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Coronal Heating by Magnetic Kink Waves

Dipankar Banerjee ¹

Indian Institute of Astrophysics, Bangalore 560034, India

M. Dikpati

*High Altitude Observatory, National Centre for Atmospheric Research,
 Boulder, Colorado 80307*

A. R. Choudhuri

*Department of Physics, Indian Institute of Science, Bangalore 560012,
 India*

Abstract. We show that the magnetic kink waves generated by the motions of the photospheric footpoints of the coronal flux tubes can supply adequate energy for heating the quiet corona. We model the solar corona as two-layer isothermal atmosphere, with the lower layer having chromospheric thickness and the temperature and the upper layer having coronal temperature.

1. Introduction

It is now generally accepted on the basis of observations (Berger & Title, 1996) that the solar magnetic field is highly structured, with most of the magnetic flux in the photosphere being clumped into small intense flux tubes, with diameters of the order 200 - 300 km. Thus the waves carrying energy from the photosphere to the corona can be modelled as waves propagating along magnetic flux tubes. When the footpoints moves rapidly for a short time, we find that much of the energy is fed into the kink mode at frequencies well above the cutoff frequency and hence can propagate upward. Until recently there was no direct observational evidence as to the nature of the footpoint motions. Berger & Title (1996) has reported the dynamics of the small scale solar magnetic field, based on high resolution images of the solar photosphere obtained at the Swedish vacuum tower telescope. The bright points move in the intergranular lanes and are primarily driven by the evolution of the local granular convection flow field. It has also been observed at Pic-du-midi (Muller *et al.* 1994.) that these bright points occasionally undergo rapid motions with velocities of the order of 3 km/s typically lasting for 3 minutes. It was pointed out by Choudhuri *et al.* (1993a) that such jerky motions of footpoints would give rise to kink modes in the flux tubes above. Choudhuri *et al.* (1993b) have studied, how the energy transport

¹Present address: Armagh Observatory, Armagh, BT61 9 DG, N. Ireland

to the corona is influenced by the temperature jump in the transition layer. The aim of the present study is to calculate the energy flux reaching the solar corona using Choudhuri *et al.* (1993a,b) formalism and applying a more recent solar atmospheric model.

2. Energy Flux

We study the propagation of a pulse along a flux tube embedded in a two-layer isothermal atmosphere, the lower layer of height h at a temperature T_1 and the upper one at temperature T_2 , with $T_2 > T_1$. Such a two-layer model is quite appropriate for the solar atmosphere (see Fontenla, Avrett and Loeser 1990). The cutoff frequency ω_{c_2} of hot upper layer will be less than that of the lower layer (*i.e.*, $\omega_{c_2} < \omega_{c_1}$). For frequencies larger than ω_{c_1} , the modes will propagate in both the layers. On the other hand, modes with frequencies less than ω_{c_2} will be evanescent in both the layers. Neglecting the non-linear effects and merger of neighbouring flux tubes for pulses generated by footpoint motions the asymptotic energy carried to the solar corona is give by (For details see Choudhuri *et al.* 1993b),

$$\mathcal{E}_{\text{corona}} = 6.5 \times 10^{26} \left\{ \frac{\rho_{1,0}}{10^{-7} \text{gmcm}^{-3}} \right\} \left\{ \frac{A_{1,0}}{10^5 \text{km}^2} \right\} \left\{ \frac{v_0}{1 \text{kms}^{-1}} \right\}^2 \left\{ \frac{H_1}{250 \text{km}} \right\} F_{\text{asy}} \quad (1)$$

where $\rho_{1,0}$ is the density, $A_{1,0}$ is the cross-sectional area of the flux-tube v_0 is the maximum velocity of the footpoint and H_1 is the scale height at the photospheric level. $F_{\text{asy}} = F(\lambda, \alpha, r, t \rightarrow \infty)/\lambda^2$ is a function of three parameters, λ , α and r (in dimensionless units), the measure of the rapidity of the footpoint motion, the height of the transition layer and the temperature contrast respectively. Defining the boundary between the chromosphere and the corona is quite difficult. We follow Mariska (1992) (see Fig. 1.7), who used a temperature of 10^6 K for the boundary between the transition region and the corona in quiet solar regions at a height of 2000 km from the photosphere (with $T_2/T_1 = 125$). It may be higher in active regions and lower in the coronal holes.

Figure 1 shows the variation of F_{asy} with the rapidity of the footpoint motions. One can now read off the value of F_{asy} for a particular λ from Figure 1 and then the energy can be calculated by using equation (1). We take $\rho_{1,0} = 3 \times 10^{-7} \text{gm cm}^{-3}$, $A_{1,0} = 0.5 \times 10^5 \text{km}^2$ and $H_1 = 250 \text{km}$. One can finally estimate the energy flux by multiplying $\mathcal{E}_{\text{corona}}$ by the number density of footpoints and the frequency of motions. Assuming that there are about 10 footpoints in an area of $10^4 \text{km} \times 10^4 \text{km}$, we get a number density of 10^{-17}cm^{-2} . Since slow footpoint motions have granular time scales, we take the frequency to be about 1 in 500 s. The faster footpoint motions are less frequent and for the purpose of rough estimate, let us take the frequency of fast motions to be once in 5000 s, *i.e.*, 10 times infrequent compared to the slow footpoint motions. Hence the energy flux due to fast footpoint motions alone and slow footpoint motions alone can be obtained by multiplying $\mathcal{E}_{\text{corona}}$ by respectively 2×10^{-21} and $2 \times 10^{-20} \text{cm}^{-2} \text{s}^{-1}$. The values of energy flux for two models are also presented in Table 1. There are several things to be noted in Figure 1 and Table 1. Firstly, the dashed line (isothermal) in Figure 1 is not very different from the solid line (two-layer

