

## DAMPING OF FAST MAGNETOHYDRODYNAMIC OSCILLATIONS IN QUIESCENT FILAMENT THREADS

IÑIGO ARREGUI,<sup>1</sup> JAUME TERRADAS,<sup>1,2</sup> RAMÓN OLIVER,<sup>1</sup> AND JOSÉ LUIS BALLESTER<sup>1</sup>

*Received 2008 May 30; accepted 2008 June 16; published 2008 July 8*

### ABSTRACT

High-resolution observations provide evidence of the existence of small-amplitude transverse oscillations in solar filament fine structures. These oscillations are believed to represent fast magnetohydrodynamic (MHD) waves, and the disturbances are seen to be damped on short timescales of the order of 1–4 periods. In this Letter, we propose that, due to the highly inhomogeneous nature of the filament plasma at the fine-structure spatial scale, the phenomenon of resonant absorption is likely to operate in the temporal attenuation of fast MHD oscillations. By considering transverse inhomogeneity in a straight flux tube model, we find that, for density inhomogeneities typical of filament threads, the decay times are of a few oscillatory periods only.

*Subject headings:* MHD — Sun: filaments — Sun: oscillations — waves

### 1. INTRODUCTION

Quiescent solar filaments form along the inversion polarity line or between the weak remnants of active regions. Early filament observations (Engvold 1998) as well as recent high-resolution H $\alpha$  observations, obtained with the Swedish Solar Telescope in La Palma (Lin et al. 2005) and the Dutch Open Telescope, have revealed that their fine structure is composed by many horizontal and thin dark threads. The measured average width of resolved threads is about 0.3" ( $\sim 210$  km), whereas the length is between 5" and 40" ( $\sim 3500$ – $28,000$  km). They seem to be partially filled with cold plasma (Lin et al. 2005), typically 2 orders of magnitude denser than that of the corona, and it is generally assumed that they outline their magnetic flux tubes (Engvold 1998; Lin 2004; Lin et al. 2005; Martin et al. 2008). This idea is strongly supported by the fact that they are inclined with respect to the filament-long axis at a similar angle to what has been found for the magnetic field (Leroy 1980; Bommier et al. 1994; Bommier & Leroy 1998).

Small-amplitude oscillations have been observed in filaments, and it is well established that these periodic changes are of a local nature. The detected peak velocity ranges from the noise level (down to  $0.1 \text{ km s}^{-1}$  in some cases) to  $2$ – $3 \text{ km s}^{-1}$ , although larger values have also been reported. Two-dimensional observations of filaments by Yi & Engvold (1991) and Yi et al. (1991) revealed that individual threads or groups of threads may oscillate independently with their own periods, which range between 3 and 20 minutes. More recently, Lin (2004) reported that spatially coherent oscillations were found over slices, with an area of  $1.4 \times 54 \text{ arcsec}^2$ , of a polar crown filament and that a significant periodicity appears at 26 minutes, which is strongly damped after 4 periods. Furthermore, Lin et al. (2007) have discovered evidence of traveling waves along a number of filament threads with an average phase velocity of  $12 \text{ km s}^{-1}$ , a wavelength of 4" ( $\sim 2800$  km), and oscillatory periods of the individual threads that vary from 3 to 9 minutes. The observed periodic signals are obtained from Doppler velocity measurements and can therefore be associated with the transverse displacement of the fine structures.

The observed small-amplitude oscillations have been interpreted in terms of magnetohydrodynamic (MHD) waves (Oliver & Ballester 2002), and theoretical models have been developed (see Ballester 2005, 2006 for recent reviews). Díaz et al. (2002) modeled a prominence thread as a straight cylindrical flux tube with a cool region representing the filament material, confined by two symmetric hot regions. They found that the fundamental fast mode is always confined in the dense part of the flux tube; hence, for an oscillating cylindrical filament thread, it should be difficult to induce oscillations in adjacent threads, unless they are very close.

