Nonlinear dynamics and wave heating in solar coronal loops

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Abstract. We present the first results of 2.5D nonlinear magnetohydrodynamic wave heating simulations of solar coronal loops with inclusion of the modeling of the coupling to the transition region and chromosphere. Magnetic flux tubes with fixed lengths are considered but the coronal extent of the loops as situated in between the two transition regions can vary dynamically. The numerical simulations were carried out with the Versatile Advection Code. The loops are excited with linearly polarized Alfvén waves at the chromospheric base. The main finding is that resonant absorption is not efficient since most of the Poynting flux that enters the loop will be used to support all the nonlinearly generated magnetoacoustic motions and the corresponding compression of coronal plasma.

1. Introduction

The solar transition region is highly dynamical (e.g. Mariska 1992). For example, it can be lifted easily over a few megameters by the pressure exerted by waves that propagate upwards from the lower atmospheric levels, a key concept in spicule formation theories (e.g. Hollweg 1982,1992; Sterling & Mariska 1990). Yet, studies of coronal wave heating based on either resonant absorption or phase mixing have mostly neglected the influence of the transition region and chromosphere. Instead, these studies focussed on the efficiency with which they can create the short length scales to generate the necessary Ohmic and viscous

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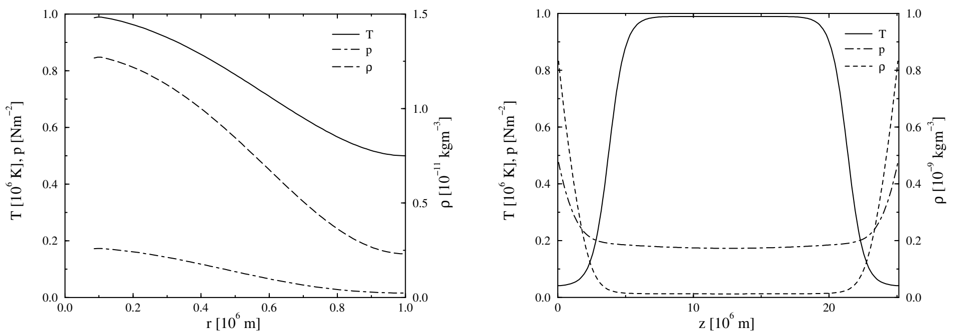

Figure 1. Radial and longitudinal variation of the initial temperature, pressure, and density profiles ($a = 10^6$ m, $L/a = 8\pi$, $B = 25 \times 10^{-4}$ T). *left panel*: at the loop top *right panel*: on axis.

dissipation rates despite the very large coronal viscous and magnetic Reynolds numbers (e.g. Kappraff & Tataronis 1978; Heyvearts & Priest 1983; Poedts & Kerner 1992; Goossens, Ruderman, & Hollweg 1995; Poedts & Boynton 1996; Ruderman, Nakariakov, & Roberts 1998).

Both resonant absorption and phase mixing rely on variation of the Alfvén speed *across* the magnetic field to yield small length scales. Therefore, the attention has been focussed on loops with variations across the magnetic field only. Loops with *fixed* lengths are considered and the dynamical effects of the dense lower atmospheric layers are lumped into line-tied or flow-through boundary conditions. The fixed finite length loops plus the boundary conditions model the crucial interference filter, or resonator cavity properties (Hollweg 1981,1984a,b; Zhugzhda & Locans 1982; Berghmans & DeBruyne 1996). However, in view of the above, it is clear that fixed lengths make sense for very large loops only ($>$ 100 Mm) where the length variations, related to the varying position of the transition region, are negligible, i.e. less than a few percent, so that the cavity will not be detuned.

The use of the line-tied or flow-through boundary conditions is an oversimplification as well because it creates a non-leaky cavity with an infinite quality factor. Coronal loops are leaky since the ratio of Alfvén speeds in the corona and the chromosphere/photosphere is finite ($\approx 10 - 100$) and leakage will affect the efficiency of resonant absorption and phase mixing (Berghmans & DeBruyne 1996). It is clear that a full understanding of the role of wave heating in the solar corona requires the coupling of the coronal part of loops with the transition region and chromosphere.

