OBSERVATIONAL EVIDENCE OF RESONANTLY DAMPED PROPAGATING KINK WAVES IN THE SOLAR CORONA

G. Verth\(^1\), J. Terradas\(^2\), and M. Goossens\(^1\)

\(^1\) Centrum voor Plasma Astrofysica en Leuven Mathematical Modeling and Computational Science Centre, KU Leuven, Celestijnenlaan 200B, 3001 Heverlee, Belgium; gary.verth@wis.kuleuven.be, marcel.goossens@wis.kuleuven.be

\(^2\) Departament de Física, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain; jaume.terradas@uib.es

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ABSTRACT

In this Letter, we establish clear evidence for the resonant absorption damping mechanism by analyzing observational data from the novel Coronal Multi-Channel Polarimeter. This instrument has established that in the solar corona there are ubiquitous propagating low-amplitude (≈1 km s\(^{-1}\)) Alfvénic waves with a wide range of frequencies. Realistically interpreting these waves as the kink mode from magnetohydrodynamic wave theory, they should exhibit a frequency-dependent damping length due to resonant absorption, governed by the Terradas–Goossens–Verth relation showing that transverse plasma inhomogeneity in coronal magnetic flux tubes causes them to act as natural low-pass filters. It is found that the observed frequency dependence on damping length (up to about 8 mHz) can be explained by the kink wave interpretation; and furthermore, the spatially averaged equilibrium parameter describing the length scale of transverse plasma density inhomogeneity over a system of coronal loops is consistent with the range of values estimated from Transition Region and Coronal Explorer observations of standing kink modes.

Key words: magnetic fields – magnetohydrodynamics (MHD) – plasmas – Sun: corona – Sun: oscillations

1. INTRODUCTION

Recently, there has been much interest generated by the observation of ubiquitous propagating Alfvénic waves in the solar corona detected by Tomczyk et al. (2007) using the innovative Coronal Multi-Channel Polarimeter (CoMP) instrument. The Alfvénic properties of these waves are undeniable since they have a phase speed of about 1 Mm s\(^{-1}\), the velocity components are perpendicular to the direction of magnetic field lines, and they exhibit only very weak intensity fluctuations, suggesting an almost incompressible wave mode. Detected in Doppler velocity, they have a low amplitude of approximately 1 km s\(^{-1}\) peak to peak, corresponding to a loop displacement amplitude of only 48 km and peak power at a period of about 5 minutes. The small spatial extent of the displacement explains why these waves could not accurately describe the oscillatory properties of coronal loops, which are finite closed magnetic flux tubes with inhomogeneous plasma structure. Coronal observations show that the EUV intensity of oscillating loops is greater than the surrounding medium, indicating that the internal plasma density is greater inside the loop than in the ambient plasma. Essentially, the simple homogeneous plasma model by Alfvén would not permit us to attempt magnetoseismology of the solar atmosphere to determine its fine structure (see, e.g., Banerjee et al. 2007 for review) and would not allow us to estimate the contribution of wave heating to the coronal plasma, since the most likely mechanisms proposed thus far require plasma inhomogeneity in the direction transverse to the direction of the magnetic field, e.g., phase mixing and resonant absorption (see, e.g., Aschwanden 2004 for review of various proposed damping mechanisms). Due to the observed plasma inhomogeneity of coronal loops, theorists concluded that the transverse oscillations detected with TRACE were best described as standing kink waves from MHD theory. This mode is a bulk transverse oscillation of magnetic flux tubes that have different internal and external Alfvén speed equilibria, primarily due to density variation in the direction transverse to the direction of the magnetic field (e.g., Edwin & Roberts 1983). Since spectroscopic EUV line ratios can be implemented to determine coronal density using the CHIANTI database (e.g., Landi et al. 2006), Erdélyi & Taroyan (2008) and Van Doorsselaere et al. (2008) exploited the spectral capabilities of EIS to determine that the coronal loops in which they detected low-amplitude Alfvénic waves had greater internal plasma density than external, naturally leading them to the kink mode interpretation, in agreement with the previous consensus regarding transverse waves in coronal loops observed by TRACE.

