A&A 471, 311–314 (2007)
DOI: 10.1051/0004-6361:20066658

Astronomy & Astrophysics

Observational evidence favors a resistive wave heating mechanism for coronal loops over a viscous phenomenon

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Received 30 October 2006 / Accepted 2 June 2007

ABSTRACT

Context. How coronal loops are heated to their observed temperatures is the subject of a long standing debate.
Aims. Observational evidence exists that the heating in coronal loops mainly occurs near the loop footpoints. In this article, analytically and numerically obtained heating profiles produced by resonantly damped waves are compared to the observationally estimated profiles.
Methods. To do that, the predicted heating profiles are fitted with an exponential heating function, which was also used to fit the observations. The results of both fits, the estimated heating scale heights, are compared to determine the viability of resonant absorption as a heating mechanism for coronal loops.
Results. Two results are obtained. It is shown that any wave heating mechanism (i.e. not just resonant absorption) should be dominated by a resistive (and not a viscous) phenomenon in order to accomodate the constraint of footpoint heating. Additionally it is demonstrated that the analytically and numerically estimated heating scale heights for the resonant absorption damping mechanism fit the observations very well.

Key words. Sun: corona – Sun: oscillations

1. Introduction

Different mechanisms have been proposed to balance the heat loss rate of the solar corona. Most authors agree that the cause for the existence of the solar corona must be sought in the ubiquitous presence of the coronal magnetic field. Because of the photospheric convective motions, the coronal magnetic field is perturbed.

If the perturbation of the magnetic field is slower than the reorganisation time of a coronal loop, DC mechanisms will dominate the heating of the corona. These mechanisms assume that, because of the convective motions, the initially ordered magnetic field is twisted and braided (Parker 1972). The stressed magnetic field is then subject to magnetic reconnection. In this process the magnetic helicity is released through so-called nano-flares. These nano-flares could thus heat the corona.

On the other hand, if the photospheric perturbations of the magnetic field work on a shorter time scale (i.e. faster) than the reorganisation time, AC mechanisms are proposed. These mechanisms assume that the photospheric motions perturb the magnetic field lines and thus generate magnetohydrodynamic (MHD) waves in the solar corona. Then, as a result of phase mixing (Heyvaerts & Priest 1983) or resonant absorption, small length scales are created, and the MHD waves are dissipated on relatively short time scales (compared to the life-time of the coronal loops). An additional indirect source of wave energy comes from impulsive events (e.g. nano-flares), in which a substantial amount of energy is released through MHD waves. Moreover, these waves may be induced in the corona itself and do not need to propagate through the chromosphere and the transition region, where they are often refracted or steepen into shocks.

Since it is thoroughly studied and well understood, resonant absorption will be used as a wave damping mechanism in this paper. It was introduced by Ionson (1978); Hollweg (1984) and developed analytically by Sakurai et al. (1991); Goossens et al. (1995). Numerical efforts were done by Hollweg (1990); Poedts & Kerner (1991); Ofman et al. (1994). Recently, resonant absorption has taken a new interest, because of the observational evidence of heavily damped oscillations in coronal loops. Recent analytical results include Ruderman & Roberts (2002); Van Doorsselaere et al. (2004b); Andries et al. (2005) and numerical studies were done by Van Doorsselaere et al. (2004a); Arregui et al. (2005); Terradas et al. (2006).

Recently, the AC mechanisms have been criticised because the frequencies of the external driver (i.e. photospheric motions and coronal disturbances) almost never match the frequencies of the fundamental modes in the magnetic loops. This argument, however, does not hold. As in any finite system, the resonant modes can *easily be excited* and the actual kind of perturbation is irrelevant. As a matter of fact, Goedbloed (1995) argued that, analogously to a bow and a violin, a kind of "slip-stick" mechanism can be used to excite high frequency waves by means of low frequency drivers. Another example is the excitation of a string with a short pulse (i.e. a broad band driver). In this example it is almost impossible to avoid to excite the fundamental mode.

Another frequently used criticism regarding wave heating mechanisms for the solar corona is that the observed amount of oscillatory energy in the solar corona is insufficient to heat it.

⋆ Postdoctoral Fellow of the National Fund for Scientific Research-Flanders (Belgium) (FWO-Vlaanderen).