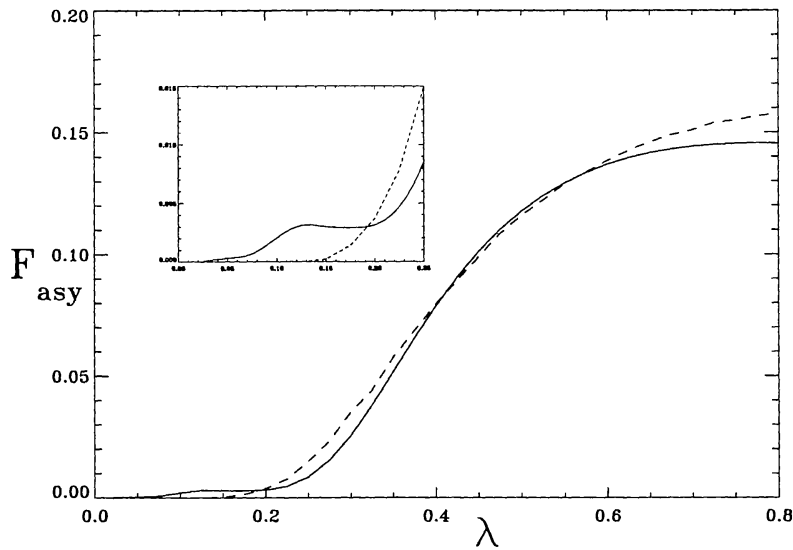


Figure 1. Asymptotic energy as a function of λ (measure of the strength of the footpoint motion). The dashed line represents the isothermal model and the solid line represents the more appropriate solar two-layer atmosphere model with (thickness of the first layer) $\alpha = 2$ and temperature contrast, $r = 0.09$.

| Rapidity of Footpoint motion | Net Flux ($\text{ergs cm}^{-2} \text{s}^{-1}$) | |
|---|--|----------------------|
| | Isothermal atmosphere | Two-layer atmosphere |
| $\lambda = 0.22$ ($v_0 = 1 \text{ km/s}$) | 1.50×10^5 | 0.91×10^5 |
| $\lambda = 0.44$ ($v_0 = 3 \text{ km/s}$) | 1.74×10^6 | 1.77×10^6 |

Table 1. Energy flux for different cases.

model). Given the other uncertainties in the model, one concludes that an isothermal atmosphere is not a bad model for the solar atmosphere as far as the propagation of magnetic kink modes are concerned. Secondly, the two-layer calculations reinforce the main conclusion of Choudhuri *et al.* (1993a,b) that the fast footpoint motions are much more important for transporting energy to the corona compared to the slow motions, even though the fast motions may be much less frequent. This is because the individual fast motions cause a much larger $\mathcal{E}_{\text{corona}}$ than the individual slow motions – both due to a larger v_0 and a larger F_{asy} . Hence, the contribution made by fast motions, though infrequent, is more substantial. In fact, as seen in Table 1, the energy flux due to slow footpoint motions alone for all the models falls slightly short of the requirement for heating the quiet corona. On the other hand, the rapid footpoint motions alone can provide the necessary energy flux. It is to be noted from Figure 1 that energy flux for rapid footpoint motions is slightly reduced in going from the isothermal model to the two-layer model, which is obviously due to reflection.

But the energy flux for slow footpoint motions may get somewhat enhanced due to tunnelling as we go to the two-layer model. To emphasise this point we enlarge the part of the diagram (shown as inset of Fig. 1) corresponding to low λ *i.e.* slow footpoint motions. Note that for two-layer model intermediate frequencies between ω_{c_2} and ω_{c_1} , the modes will be evanescent in the lower layer and propagating in the upper layer. If the lower layer extended over many scale heights, then these intermediate modes would not be able to take away any energy flux. On the other hand, if the lower layer were sufficiently thin, then these modes could “tunnel” through it and then propagate in the upper layer. Hence, under certain circumstances, the asymptotic energy flux, instead of becoming less than what it would have been in an isothermal atmosphere with temperature T_1 , actually becomes more if there is a temperature jump from T_1 to T_2 with a hotter layer above.

3. conclusion

In this work, we have neglected the ‘merging’ of neighbouring fluxtubes throughout our domain of calculation. The fluxtubes fans out and merges with the neighbouring tube after a certain height which may be a few to several scale heights, but certainly much before the fluxtube reaches the corona. So the flaring fluxtube forms a uniform magnetic canopy after a certain height and this change in geometry may affect the amount of energy transmitted to the corona, this study is in progress. Another assumption was to neglect the nonlinearities which must become important in higher regions where the amplitudes are large. Kalkofen (1997) has interpreted the oscillations in chromospheric bright points in terms of kink and sausage waves propagating upwards inside magnetic flux tubes. He proposes that the waves are generated impulsively in the photosphere as kink waves and as they propagate upwards they become nonlinear and transfer their power to sausage mode. Similar work has been reported by Huang *et al.* (1995), who numerically investigated the non-linear time-dependent response to purely transverse shaking of a thin exponentially spreading vertical flux tube embedded in a solar convection zone and atmosphere model. Though our calculation was done for kink waves we expect that purely acoustic waves and sausage waves to behave similarly.

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