Notably, the observed coronal loop standing kink waves observed with TRACE are heavily attenuated in 1–4 fundamental periods (see, e.g., Aschwanden et al. 2003), and the most likely physical mechanism for this proposed thus far is resonant absorption caused by naturally occurring gradients in the transverse Alfvén speed of coronal loops (see, e.g., Goossens 2008 for review). Although resonant absorption is still a robust

2. KINK WAVES IN CORONAL LOOPS

When the first EUV post-flare transverse coronal loop oscillations were directly imaged by TRACE (Aschwanden et al. 1999; Nakariakov et al. 1999), it was clear that the simple model of Alfvén waves originally derived by Alfvén (1942) based on an infinite homogeneous plasma in planar geometry could not accurately describe the oscillatory properties of coronal loops...
damping mechanism in more complex geometries, e.g., multi-thread loop structures (Terradas et al. 2008), as an illustration of the basic process we assume a coronal loop to be a cylindrical magnetic flux tube. Then the kink phase speed in the long wavelength limit for an axially homogeneous magnetic cylinder with differing internal and external plasma density and constant magnetic field strength is

$$v_{\text{ph}} = B \sqrt{\frac{2}{\mu (\rho_i + \rho_e)}},$$  

(1)

where $\rho_i$ and $\rho_e$ are the internal and external plasma density, $B$ is the magnetic field strength, and $\mu$ is the magnetic permeability. Equation (1) shows that the kink speed is intermediate between the external and internal Alfvén speeds. Regarding kink waves in coronal loops, it is observed that $\rho_i > \rho_e$, so naturally occurring density gradients between the internal and external plasma will cause the local Alfvén frequencies in this intermediate layer to match the global kink frequency at some magnetic surface, thus causing a resonance. This generates azimuthal Alfvénic motions in the resonant surface which grow in amplitude, damping the global kink mode as energy is transferred to this localized mode. For kink waves excited by a broadband disturbance there will be many resonances within a loop and smaller length scales will be created due to phase mixing, causing a cascade of energy to smaller scales where dissipation becomes more efficient.

In the follow-up paper by Tomczyk & McIntosh (2009), a more detailed analysis of the same CoMP data set showed that propagating waves traveling a larger distance suffered greater damping. This inspired Pascoe et al. (2010) and Terradas et al. (2010) to model propagating kink waves damped by the process of resonant absorption. Most relevant to the present study, Terradas et al. (2010) derived simple analytical expressions for the damping length of kink waves, showing that damping length is a monotonically decreasing function of frequency, the Terradas–Goossens–Verth (TGV) relation. This has a consequence that solar waveguides with transverse inhomogeneity, e.g., coronal loops, will act as low-pass filters for propagating kink waves. It is the main purpose of this Letter to investigate how the propagating Alfvénic waves observed by Tomczyk et al. (2007), realistically interpreted as the kink mode from MHD wave theory, exhibit this frequency-dependent damping.

### 3. THEORETICAL MODEL

Traditionally, since standing kink waves in coronal loops were observed using TRACE, the measurement of damping times was of primary interest; see, e.g., Aschwanden et al. (2003) and Arregui et al. (2007). However, for propagating kink waves it is more appropriate to study the damping length $L_D$, with the expression for wave amplitude given by

$$A(s) = A_0 \exp \left( -\frac{s}{L_D} \right),$$  

(2)

where $s$ is the distance along the waveguide and $A_0$ is the initial amplitude. From Tomczyk et al. (2007), the transverse scale of propagating disturbances has an upper limit of about 9 Mm and wavelengths are $\lambda \gtrapprox 180$ Mm, so assuming that the average waveguide observed with CoMP is a flux tube of radius $R \lesssim 4.5$ Mm, kink waves are in the long wavelength regime where $R/\lambda \ll 1$. In this limit it was shown by Terradas et al. (2010) that the TGV relation is simply given by

$$L_D = \frac{v_{\text{ph}} \xi_E}{f},$$  

(3)

where $f$ is the frequency defined by $f = v_{\text{ph}}/\lambda$ and $\xi_E$ is an equilibrium parameter dependent on length scale of the density inhomogeneity. Equation (3) demonstrates that $L_D$ is inversely proportional to $f$, i.e., the rate of damping per unit length will be greater for higher frequency waves than low frequency waves. The parameter $\xi_E$ can be calculated precisely for a chosen equilibrium model; e.g., if we choose a thin inhomogeneous boundary layer with a continuous sinusoidal profile decreasing between $\rho_i$ and $\rho_e$ then

$$\xi_E = \frac{2R}{\pi l} \frac{\rho_i + \rho_e}{\rho_i - \rho_e},$$  

(4)

where $l$ is the thickness of the boundary layer (see, e.g., Goossens et al. 1992, 2002; Ruderman & Roberts 2002). Hence, Equations (3) and (4) demonstrate that the efficiency of damping due to resonant absorption also depends on the thickness of the non-uniform layer and the steepness of the transverse gradient in density.