However, numerical studies of the resonant absorption heating mechanism in periodic cylindrical plasmas have shown that the obtained resonances have, in fact, a low "quality" (Poedts et al. 1994). This means that the amount of energy that is dissipated in one cycle (one wave period) is a substantial part of the total amount of energy that is pumped into the system to set up the resonance. The simulations of Poedts & Boynton (1996) also show that during the steady state that sets in after a relatively short time interval, the kinetic energy of the loops remains constant at a fairly low level while all extra energy pumped into the system is converted into heat. The conclusion of these simple numerical studies thus comes down to the fact that neither the efficiency of the heating mechanism, nor the energy dissipation rate is solely determined by the kinetic energy.

We thus propose the following as a heating mechanism for coronal loops. Given the turbulent nature of the corona, it is safe to assume that the observed coronal loops are under constant excitation by external shock waves. The coronal loops are oscillating preferentially with the fundamental mode, as this is the natural response to a broad band driver. Because the loop is under constant excitation, it oscillates in a small amplitude steady state, where all externally delivered energy is exactly dissipated in the resonant layer. As argued before, the excess external energy is unrelated to the actually observed oscillatory energy in the loop, but rather to the external source of incoming disturbances. It is thus possible for coronal loops to not exhibit waves (at the current observational resolution), and still dissipate the necessary energy to heat itself and its surroundings.

From an observational point of view, several guesses concerning the form of the heating function have been made. Priest et al. (1998, 2000) concluded that uniform heating was slightly more likely than heating at the loop top. This, however, was contradicted by Mackay et al. (2000) and Aschwanden et al. (2000). Moreover, Aschwanden et al. (2001) fitted the observed temperature profile in solar coronal loops with exponential heating functions and estimated the heating scale height for 41 coronal loops.

2. Results

The present results are obtained within the framework of the MHD equations, given by:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{V}), \tag{1a}$$

$$\rho \frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = -\nabla p + \rho \boldsymbol{g} + \frac{1}{\mu} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}, \tag{1b}$$

$$\frac{\mathrm{d}p}{\mathrm{d}t} = -\gamma p \nabla \cdot \boldsymbol{V} + (\gamma - 1)\eta \frac{|\nabla \times \boldsymbol{B}|^2}{\mu}, \tag{1c}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}, \tag{1d}$$

$$\nabla \cdot \boldsymbol{B} = 0. \tag{1e}$$

In these equations ρ denotes the plasma density, $\boldsymbol{V}$ the plasma velocity, p the gas pressure, $\boldsymbol{g}$ the gravity and $\boldsymbol{B}$ the magnetic field. The parameter μ denotes the magnetic permeability, γ is the ratio of specific heats and η is the magnetic diffusivity of the plasma, which is assumed to be constant over the entire space.

If the perturbations from the equilibrium are small, the MHD equations (Eqs. (1a)–(1e)) can be linearised. In this paper, we ignore flow ($\boldsymbol{V} = 0$) and gravitation ($\boldsymbol{g} = 0$). For such a static, gravitationless equilibrium, the linearised MHD equations may be given as:

$$\frac{\partial \rho'}{\partial t} = -\nabla \cdot (\rho \boldsymbol{V}'), \tag{2a}$$

$$\rho \frac{\partial \boldsymbol{V}'}{\partial t} = -\nabla p' + \frac{1}{\mu} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}' + \frac{1}{\mu} (\nabla \times \boldsymbol{B}') \times \boldsymbol{B}, \tag{2b}$$

$$\frac{\partial p'}{\partial t} = -\boldsymbol{V}' \cdot \nabla p - \gamma p \nabla \cdot \boldsymbol{V}', \tag{2c}$$

$$\frac{\partial \boldsymbol{B}'}{\partial t} = \nabla \times (\boldsymbol{V}' \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}'. \tag{2d}$$

Additionally, the solenoidal constraint (Eq. (1e)) also has to be fulfilled for $\boldsymbol{B}'$ as an initial condition. All primed quantities Q' denote perturbations of the equilibrium quantity Q: $Q'(\boldsymbol{r}, t) = Q(\boldsymbol{r}, t) - Q(\boldsymbol{r})$.

Our main interest in this paper will go out to the Ohmic dissipation rate $\eta J'^2 = \eta \left(\frac{1}{\mu} \nabla \times \boldsymbol{B}'\right)^2$, which quantifies the energy of the perturbation dissipated by the resistivity (see Poedts et al. 1992, for example).

As a model for a coronal loop, we take a pressureless ($p = 0$) cylinder (r, φ, z-coordinates) aligned with the constant background magnetic field ($\boldsymbol{B} = B\boldsymbol{e}_z$).

