaerts, 1977). Such flows are therefore only possible if very efficient reconnection occurs in the cool part of the prominence. An additional requirement for the reconnection mechanism is that the fields are stretched sufficiently downward to lead to the right magnetic field topology. This reconnection could then result in the required effective resistivity of the prominence plasma. But when the prominence material starts moving downward it also has to convert its kinetic energy into heat. The question how this can be achieved is also open at present. Therefore we think that this mechanism looks promising, but there are still many details which will have to be worked out.

5. Discussion

This investigation shows that only prominences with a low column mass can be heated sufficiently by the inflow of enthalpy and of ionisation energy from the surrounding corona. This result holds if the central temperature in the prominence is around 8 000 K. If the central temperature becomes sufficiently low then also more massive prominence could be heated in this way. In particular Heasley & Mihalas (1976) have found that if the model is in radiative equilibrium,the central temperature reaches some 4600 K and no heating is needed in these regions. But the value of this equilibrium temperature is so low that it seems very implausible that quiescent prominences are in such an "equilibrium state".

There are still some other unsolved problems related to this heating mechanism.

1. As can be seen from the figures presented in AH the gradients of the temperature and the ionisation degree go to zero in the central parts of the prominence. Therefore the inflow of energy into these regions will also vanish and our heating mechanism does not work there. On the other hand one sees that the radiative loss curves have a maximum in the mid–plane of our slab models because of the density peak. Therefore some additional heating will still be required in the center.
2. Our simple model is not fully self–consistent: as long as there is no flow across magnetic field lines the inflowing plasma has to pile up in the central regions of the prominence. Therefore the prominence mass would grow infinitely. For typical prominence parameters one would have a systematic doubling of the mass within a time of several hours. This obviously is in disagreement with the observations. For this reason one is forced to postulate that in the central regions the plasma can slowly move across the field lines and diffuse downward to leave the prominence at this bottom. But at present it is not clear how this diffusion could occur.

   However if this systematic downflow actually occurs it represents an additional source of energy. For our models the energy associated with this downflow is typically twice as large as that of the inflow of enthalpy and ionisation energy. Therefore it could be a powerful heating source. But we have not yet a model describing the energy conversion into heat for this downflow.

   The investigation presented in this paper only deals with the global energy balance. It does not solve the local heating problem. Such a detailed modelling of the local energetics will be the subject of a forthcoming paper and will require the simultaneous solution of the equation for the flux divergence and the full non–LTE radiative transfer equations.

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