DAMPING OF KINK OSCILLATIONS BY COOLING OF CORONAL LOOP PLASMA

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ABSTRACT

We present here a comparative study between the observed damping of fast kink oscillations and the theoretical model of damping due to the cooling of the coronal loops. A recent time dependent model of a cooling coronal loop predicts that transverse oscillations of the loop could be significantly damped due to the cooling process. The theory is applied to examples of TRACE observations of damped kink oscillations. We find that, for cooling timescales that are typical of EUV loops (500 − 2000 s), the observed damping of the kink oscillations can be accounted for almost entirely by the cooling process in half of the examples. In the other examples the cooling process could still have significant influence on the damping, however, another mechanism(s) of damping, e.g. resonant absorption, may be additionally required to account for the remaining decay of oscillations.

Subject headings: magnetohydrodynamics (MHD) - plasmas - Sun: corona - Sun: photosphere - waves

1. INTRODUCTION

The first spatially resolved oscillations in coronal loops where reported with the Transition Region And Coronal Explorer (TRACE) satellite (Aschwanden et al., 1999; Nakariakov et al., 1999). Due to the transverse nature of these oscillations, they where identified as the fast kink mode. Since then, there have been a relatively large number of observations of kink oscillations making them a useful tool for diagnostics of the coronal plasma (see e.g. Andries et al., 2009 and Ruderman and Erdélyi, 2009 for the most recent reviews on kink waves). One outstanding problem associated with the kink oscillations is they are observed to be heavily damped, usually within 4 − 5 periods. The method of the damping is, to date, still unknown, although resonant absorption is thought to be a strong candidate (Ruderman and Roberts, 2002; Goossens et al., 2002).

In general, models of coronal loops that support MHD oscillations have been assumed to be static with respect to the background plasma quantities. However, the solar corona is known to be of a highly dynamic nature. One such dynamic feature which is ubiquitous in the corona and has been observed on numerous occasions is the cooling of hot coronal loops (López Fuentes et al., 2007; Aschwanden and Terradas, 2008). A large number of loops appear to have been heated to soft X-ray temperatures, $T > 2$ MK, before cooling down through to the EUV temperature range, $T \approx 1 − 2$ MK (Nagata et al., 2003; Winebarger and Warren, 2005). Cooling timescales for EUV loops have been estimated in Aschwanden and Terradas (2008) to be around 500 − 2000 s. These cooling timescales are mostly larger though sometimes comparable to the characteristic timescale of the transverse oscillations, e.g. for fast kink modes the oscillations have typical periods of 300 s and last for four to five periods, so the cooling of the loops is expected to influence the oscillations and the use of static background in the theoretical modelling of coronal loops is not justified (Aschwanden and Terradas, 2008).

A theoretical model of cooling coronal loops suggested by Morton and Erdélyi (2009) shows that as a coronal loop cools, transverse MHD oscillations of the loops are considerably damped by the cooling of the plasma. Here we put the theory developed by Morton and Erdélyi (2009) to the test by taking numerous known examples of damped kink oscillations observed with the Transition Region And Coronal Explorer (TRACE) and compare the observed rate of damping with the theoretically predicted damping due the cooling of the loop.

2. MODEL OF COOLING LOOP

Using a cylindrical coordinate system, a coronal loop is modelled as a magnetic flux tube of length $2L$ centered at $z = 0$, with a straight, constant magnetic field both inside and outside of the tube. The temperature of the loop is assumed to evolve over time with an exponential profile, i.e.

$$ T(t) = T_0 \exp \left( \frac{t}{\tau_{\text{cool}}} \right) , \quad (1) $$

where $T_0$ is the initial temperature of the loop plasma and $\tau_{\text{cool}}$ is the characteristic cooling time of the loop. The temperature profile along the loop is assumed to be isothermal. These assumptions serve as a good approximation of the observed cooling of loops (Aschwanden and Terradas, 2008; Ugarte-Urra et al., 2009). A microphysical process of cooling (i.e. conduction or radiation) is ignored and the effect of cooling on the density profile of the loop is concentrated on.

To achieve this, the relationship between scale height and temperature is exploited, namely

$$ H(t) = 47 T(t) \left[ \frac{\text{Mm}}{\text{MK}} \right] , \quad (2) $$

providing a time dependent scale height where $T(t)$ is measured in MK. A density profile that is dependent upon scale height is then chosen,

$$ \rho(z, t) = \rho_f \exp \left( \frac{h_0}{H(t)} \cos \left( \frac{\pi z}{2L} \right) \right) , \quad (3) $$

$$ T_0 = 2 \text{ MK} \quad \text{and} \quad \tau_{\text{cool}} = 2000 \text{ s} \quad \text{in the test case.}$$

$$ H(z, t) = H_0 \exp \left( \frac{h_0}{H(t)} \cos \left( \frac{\pi z}{2L} \right) \right) , \quad (4) $$

$$ h_0 = 500 \text{ Mm} \quad \text{in the test case.}$$

$$ H(z, t) = H_0 \exp \left( \frac{h_0}{H(t)} \cos \left( \frac{\pi z}{2L} \right) \right) , \quad (5) $$

$$ h_0 = 500 \text{ Mm} \quad \text{in the test case.}$$
**Fig. 1.**— Damped periodic oscillations identified as the kink mode by Aschwanden et al. (2002). The crosses are the observed data points, solid black line is the fitted sine function given by Eq. (7). The broken lines are the damping profiles due to cooling. In the text the individual plots are referred to as such, from left to right, top to bottom, a, b, c, d, e and f, respectively.