2.1. A 1D model

As a basic model for a coronal loop, we consider a dense plasma cylinder embedded in homogeneous medium. We assume that the whole medium is a cold plasma ($\beta = 0$), which is penetrated by a constant magnetic field along the z-direction. The dense core of the loop is connected with the homogeneous surrounding medium by a layer where the density varies continuously from its value in the loop to the coronal value. In this equilibrium, a resonance occurs for an oscillation with a frequency between the Alfvén frequencies inside and outside the loop, such as a kink oscillation (for more information, see Van Doorsselaere et al. 2004a).

In the z-direction, we take line-tying boundary conditions to mimic a rigid photosphere: $\boldsymbol{V}'$ has to be zero at $z = 0$ and $z = L$ in a cylinder of length L. For such line-tied oscillation, the velocity profile of the fundamental mode has a z-dependency $\sim \sin \pi z/L$. As can be derived from Eq. (2d), the azimuthal component of the magnetic field B'_φ is dominated by the z-derivative of the velocity, and thus has a z-dependency $\sim \cos \pi z/L$.

For quasi-mode oscillations, the term $\eta J'^2$ is mainly dominated by the contribution of J'_z, which in turn is largely dominated by the contribution of $\partial B'_\varphi / \partial r$. The value for this derivative will become extremely large in the layer where the local Alfvén frequency matches the global quasi-mode frequency. The current will obtain the largest values where the radial variation of B'_φ is the largest. Since the azimuthal component of the magnetic field has a cosine dependency in the z-direction, the largest variation of B'_φ and thus the largest values for J'_z will be found at $z = 0$ and $z = L$. Such a behaviour was already shown by Poedts & Boynton (1996) in simulations of footpoint driven coronal loop models.

We can conclude that the term $\eta J'^2$ has a z-dependency $\sim \cos^2 \pi z/L$. This means that the bulk of the oscillation energy will be deposited near the loop footpoints, rather than at the loop top.

Were the damping mechanism dominated by a viscous mechanism, the energy deposition could be calculated as $\nu (\nabla \times \boldsymbol{V}')^2$, with ν the viscosity. This viscous heating would be dominated by the contribution of $\partial V'_\varphi / \partial r$. Given the fact that, for line-tied oscillations, the velocity follows a $\sim\sin \pi z/L$, the viscous heating profile would be dominated by a $\sim\sin^2 \pi z/L$ and would thus mainly heat near the loop top.

This result is independent of the assumed wave heating mechanism. It is solely based on line-tied oscillations. Thus, for any line-tied wave heating mechanism, *viscous and resistive damping mechanisms can be observationally distinguished by determining the location of the heating*. Viscous heating delivers energy near the loop top, resistive heating deposits energy near the loop footpoints.

The fact that the energy is deposited at the loop footpoints by a dissipative phenomenon agrees with the conclusion of the observational study by Aschwanden et al. (2000) that coronal loops are heated at the footpoints. In their sequel paper (Aschwanden et al. 2001), it is assumed that the heating of the loops is done by an exponential heating function, with a dependency $\sim\exp(-z/s_{\rm H})$, where $s_{\rm H}$ is the heating scale height.

When trying to fit the $\cos^2(\pi z/L)$ heating profile with an exponential heating function, we obtain a heating scale height $s_{\rm H}/L = 0.236$ which is constant for all loops. This estimate is only compatible with the observationally estimated heating scale heights ((Col. 3)/(2 Col. 2) in Table 1 of Aschwanden et al. 2001), for the 4 shortest loops.

2.2. 2D coronal loop model

From the previous section, it is clear that a 1D wave heating model holds for short loops. For long loops, however, the heating scale height estimated by the model seems to be incompatible with the observed values. In contrast to the short loops, the density stratification in the corona will play an important role in longer loops. Incorporating the density stratification along the loop will modify the longitudinal form of the eigenfunction.

In this section, we modify the equilibrium employed above to include the gravitational density stratification by varying the density along the z-direction. In our model, an exponential, vertically stratified atmosphere with scale height H is assumed. The vertical, exponential density profile is then projected onto the cylindrical coronal loop model. As a result, a density function symmetric with respect to $z = L/2$ is obtained.

While this model accounts for the density variation in the corona itself, it does not incorporate the influence of the chromosphere. It may thus be expected that the model disagrees with the observational estimates near the loop footpoints.