The time damping of prominence oscillations has been unambiguously determined in some observations. Reliable values for the damping time have been derived from different Doppler velocity time series, by Molowny-Horas et al. (1999) and Terradas et al. (2002) in prominences and by Lin (2004) in filaments. The values thus obtained are usually between 1 and 4 times the corresponding period, and large regions of prominences/filaments display similar damping times. The damping of perturbations is probably a common feature of filament oscillations; hence, theoretical mechanisms must be explored, and their damping timescales should be compared with those obtained from observations. Linear nonadiabatic MHD waves have been proposed by Carbonell et al. (2004), Terradas et al. (2001, 2005), and Soler et al. (2007, 2008) as a potential mechanism to explain the observed attenuation timescales. Using thermal mechanisms only, these authors found that slow waves can be damped in an efficient manner, whereas fast waves remain almost undamped. Ion-neutral collisions provide a possible mechanism to damp fast waves (as well as Alfvén waves) that is able to reproduce observed damping times for given parameter values, in particular for a quasi-neutral gas (Forteza et al. 2007).

Apart from the mentioned nonideal damping mechanisms, there is another possibility to attenuate fast waves in thin filament threads. The phenomenon of resonant wave damping is well documented for fast kink waves in coronal loops (see, e.g., Goossens et al. 2006 and Goossens 2008 for recent reviews) and provides a plausible explanation for the quickly damped transverse loop oscillations observed by *TRACE* (Nakariakov et al. 1999; Aschwanden et al. 1999). In this Letter, we address the resonant damping mechanism in the context of filament thread oscillations and assess its relevance in explaining the observed attenuation timescales.

<sup>1</sup> Departament de Física, Universitat de les Illes Balears, Palma de Mallorca E-07122, Spain; inigo.arregui@uib.es, jaume.terradas@uib.es, ramon.oliver@uib.es, joseluis.ballester@uib.es.

<sup>2</sup> Centre Plasma Astrophysics, Katholieke Universiteit Leuven, Leuven B-3001, Belgium.

## 2. ONE-DIMENSIONAL NONUNIFORM FILAMENT THREAD MODEL

Given the relatively simple structure of filament threads, when compared to the full prominence/filament structure, the magnetic and plasma configuration of an individual and isolated thread can be theoretically approximated using a rather simplified model. We consider a gravity-free, straight, cylindrically symmetric flux tube of mean radius  $a$  (see Fig. 1). In a system of cylindrical coordinates  $(r, \varphi, z)$  with the  $z$ -axis coinciding with the axis of the tube, the magnetic field is pointing in the  $z$ -direction,  $\mathbf{B} = B\hat{e}_z$ . We neglect gas pressure, which allows us to concentrate on the oscillatory properties of fast and Alfvén MHD waves and their mutual interaction. In our straight field configuration, this zero- $\beta$  approximation implies that the field strength is uniform and that the density profile can be chosen arbitrarily. The inhomogeneous filament thread is then modeled as a density enhancement with a one-dimensional nonuniform distribution of density,  $\rho(r)$ , across the structure. The internal filament plasma, with uniform density,  $\rho_f$ , occupies the full length of the tube and is connected to the coronal medium, with uniform density,  $\rho_c$ , by means of a nonuniform transitional layer of thickness  $l$ . The  $l/a$  ratio provides us with a measure of the transverse inhomogeneity length scale, which can vary between  $l/a = 0$  (homogeneous tube) and  $l/a = 2$  (fully non-uniform tube).

## 3. DAMPING OF LINEAR FAST KINK WAVES

The magnetic flux tube model adopted here is a waveguide for a number of MHD oscillatory solutions. In the zero- $\beta$  approximation, slow waves are absent. The properties of the remaining small-amplitude fast and Alfvén waves can readily be described by considering the linear MHD wave equations for adiabatic changes of state for perturbations of the form  $f(r) \exp[i(\omega t + m\varphi - k_z z)]$ . Here  $m$  and  $k_z$  are the azimuthal and longitudinal wavenumbers, respectively, and  $\omega$  the oscillatory frequency. We further concentrate on perturbations with  $m = 1$ , which represent fast kink waves that produce the transverse displacement of the tube as they propagate along the density enhancement.

