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Alfvénic-turbulence-heated magnetic loops: effects of lateral expansion and magnetic twist

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Using a 1.5-dimensional two-fluid magnetic loop model in which loops are heated by Alfvénic turbulence, we explore the effects on the loop parameters of the varying cross-section and the magnetic twist. The introduced magnetic twist is set to be around the kink instability threshold for a curved loop. It is found that: (i) The lateral expansion, which takes place close to footpoints, can significantly influence the heating profile, leading to a significant footpoint plasma flow. When observed on disc, the corresponding footpoint blue/red shift may be found for upper transition region lines. (ii) The effects introduced by magnetic twist are twofold. Firstly, the twist-related force may contribute to the axial force balance. Secondly, the projection effect reduces the electron and proton thermal conductivities. The former is found to be of little significance; however, the latter gives rise to considerable changes compared to the untwisted case.

Keywords: solar coronal loop; turbulence heating; lateral expansion; magnetic twists

1. Introduction

Tremendous observational and modelling efforts made in the study of coronal loops have resulted in a great enrichment of the knowledge of coronal heating. Recently, Li & Habbal (2003) demonstrated the potential of a heating mechanism by Alfvénic turbulence. It is the intention of the present paper to extend their study by including lateral expansion and magnetic twist.

The magnetic field strength at the photospheric footpoints of coronal loops is of the order of kilogauss. Direct measurements of coronal magnetic field prove difficult, but the inferred magnitude is typically 20–30 G. On the other hand, loops show little variation of cross-section area a along the visible segment (e.g. Klimchuk *et al.* (2000)). Loops, therefore, undergo a lateral expansion which terminates at heights where electron temperature is below the coronal value. Moreover, many loops appear twisted in images, as would be expected theoretically, since a substantial twist can be efficiently achieved, say, by photospheric granulation (Berger 1991).

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One contribution of 20 to a Discussion Meeting Issue 'MHD waves and oscillations in the solar plasma'.

2. Model description and results

The loop is approximated by a semi-circular torus with length $L=1.5\times10^5$ km and small radius ξ ($\xi/L\ll1$). ξ is related to a by $a\propto\xi^2$. The standard two-fluid magnetohydrodynamics (MHD) equations are cast in local cylindrical coordinates $(\tilde{\xi}, \phi, s)$, where s is the arclength along the loop axis. $\partial/\partial\tilde{\xi}=0$ and $\partial/\partial\phi=0$ are assumed; however, angular components v_ϕ and B_ϕ are retained, rendering the model 1.5-dimensional. The governing equations are those in Li & Habbal (2003), to which two equations governing v_ϕ and B_ϕ are appended. Besides, the momentum equation accommodates twist-related terms (cf. eqns. (5)–(7) in Hollweg *et al.* (1982)). Optically thin radiation is considered, field-aligned heat fluxes $\mathbf{q}$ are assumed for both electrons (e) and protons (p), i.e. $\boldsymbol{q}_\mathrm{i}=-\kappa_\mathrm{i}(\boldsymbol{BB})/B^2\boldsymbol{\cdot}\nabla T_\mathrm{i}$, i=e, p.

The Alfvén wave energy which eventually goes to proton heating via proton cyclotron resonance is assumed to be that cascaded from low to high frequency range at the Kolmogorov rate, $Q=nm_\mathrm{p}\zeta^3/L_\mathrm{c}$, where n is the number density, m_p the proton mass, ζ the wave-associated velocity amplitude. The wave dissipation length L_c scales as $L_\mathrm{c}\propto a$, whereas the axial magnetic field $B_\mathrm{s}\propto1/a$. For nonuniform loops, a evolves in such a way that B_s decreases sharply from 120 G at the solar surface (the vertical height being zero) to 30 G at the height of 400 km and remains constant thereafter. A constant $B_\mathrm{s}\equiv30$ G is assumed for uniform loops.

Including v_ϕ and B_ϕ may affect the loop dynamics by introducing the twist-related force. Moreover, due to the projection effect $(\nabla\boldsymbol{\cdot}\mathbf{q}_i=-(1/a)\,(\partial/\partial s)\,(a\kappa_\mathrm{i}\cos^2\Phi(\partial T_\mathrm{i}/\partial s)))$, the conductivities ($\kappa_\mathrm{e}$ and κ_p) are in effect reduced by a factor of $\cos^2\Phi$, where Φ is the angle between the magnetic field and the loop axis, $\tan\Phi\equiv\eta=B_\phi/B_\mathrm{s}$.

Temperatures T_i (i=e,p) are fixed at 2×10^4 K at $s=0$ and $s=L$. Subscript 0 will denote relevant values at $s=0$. ζ and B_ϕ are prescribed in terms of ζ_0 and η_0 at $s=0$, but are allowed to change freely at $s=L$. The two footpoints serve as free boundaries for n, v_s and v_ϕ. Steady state solutions are solved for.