According to Andries et al. (2005), when only a small longitudinal density stratification is taken into account, the fundamental mode is coupled to the higher harmonics. In this case, the dominant extra contribution will come from the next (longitudinally) symmetric (with respect to $z = L/2$) eigenfunction. Thus, the longitudinal eigenfunction for V'_φ is modified to $\sim\sin(\pi z/L)+a\sin(3\pi z/L)$, where a is a small quantity. Similar to the previous subsection, it can be found that the z-dependency of B'_φ is $\sim\cos(\pi z/L) + 3a\cos(3\pi z/L)$. This shows that $\eta J'^2$ roughly follows $\sim\cos^2(\pi z/L) + 6a\cos(\pi z/L)\cos(3\pi z/L)$ (if a is sufficiently small). It is clear that such a modification of the longitudinal eigenfunction with a reasonably small parameter a (say $a = 0.1$) can lead to a heating function which is significantly more concentrated near the loop footpoints.

In order to compare our results with actual observations, we used the results from Aschwanden et al. (2001). Aschwanden et al. fitted the emission measure of a coronal loop by a 1D hydrostatic coronal loop model, in which an exponential heating profile is assumed. As a result of their study, a heating scale height was estimated in 41 loops.

Because a simple model was used in their study, the observational estimates of Aschwanden et al. for the heating scale height may not represent the actual heating function occuring in the corona. To properly compare our results with the observations, forward modeling of the expected line emission should be performed, such as done by Peter et al. (2006). However, to do so, a full 3D computational model of oscillating loops should first be constructed.

Following the approach of Aschwanden et al., we calculate the full (numerically obtained) heating profile in the longitudinal direction in our model for various values of the density stratification strengths $L/\pi H$. These heating profiles are then fitted with an exponential heating function, as in Aschwanden et al. (2001).

However, it is clear from the previous subsection that the heating profiles we obtain are essentially a cosine squared. Thus, the heating profile flattens out near the loop footpoints. Comparison with the results of Aschwanden requires a fit with an exponential which is clearly inappropriate near the footpoints. It is thus more appropriate to perform the fit only on the sloping part of the heating profile.

Moreover, as mentioned before, our model does not include the chromosphere. It may be that the chromospheric part of the coronal loop follows substantially different physics than the coronal part. Additional heat sources, such as steepening of acoustic waves, may be present and heat this part of the loop significantly. Also, we did not include the strong temperature gradients in the transition region in our model, which would allow for additional dissipation mechanisms in more realistic models.

Also, loop footpoints are usually not well resolved in the observations and it is often difficult to measure the loop length. Furthermore, it is likely that coronal loops are anchored deeper into the photosphere than can be observed with the TRACE satellite, and thus form an effective waveguide which extends further into the photosphere than can be estimated from the observations. In this respect, Mackay et al. (2000) concluded that the observed length of the loops is actually not enough to sustain the drop of the temperature from coronal to chromospheric values. These authors fitted the observed temperature profiles of coronal loops observed with YOHKOH and found that the loops needed to be 10% longer than actually observed.

By assuming a fixed density scale height $H = 50$ Mm throughout the entire corona, our heating profiles can be compared with the values of Aschwanden et al. (2001). Two fits were made: fitting the full heating profile, and following the result of Mackay et al. (2000), a fit in the body of the loop, by discarding 10% of the loop footpoints. The results of both fits are shown in Fig. 1.

It is clear that the trend of the observations (indicated with $\times$) is more or less explained by the full fit (indicated with $-+-$). The curve of the estimated values, however, seems to be shifted with respect to the observationally determined values. This shift is in the direction of higher heating scale heights, because the fit is strongly influenced by the flattening of the predicted heating profile near the footpoints.

As argued before, several arguments exist to only fit the predicted heating profile in the sloping part. When the 10% footpoints are left out of the fitting region, a much better fit is obtained in the body of the loop (Fig. 2).

Using the restricted fitting interval, i.e. fitting between $z = 0.1L$ and $z = 0.5L$, different values are obtained for the heating scale height. These values are indicated with $\cdots * \cdots$ in Fig. 1.