From Figure 1 (panel (A)) in Tomczyk & McIntosh (2009), it can be seen that the integrated wave path in the coronal loop system is off limb and assumed to be in the plane of sky. The approximate semi-circular annular geometry of this wave path is shown in Figure 1, with the direction of outward and inward propagating waves denoted by arrows. We show the analyzed wave paths by the shaded gray region, which consists of many waves traveling along different coronal loop structures, integrated by Tomczyk & McIntosh (2009) to improve the signal-to-noise ratio (S/N); cf. Figure 4 (panels (B) and (C)) in Tomczyk & McIntosh (2009). Although Tomczyk & McIntosh (2009) did not integrate the entire loop lengths, i.e., from the outward footpoint ($s = 0$) to the inward footpoint ($s = 2L$), the important point is that in the gray region, inward waves have traveled further and therefore the damping will be greater relative to the outgoing waves.

Let the initial outward at $s = 0$ and inward power at $s = 2L$ for frequency $f$ be denoted by $P_{\text{out}}(f)$ and $P_{\text{in}}(f)$, respectively. Then since $P(f) \propto \xi_E^2(f)$, by Equations (2) and (3) the spatially averaged outward power in the shaded gray region $s \in [0, L]$ for frequency $f$ is

$$(P(f))_{\text{out}} = \frac{1}{L} \int_0^L P_{\text{out}}(f) \exp \left( -\frac{2f}{v_{\text{ph}}} s \right) ds,$$  

(5)
In this Letter, we established more evidence for the damping mechanism of resonant absorption by analyzing observational data from the CoMP. Crucially, this instrument has established that in the solar corona there are ubiquitous propagating low-amplitude ($\approx 1 \text{ km s}^{-1}$) Alfvénic waves with a wide range of frequencies. Realistically interpreting these propagating waves as kink modes, it was predicted that they should exhibit a frequency-dependent damping length due to resonant standing kink waves in individual coronal loops observed by TRACE where $\xi_{E} \approx 1-4$ (Aschwanden et al. 2003). It is interesting to note that the average half-length of loops estimated with TRACE data is about $L = 110$ Mm due to its restricted field of view. The longer value of $L = 250$ Mm observed with CoMP suggests that the rate of damping is independent of loop length; i.e., long loops have similar transverse length scale density inhomogeneities as short loops. This has also been independently confirmed recently by Verwichte et al. (2010) in the study of a long loop of $L = 345$ Mm using combined Solar and Heliospheric Observatory, TRACE, and Solar Terrestrial Relations Observatory observations, where they found $\xi_{E} = 1.48$ for a post-coronal mass ejection (CME) standing kink wave. Thus, the analysis of observational cases so far suggests that they are all within the valid regime of the thin tube approximation of resonantly damped kink waves.

Another interesting feature shown in Figure 2 is the estimated least squares value of $P_{\text{out}}/P_{\text{in}} \approx 1$, suggesting that power generated at both the outward and inward footpoints is approximately equal. The 95% confidence intervals for the simultaneous functional bounds, i.e., calculated with all predictor values, are also shown in Figure 2 by the dashed lines. It can be seen that there is a trend of decreasing confidence for $f \gtrapprox 3$ mHz, most likely due to the fact that the S/N for the CoMP data decreases with increasing frequency.

From the estimates of $L$, $v_{\text{ph}}$, and $\xi_{E}$, using Equations (2) and (3), we can calculate the percentage power loss as a function of frequency for the observed propagating kink waves after one travel time between the two loop footpoints, $s = 0$ and $s = 2L$ (see Figure 3). The kink waves with $f \gtrapprox 2.5$ mHz lose at least 50% of their power, and as explained previously in Section 2, this broadband frequency power is converted into Alfvénic azimuthal motions in many resonant surfaces.

5. CONCLUSIONS

In the next section, we shall do an exponential least squares fit using Equation (7) with CoMP data from the same observation by Tomczyk & McIntosh (2009) in the frequency range 0–4 mHz, where the S/N is strongest.