### 3.1. Analytical Theory

In the long-wavelength or thin-tube approximation ( $k_z a \ll 1$ ), the frequency of the  $m = 1$  fast kink wave can be written down analytically (see Edwin & Roberts 1983) as

$$\omega = k_z \sqrt{\frac{\rho_f V_{A,f}^2 + \rho_c V_{A,c}^2}{\rho_f + \rho_c}}, \quad (1)$$

with  $V_{A,f,c} = B/(\mu\rho_{f,c})^{1/2}$  the filament and coronal Alfvén velocities. By defining  $c = \rho_f/\rho_c$ , for the density contrast, the period of kink oscillations with a wavelength  $\lambda = 2\pi/k_z$  can be written as

$$P = \frac{\sqrt{2}}{2} \frac{\lambda}{V_{A,f}} \left( \frac{1+c}{c} \right)^{1/2}. \quad (2)$$

The factor containing the density contrast varies between  $\sqrt{2}$  and 1, when  $c$  is allowed to vary between a value slightly larger than 1 (extremely tenuous thread) and  $c \rightarrow \infty$ . For typical filament thread densities, which are 2 orders of magnitude larger than coronal densities, this factor is near unity. Equation (2) then predicts Alfvén velocities in the thread as low as a few

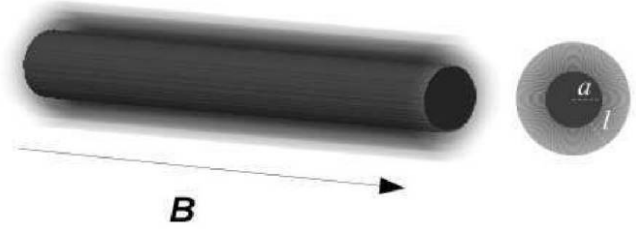


FIG. 1.—Sketch of the model used to represent a radially nonuniform filament fine structure of mean radius  $a$ , with a transverse inhomogeneity length scale  $l$  (see detail in the cross section).

kilometers per second or as large as  $\sim 200 \text{ km s}^{-1}$ , for combinations of periods between 3 and 20 minutes and wavelengths between 3000 and 20,000 km.

For fast kink waves to be damped by resonant absorption, transverse inhomogeneity in the Alfvén velocity has to be considered. In our uniform field model, this is obtained by considering  $l \neq 0$ . Then the  $m = 1$  solution is resonantly coupled to local Alfvén waves. The coupling produces the temporal attenuation of fast transverse motions that are converted into localized azimuthal Alfvénic oscillations. Asymptotic analytical expressions for the damping time,  $\tau_d$ , can be obtained under the assumption that the transverse inhomogeneity length scale is small ( $l/a \ll 1$ ). This is the so-called thin-boundary approximation. When the long-wavelength and thin-boundary approximations are combined, the analytical expression for the damping time divided by period can be written as (e.g., Hollweg & Yang 1988; Sakurai et al. 1991; Goossens et al. 1992, 1995; Ruderman & Roberts 2002)

$$\frac{\tau_d}{P} = F \frac{a c + 1}{l c - 1}; \quad (3)$$

here  $F$  is a numerical factor that depends on the particular variation of the density in the nonuniform layer. For a linear variation,  $F = 4/\pi^2$  (Hollweg & Yang 1988; Goossens et al. 1992); for a sinusoidal variation,  $F = 2/\pi$  (Ruderman & Roberts 2002). For example, considering  $c = 200$ , a typical density contrast, and  $l/a = 0.1$ , equation (3) predicts a damping time of  $\sim 6$  times the oscillatory period.

Figure 2 shows analytical estimates computed using equation (3) (*solid lines*). The damping is affected by the density contrast in the low-contrast regime, and  $\tau_d/P$  rapidly decreases for increasing thread density (Fig. 2a). Interestingly, it stops being dependent on this parameter in the large-contrast regime, which is typical of filament threads. The damping time divided by period is independent of the wavelength of perturbations (Fig. 2b) but rapidly decreases with increasing inhomogeneity length scale (Fig. 2c). These results suggest that resonant absorption is a very efficient mechanism for the attenuation of fast waves in filament threads, especially because large thread densities and transverse plasma inhomogeneities can be combined together.