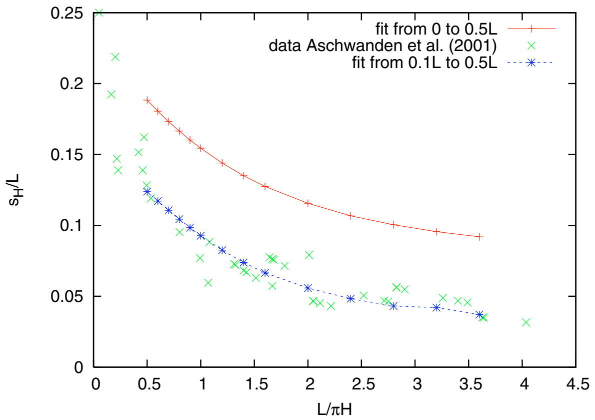

Fig. 1. A comparison between the observationally and numerically estimated heating scale heights. The × represent the observations, while the numerically estimated heating scale heights are indicated with $-+-$. The $\cdots * \cdots$ are the heating scale heights, estimated when only taking into account the heating function from $0.1L$ to $0.5L$.

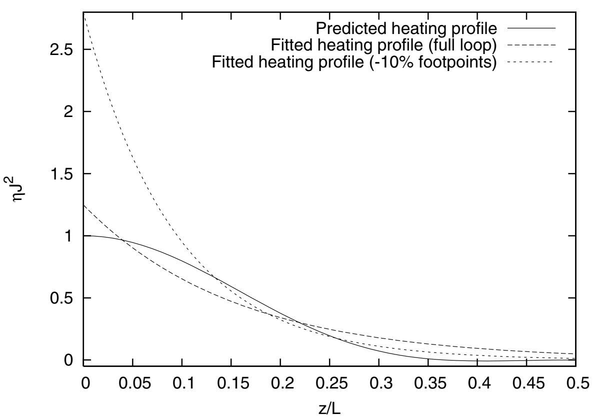

Fig. 2. The predicted heating profile for $L/\pi H = 1$ (full line) is overplotted with the fit including the footpoints (long dashes) and discarding the footpoints (dotted line).

A good agreement between the observed and numerically estimated heating scale heights is obtained.

In this article, only the heating by the fundamental oscillation mode is taken into account. For overtones, the heating is expected to be more distributed along the loop. However, for all line-tied oscillations and a resistive damping mechanism, a maximum of the heating function occurs near the loop footpoints, so that all modes contribute to the footpoint heating. The loop top, however, is only heated by half of the oscillations, and the rest by a smaller fraction. The current concentration of heating near the footpoints is thus somewhat decreased when multiple longitudinal modes are excited, but the main idea still holds.

3. Conclusions

Our paper contains crucial new information contradicting a long lasting fundamental misconception about wave heating and providing a means for observational verification. We have pointed out that the location of loop heating strongly depends on the dissipative mechanism that is active, in contrast to earlier claims.

In this paper, two main results were obtained.

Firstly, we have shown in a cartoon model that the location of heating of line-tied oscillations in loops strongly depends on the viscous or resistive character of the wave damping mechanism. Viscous mechanisms mainly heat the loop near the loop top, whereas resistive mechanisms deposit energy preferentially near the loop footpoints. This difference is present for all line-tied oscillations, regardless of the assumed mechanism to create small length scales. It thus provides *an observational test to determine the nature of the dissipative mechanism*.

Secondly, we calculated the analytically and numerically predicted heating profiles and compared them with the observations. To do that, the predicted profiles were fitted with an exponential heating function, yielding a heating scale height. These heating scale heights could then be directly compared with the results of Aschwanden et al. (2001). When 10% of the loop footpoints were left out of the fit, *a remarkable agreement is found between the predicted and observed heating scale heights*.

In this article, we have determined a general form for the heating profile in coronal loops, if they are heated by a wave heating mechanism. To confirm our results, the observations should be fitted with the predicted profile, rather than an exponential function. Two fitting parameters then need to be determined: the amplitude of the heating profile (i.e. the total heat input) and the longitudinal eigenfunction (i.e. the parameter a). When these parameters are measured, together with the density scale height, a quantitative comparison between the models and the observations can be done.

Even stronger, when the observed heating profile is estimated, and a value for a is obtained, this can be used as a seismological tool to find the density scale height in the neighbourhood of the loop, if it is assumed that the heating is caused by the fundamental mode only, which would require independent observational confirmation.

Acknowledgements. T.V.D. acknowledges the financial support of the Onderzoeksfonds, K.U. Leuven and PPARC. T.V.D. would like to thank E. Verwichte and V. M. Nakariakov for their comments on the early manuscript.

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