**TABLE 1**

<table>
<thead>
<tr>
<th>Panel</th>
<th>Date</th>
<th>Start time</th>
<th>Duration</th>
<th>Flare Class</th>
<th>$h_a$</th>
<th>Best fit $\tau_{cool}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig.1a</td>
<td>14 July 1998 (1a)</td>
<td>12:59:57</td>
<td>2622 s</td>
<td>M 4.6</td>
<td>56 Mm</td>
<td>700 s</td>
</tr>
<tr>
<td>Fig.1b</td>
<td>14 July 1998 (1f)</td>
<td>12:56:32</td>
<td>1563 s</td>
<td>M 4.6</td>
<td>49 Mm</td>
<td>500 s</td>
</tr>
<tr>
<td>Fig.1c</td>
<td>23 Nov 1998</td>
<td>06:35:57</td>
<td>3179 s</td>
<td>X 2.2</td>
<td>134 Mm</td>
<td>1200 s</td>
</tr>
<tr>
<td>Fig.1d</td>
<td>14 July 1998 (1d)</td>
<td>12:57:38</td>
<td>898 s</td>
<td>M 4.6</td>
<td>46 Mm</td>
<td>700 s</td>
</tr>
<tr>
<td>Fig.1e</td>
<td>14 July 1998 (1g)</td>
<td>13:02:26</td>
<td>1591 s</td>
<td>M 4.6</td>
<td>38 Mm</td>
<td>500 s</td>
</tr>
<tr>
<td>Fig.1f</td>
<td>21 March 2001</td>
<td>02:32:44</td>
<td>2456 s</td>
<td>M 1.8</td>
<td>135 Mm</td>
<td>1000 s</td>
</tr>
<tr>
<td>Fig.2</td>
<td>14 July 1998</td>
<td>12:55</td>
<td>1500 s</td>
<td>M 4.6</td>
<td>41 Mm</td>
<td>500 s</td>
</tr>
</tbody>
</table>
where \( \rho_f \) is the density at the loop footpoints and \( h_a \) is the height of the loop apex measured from the photosphere. A density profile of this nature, describes a longitudinally stratified semi-circular loop embedded in a gravitationally stratified atmosphere. Upon substitution into the equation of motion for MHD plasmas, the time dependent density profile requires that the loop has a background flow in the \( z \) direction. The background profile of the loop describes the loop being slowly evacuated as it cools and the plasma flows out of the loop at the footpoints.

From the ideal MHD equations a governing equation can be obtained (see Morton and Erdélyi, 2009 for details) which is solved in the zeroth order using the WKB method. This involves a substitution for the radial velocity component in cylindrical geometry, i.e. \( v_r \), where

\[
v_r = \Re \left\{ Q(z, t) \exp \left( i \delta^{-1} \int \omega dt \right) \right\}.
\] (4)

Here \( \delta = P/\tau_{cool} \) where \( P \) is the characteristic period of the oscillation, \( Q(z, t) \) is the amplitude, \( \omega \) is the frequency of the oscillations and \( \Re \) refers to the real part of \( v_r \). The zeroth order approximation obtained is governed by

\[
\frac{\partial^2 Q(z, t)}{\partial z^2} + \frac{\omega^2}{c^2_k(z, t)} Q(z, t) = 0,
\] (5)

where

\[
c^2_k(z, t) = \frac{2B^2}{\mu_0(\rho_l(z, t) + \rho_c(z, t))},
\]

is the kink speed. Eq. (5) is a time dependent Sturm-Liouville equation, a generalisation of that derived by Dymova and Ruderman (2005) for a static, longitudinally stratified prominence. The validity of the approximate solution to Eq. (5), is subject to the condition that the cooling timescale is (much) greater than the characteristic period, \( P \), of the oscillation, i.e. \( P/\tau_{cool} \ll 1 \).

There are a number of interesting effects on the transverse oscillations as the loop cools. Solutions to Eq. (5) show that as the loop cools, transverse oscillations of the loop are damped due to the cooling process. The rate of damping was also found to depend on the initial temperature of the loop as the oscillation started, the height of the loop apex in the atmosphere and the cooling timescale, \( \tau_{cool} \). Another effect that should be emphasised is the change in period of the modes. An analytic expression can be found for the period change if a solution to Eq. (5) is sought using the variational approach suggested by, e.g McEwan et al. (2006). Assuming that \( h_a/H \ll 1 \), then it is obtained for the fundamental mode

\[
P_1 \approx \frac{1}{c_k} \frac{4L}{\pi^{3/2}} \left[ \frac{\pi}{4} - \frac{2h_a}{141T(0)} \left( \frac{\text{MK}}{\text{Mm}} \left( 1 + \frac{t}{P} \right) \right)^{1/2} \right]^{1/2},
\] (6)

where \( c_{k,f} \) is the kink speed at the loop foot points. It can clearly be seen that the period decreases as time increases, i.e. the loop cools.