4. LEAST SQUARES FIT TO DATA

In Figure 2, it can be seen that the CoMP data (see triangles) show a clear trend of $\langle P(f) \rangle_{\text{ratio}}$ increasing with frequency $f$; i.e., higher frequency waves are damped more than their lower frequency counterparts. We add the caveat that in the CoMP data this trend continues to about 8 mHz, then there is a turnover in the ratio $\langle P(f) \rangle_{\text{ratio}}$. At the present time, it is unclear if this is simply due to background noise or is the result of some other physical mechanism(s). Understanding this high frequency trend should be the focus of a future study. However, there is a strong level of confidence in the trend of $\langle P(f) \rangle_{\text{ratio}}$ in the range 0–4 mHz, which can be explained by the theory of propagating kink wave resonant damping. To illustrate this, we implement a least squares fit of the power ratio function given in Equation (7) to the CoMP data in this range. From the estimates of Tomczyk & McIntosh (2009), our fixed parameters are $v_{\text{ph}} = 0.6$ Mm s$^{-1}$ and $L = 250$ Mm for both outward and inward waves, leaving the free parameters as $P_{\text{out}}/P_{\text{in}}$ and $\xi_{E}$. It is found that the best estimates are $P_{\text{out}}/P_{\text{in}} = 0.91$ and $\xi_{E} = 2.69$ (see solid line in Figure 2) with 95% confidence bounds $P_{\text{out}}/P_{\text{in}} = 0.67-1.89$ and $\xi_{E} = 1.15-3.49$. Although the wave paths analyzed by Tomczyk & McIntosh (2009) are integrated over many coronal loop structures, the spatially averaged estimate of $\xi_{E}$ is consistent with the damped

and for the inward power is

$$\langle P(f) \rangle_{\text{in}} = \frac{1}{L} \int_{L}^{2L} P_{\text{in}}(f) \exp \left( -\frac{2f}{v_{\text{ph}}\xi_{E}} s \right) ds. \quad (6)$$

Note that for Equation (6) integrating the power in the gray region from $s = L$ to $s = 0$ for the inward wave is equivalent to integrating from $s = L$ to $s = 2L$ for the outward wave. Defining $\langle P(f) \rangle_{\text{ratio}} = \langle P(f) \rangle_{\text{out}} / \langle P(f) \rangle_{\text{in}}$, it can be shown by Equations (5) and (6) that

$$\langle P(f) \rangle_{\text{ratio}} = \frac{P_{\text{out}}(f)}{P_{\text{in}}(f)} \exp \left( \frac{2L}{v_{\text{ph}}\xi_{E}} f \right). \quad (7)$$

In the next section, we shall do an exponential least squares fit using Equation (7) with CoMP data from the same observation by Tomczyk & McIntosh (2009) in the frequency range 0–4 mHz, where the S/N is strongest.
absorption, governed by the TGV relation which shows that naturally occurring transverse plasma inhomogeneity in coronal magnetic flux tubes causes them to act as low-pass filters. It was found that the observed frequency dependence on damping length can be explained by the kink wave interpretation, at least up to about $f = 8$ mHz, and furthermore, the spatially averaged equilibrium parameter describing the length scale of transverse plasma density inhomogeneity over a system of coronal loops is consistent with the range of values estimated from TRACE observations of standing kink modes. Due to its restricted field of view, full loops observed with TRACE are shorter than the average loop length of the coronal loop system observed with CoMP. The similar inferred transverse plasma inhomogeneity length scales suggest that this parameter is independent of loop length. Importantly, it was also found that the estimated least squares value of the ratio of initial outward and inward power was approximately unity, suggesting that the kink wave power generated at both footpoints in the lower atmosphere was almost equal.

Previously, much work has been undertaken to study the properties of the well-known standing kink modes in post-flare coronal loops. The results of this Letter now open the way to investigating the wave contribution to coronal heating by exploiting the latest high spatial/temporal resolution observations of propagating kink waves modes. An accurate estimate of coronal kink wave damping rates due to resonant absorption is crucial in order to quantify the amount of this wave energy that can contribute to plasma heating. Broadband frequency disturbances propagating along transversally inhomogeneous coronal flux tubes will generate many resonances that will phase mix, causing a cascade of energy to smaller scales where dissipation becomes more efficient, thereby creating the necessary conditions for plasma heating. Unlike the large amplitude standing kink mode coronal loop oscillations which need relatively high energy but rare excitation events like flares or CMEs, small amplitude propagating kink waves are ubiquitous. This makes them an ideal candidate for study with coronal observing instruments of sufficient Doppler velocity resolution such as CoMP, Hinode, and the planned Advanced Technology Solar Telescope (ATST).

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