### 3.2. Numerical Results

The two approximations used to derive equations (2) and (3) may impose limitations on the applicability of the obtained results to filament thread oscillations. To start with, it is not clear how accurate the long-wavelength approximation can be, especially for short wavelengths. The period in equation (3) corresponds to the long-wavelength limit (eq. [2]), which is

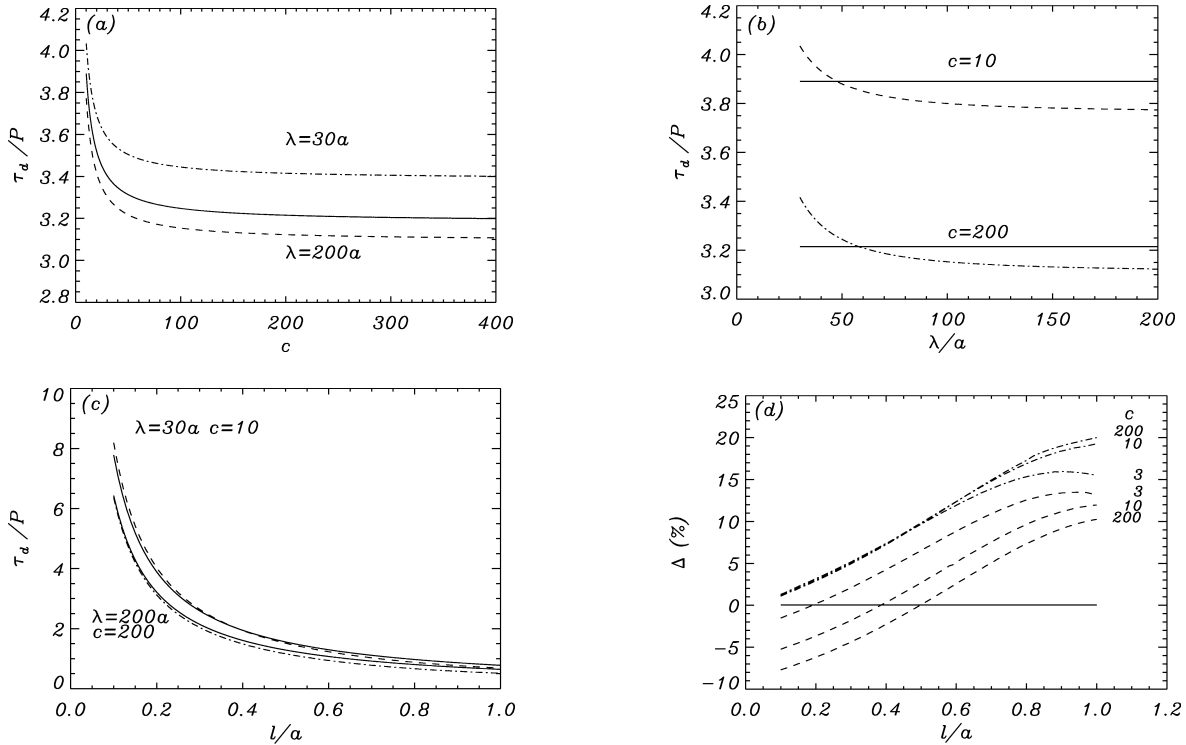


FIG. 2.—(a)–(c) Damping time over period for fast kink waves in filament threads with  $a = 100$  km. In all plots, solid lines correspond to analytical solutions given by eq. (3), with  $F = 2/\pi$ , (a) as a function of density contrast, with  $la = 0.2$  and for two wavelengths, (b) as a function of wavelength, with  $la = 0.2$  and for two density contrasts, and (c) as a function of transverse inhomogeneity length scale, for two combinations of wavelength and density contrast. (d) Percentage difference,  $\Delta$ , with respect to analytical eq. (3) for different combinations of wavelength— $\lambda = 30a$  (dashed lines) and  $\lambda = 200a$  (dash-dotted lines)—and density contrast.