3. COMPARISON TO OBSERVED OSCILLATIONS

In Figs. 1 and 2, we have selected observations that have been identified as damped fast kink oscillations, where as the loop cooled, it continued to show damped periodic oscillations identified as the kink mode by Nakariakov et al. (1999). The crosses are the observed data points, solid black line is the fitted sine function given by Eq. (7). The broken lines are the damping profiles due to cooling, each of them observed by the TRACE satellite (Aschwanden et al., 2002; Nakariakov et al., 1999). Information on the oscillations is given in Table. 1. The data points from the observations have been fitted with a damped sine function of the form

\[
f(t) = A_0 \sin(\omega t - \phi) \exp \left( -\frac{t}{\tau_d} \right),
\] (7)

where \( \phi \) is the phase shift, \( A_0 \) is the amplitude at \( t = 0 \) and \( \tau_d \) is the damping time. The individual values for each observation are given underneath the plot of each oscillation.

The coronal loops all appeared in the TRACE EUV filters, either in the 171 Å or the 195 Å filter. The filters have a broad temperature response where the 171 Å filter has a peak response at \( T \approx 0.96 \) MK and the 195 Å at \( T \approx 1.37 \) MK (Aschwanden et al., 2000). This suggests that the loop enters the 195 Å filter at a temperature of around 1.5 MK, so we set the initial temperature of the loop as the oscillation begins to 1.5 MK and select a number of cooling timescales that are representative of EUV loops, i.e. 500 – 2000 s. The height of the loop apex is also required and is given in Table. 1. The damping profile is obtained by calculating the value of \( v_r \) at the loop apex, i.e. the maximum value for the fundamental mode, and normalising with respect to the initial value of \( v_r \), i.e. the value at \( t = 0 \).

4. DISCUSSION AND CONCLUSIONS

It can be seen in Figs. 1 and 2 that in most cases the damping due to cooling is more than able to account for a significant amount of the observed damping. In Figs. 1a, c, e and f it can be seen that the profile of the damping due to cooling coincides very closely with that of the fitted damping. In Figs. 1a and e, the best fit cooling damping profile even encompasses some of the data points that are outside the envelope of the analytically
fitted damping profile. Although without error bars for the data points, we cannot rule out these outlying data points could fall within the fitted damping envelope. In Figs. 1c, d and Fig. 2, there is a slightly greater difference between the best fit damping profile due to cooling and the analytically fitted damping profile. For each of these oscillations, the timescale of the period, $P$, is close to that of the fitted damping time, $\tau_d$, i.e. the damping is rapid compared to the period of the oscillation. The reason that we have a small disagreement between these cooling and best fit damping profiles could be that the characteristic cooling is less than 500 s. The restriction placed upon the allowed values of the ratio $P/\tau_{cool}$ by the WKB method, means that damping profiles calculated for smaller values of $\tau_{cool}$ could have a pronounced error and we do not calculate the profiles for less than 500 s here. An alternative explanation for the minor discrepancy between the calculated damping profiles and the observed profiles could be that another method, e.g. resonant absorption, has important influence on the damping of those particular observations than the cooling. Even so, it is clear that the cooling could still provide a significant contribution to the damping for these examples.

As mentioned in the previous section, while the loop cools the period of the loop should also change. In the observations of the damped kink oscillations analysed by Nakariakov et al. (1999) and Aschwanden et al. (2002), the fitted sine function has a constant period and appears to agree well with the observations. The cadence for the TRACE EUV imager, however, is around 75 s, which will place a lower limit on the periodicity that analysis will be able to determine from the observations. In Fig. 3 we plot the expected change in period if the loop is cooling with a typical rate, say, $\tau_{cool} = 1000$ s and starts oscillating with the observed initial period 423 s. It can be seen that the revised time-dependent profile fits the observations equally as well if not better than the previous fit with constant period. There is, however, around a 70% change in the period, where the period at the end of the oscillation is around 100 – 120 s. An improved cadence data is required to make further progress.

We conclude that the damping due to cooling could have significant influence on the observed decay of transverse oscillations in coronal loops. The damping due to cooling (i.e. variable background) seems to be a very plausible physical mechanism in many of the loops. In certain observed cases, the cooling can account almost entirely for the observed damping. However, it appears another mechanism(s) of damping may still be required so that the observed damping can be explained in all cases. We also suggest that an observational signature of damping due to cooling would be the decreasing period of the oscillation. Whether we will be able to detect the change in period with current cadences onboard satellites will remain to be seen.

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