We have performed a series of 2.5D numerical simulations in which we launch an Alfvén wave at one of the chromospheric boundaries to study wave dynamics and the efficiency of resonant absorption. Simulations have been performed with and without the inclusion of optically thin radiative losses and thermal conduction in order to be able to separate the effects of the thermal structuring alone and the additional effects of the losses. For a full description of all the results, including the runs that include the radiative and conductive losses, see Beliën, Martens, & Keppens (1999).

2. Loop model

Our loop model consists of an axisymmetric straight cylindrical flux tube of radius a and length L. The end regions of the tube represent the chromosphere and the loop top is located at the mid plane. Note that although the length of the flux tube is fixed the coronal extent of the loop as situated in between the transition regions varies dynamically. The initial plasma state is in ideal magnetohydrostatic balance. We consider an initial magnetic field which is untwisted and aligned along the loop axis at the chromospheric end planes. The magnetic field is directed along the loop axis in most of the loop. A small radial magnetic field is present in the chromospheric regions (pressure scale height effect). The longitudinal and radial variations of the initial temperature, pressure, and density profiles are plotted in Fig. 1.

The initial state is being perturbed by a shear Alfvén wave perturbation at one of the chromospheric end planes, viz.,

$$v_\phi = \begin{cases} 0 & 0.0 \leq r/a < 0.3 \\ v_{\mathrm{d}}\,(10/3)^4\,(r/a-0.3)^2\,(r/a-0.9)^2\sin\left(2\pi t/P_{\mathrm{d}}\right) & 0.3 \leq r/a \leq 0.9 \\ 0 & 0.9 < r/a \leq 1.0 \end{cases} \qquad (1)$$

where a is the loop radius, v_{d} is the maximum amplitude at $r = 0.6a$ and P_{d} is the period of the excitation. We consider here a mono-periodic driver only.

The evolution of the coronal loop plasma is described by the magnetohydrodynamic (MHD) equations. We have solved the MHD equations using the Versatile Advection Code (Tóth 1996; Tóth & Odstrčil 1996). From the different numerical schemes available within VAC, the Total Variation Diminishing (TVD) scheme with approximate Riemann solver is used since it has the least numerical diffusion while still being very stable. We used a Lundquist number of $L = 8 \times 10^4$ and a 100×200 grid.

3. First Results

In Fig. 2 the evolution of some volume averaged quantities are shown for a simulation with $v_{\mathrm{d}} = 23.5$ km/s and $P_{\mathrm{driver}} = 41.1$ s. This particular driver period corresponds to a local Alfvén period at $r \approx 0.7a$. Note that some curves present averages over only part of the loop structure, most often coronal regions.

It is evident from the bottom right panel of Fig. 2 that large coronal density oscillations are present on top of a trend. The trend scales linearly with the driver amplitude while the variations scale quadratically. The quadratic scaling indicates that the oscillations are the result of nonlinearly generated magnetoacoustic waves and the motions of the transition region. Two dominant periods are present, ≈ 280 s and ≈ 140 s. These periods correspond to the principal and first overtone of the slow magnetosonic wave in the coronal cavity. The mass flows in and out of the corona and the upward motion of the transition region (not shown here) means that work has to be done by the chromospheric and transition region plasma.

A typical behavior for resonant absorption in line-tied loop systems is the continued growth of the kinetic and magnetic energy in the first ten to twenty