The smallness of axial Alfvén Mach number M ($M^2=4\pi nm_\mathrm{p}v_\mathrm{s}^2/B_\mathrm{s}^2$) allows η and v_ϕ to be approximated satisfactorily by

$$v_\phi=\left[v_{\phi,0}+\eta_0\left(v_\mathrm{s}-v_{\mathrm{s},0}\right)\right]\frac{\xi}{\xi_0}, \tag{2.1}$$

$$\eta=\left\{\eta_0+\left[\eta_0\left(1-\frac{v_{\mathrm{s},0}}{v_\mathrm{s}}\right)+\frac{v_{\phi,0}}{v_\mathrm{s}}\left(1-\frac{\xi_0^2}{\xi^2}\right)\right]M^2\right\}\frac{\xi}{\xi_0}. \tag{2.2}$$

It follows that η is nearly in proportion to the loop radius ξ. Although not shown, the above analytical expectations are excellently reproduced by the numerical results.

Presented in figure 1 are four cases characterized by different combinations of expansion and η_0. They can be summarized as Case A: N/0, B: Y/0, C: N/1, D: Y/0.5, where N and Y correspond to loops without and with lateral expansion, respectively. The choice for η_0 ensures that η is about 1 for coronal segment. The resulting twist $\int_0^L(\eta/\xi)\,\mathrm{d}s$ is nearly 10 if assuming $\xi/L=0.1$ for coronal portion,

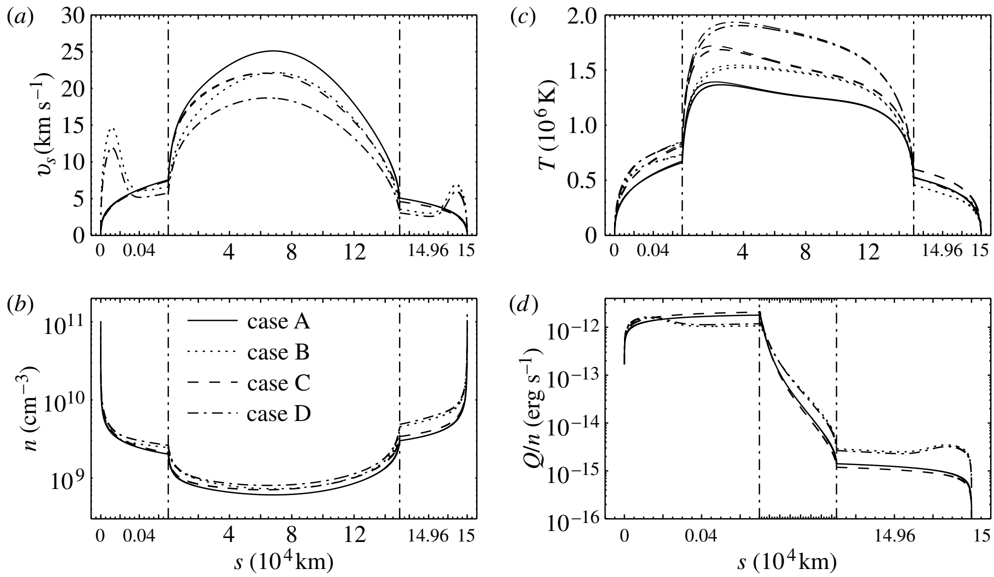

Figure 1. The axial dependence of (*a*) axial flow v_s, (*b*) electron density n, (*c*) electron (T_e, thin lines) and proton (T_p, thick lines) temperature and (*d*) heating rate per proton Q/n. Note that different scales are applied to different segments of the abscissa to better show footpoint variations. All curves are smoothly connected at positions delineated by vertical dash-dotted lines. Panel (*d*) emphasizes the footpoint segment even stronger. Line indices indicate different cases, as labelled in panel (*b*). At $s=0$, fixed values are specified for wave amplitude $\zeta_0=10\ \mathrm{km\ s^{-1}}$ and dissipation length $L_{c0}=100$ km for all cases.

which almost reaches the threshold for kink instability for a curved loop (3.4π, as given by Gerrard *et al.* (2004)).

Inspection of figure 1 reveals that for cases B and D, the rather abrupt footpoint expansion induces significant footpoint axial flow near $s=0$, which nearly reaches $15\ \mathrm{km\ s^{-1}}$ for Case B. A similar axial flow hump appears at the outflowing end $s=L$, although smaller in magnitude. The deceleration region close to $s=0$ is found to be associated with negative proton pressure gradient force, although electron pressure acts to accelerate the plasma. That is, the footpoint expansion alters the heating profile, leading to protons and electrons being out of perfect thermo-equilibrium (hardly discernible though). Similarly, near $s=L$, the altered heating profile results in a reduced electron and proton pressure gradient (in magnitude), the projected gravity acts to produce the acceleration region. Comparing C with A or D with B, it is obvious that introducing twist leads to an enhanced density, temperature as well as a reduced axial flow speed. It is found that, as expected from equations (2.1) and (2.2), the twist-related force is only discernible where substantial expansion occurs. One may expect that it plays a role in energy balance; this, however, turns out not to be the case. The work done by the twist-related force is found to be negligible in the energy budget. Thus, the considerable changes in thermodynamic parameters, T_{e} for instance, are solely caused by the reduced thermal conductivities due to projection effect.

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