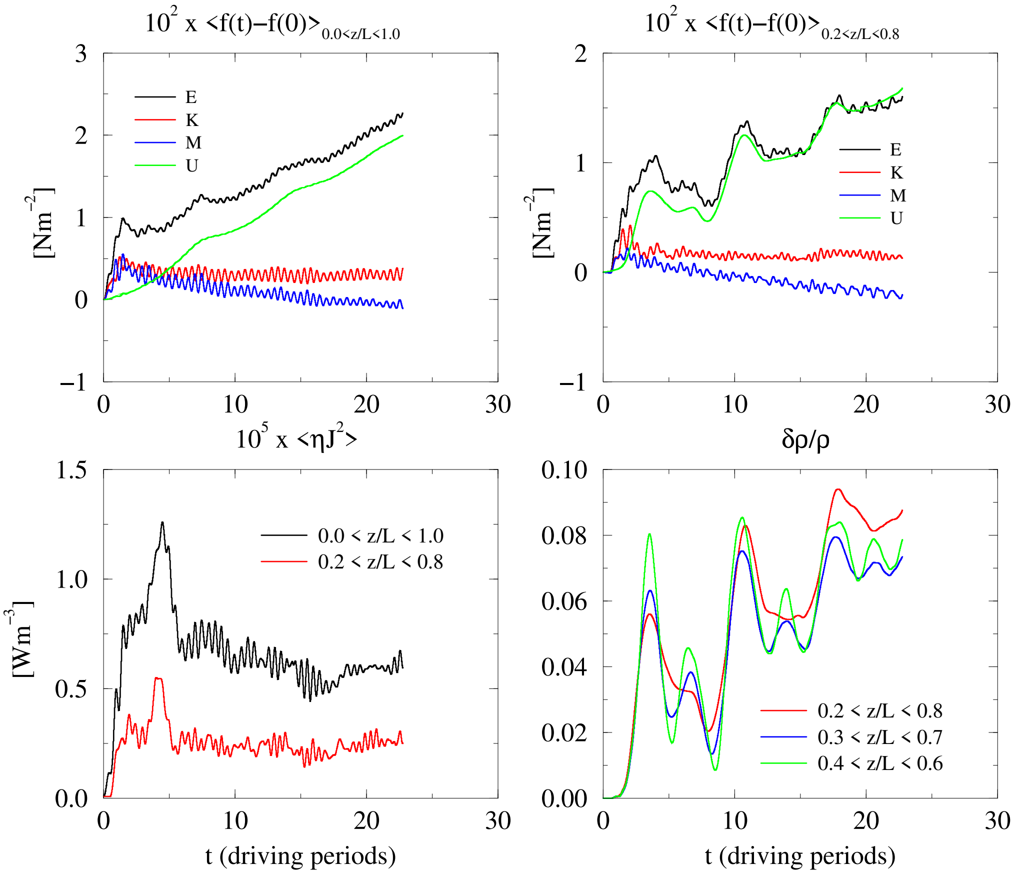

Figure 2. The evolution of volume averaged quantities for $v_{\rm d}$ = 23.5 km/s and $P_{\rm driver}$ = 41.1 s. *Upper-left panel*: Variation w.r.t. the initial state of the kinetic energy K, the magnetic energy M, the internal energy U, and the total energy (not including gravitational energy) $E = K + M + U$ averaged over the whole loop structure. *Upper-right panel*: Same as the top left plot but averaged over the corona only. *Lower-left panel*: Ohmic dissipation rates. *Lower-right panel*: Relative density variations averaged over different parts of the corona.

driving periods (e.g., Poedts & Boynton 1996). The kinetic and magnetic energy in the resonant layer grows until the gradients in the layer are large enough that dissipation will become important and all the energy input is dissipated. However, from Fig. 2, it is clear that the kinetic and magnetic energy reach their maximum already after two driving periods after which they more or less remain constant. Also, the internal energy keeps increasing because the coronal plasma is being compressed. As soon as the compression sets in almost the entire Poynting flux into the loop (the difference between the Poynting flux entering through the chromospheric end plane at which the excitation takes places and the flux leaving at the other end plane) is being used to *compress* the coronal plasma. No more energy is being pumped into the resonant layer. Hence, the

Ohmic dissipation rate levels off quickly and saturates at a low value as can be seen in the lower left panel of Fig. 2.

4. Conclusions

The results of our resonant absorption simulations using coronal loop models that include the chromosphere and transition region indicate that the efficiency of resonant absorption might be much less than was previously concluded from studies of resonant absorption in line-tied loops. The indirect heating of the solar corona by the nonlinear generation of compressional motions, especially slow magnetosonic waves that can be dissipated very efficiently by thermal conduction in the corona, will likely play a crucial role in coronal wave heating and needs much more attention. It is interesting to note that this was already suggested some twenty years ago (Wentzel 1978; Hollweg 1981, Hollweg, Jackson, & Galloway 1982). It has seen a revival only recently (see, for example, Nakariakov et al. this conference).

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