independent of the radius of the structure, and does not include effects due to radial density inhomogeneity. Also, equation (3) is only valid as long as the damping time is sufficiently larger than the period, an assumption made in order to derive the expression, and clearly contradicted by the obtained results. The accuracy of the damping in equation (3) was assessed by Van Doorselaere et al. (2004) in the relatively low density contrast regime corresponding to damped coronal loop oscillations. Some degree of inaccuracy in the large-contrast regime, characteristic of filament threads, is also to be expected. We have therefore computed numerical approximations to the solutions by solving the full set of linear, resistive, small-amplitude MHD wave equations for the  $m = 1$  transverse kink oscillations (see, e.g., eqs. [1]–[5] in Terradas et al. 2006), using the PDE2D code (Sewell 2005).

Figure 2 shows the obtained numerical results. Analytical and numerical solutions display the same qualitative dependency (or behavior), with density contrast and transverse inhomogeneity length scale (Figs. 2a and 2c). Now the damping time divided by period slightly depends on the wavelength of perturbations (Fig. 2b). Equation (3) underestimates (overestimates) this magnitude for short (long) wavelengths. The differences are small, of the order of 3% for  $c = 10$ , and do not vary much with density contrast for long wavelengths ( $\lambda = 200a$ ), but the differences increase to 6% for short ones ( $\lambda = 30a$ ). The long-wavelength approximation is responsible for the discrepancies obtained for thin nonuniform layers (Fig. 2c). Figure 2d shows how accurate equation (3) is for different combinations of wavelength, density contrast, and inhomogeneity length scale. For thin layers ( $la = 0.1$ ), the inaccuracy of the long-wavelength approximation produces differences of up to  $\sim 10\%$  for the combination of short wavelength with high-contrast thread. For thick

layers, differences of the order of 20% are obtained (in agreement with Van Doorselaere et al. 2004). Here, the combination of large wavelength with high-contrast thread produces the largest discrepancy. Numerical results allow for the computation of more accurate values but do not change our previous conclusions regarding the efficiency of resonant damping of transverse oscillations in filament threads or regarding their properties.

#### 4. DISCUSSION

In this Letter, we have shown that, due to the highly inhomogeneous nature of filaments at their transverse scales, the process of resonant absorption is an efficient damping mechanism for fast MHD oscillations propagating in these structures. The relevance of the mechanism has been assessed in a flux tube model, with the inclusion of transverse inhomogeneity in the Alfvén velocity. Also, the accuracy of the analytical estimates, in terms of wavelength, density contrast, and transverse inhomogeneity, has been quantified. For the typical large filament-to-coronal density contrast, the mechanism produces rapid damping on timescales of the order of a few oscillatory periods only. The obtained damping rates are only slightly dependent on the wavelength of perturbations. An important result is that the damping rate becomes independent of density contrast for large values of this parameter. This has two seismological consequences. First, the observational determination of density contrast is less critical than it is in the low-contrast regime. Second, according to seismic inversion results that combine the theoretical and observed periods and damping times (Arregui et al. 2007; Goossens et al. 2008), high-density thread models would be compatible with relatively short transverse inhomogeneity length scales. Analytical estimates of

$l/a \sim 0.15$  can even be calculated using equation (3) for a given observed  $\tau_d/P = 4$ , taking the limit  $c \rightarrow \infty$ .

We believe our conclusion on the relevance of resonant damping in filament thread oscillations is robust in front of the main simplification adopted for the present study. Observations show that threads are only partially filled with cool and dense plasma, and our one-dimensional model misses this property. Although the resonant damping mechanism relies on the Alfvén velocity inhomogeneity in the direction transverse to the magnetic field, an investigation of the damping properties in such a two-dimensional configuration is necessary. Finally, the presence of flows is commonly observed along filament threads,

and the interplay between resonant damping and flows must also be explored in this context.

The authors acknowledge the funding provided under projects AYA2006-07637 (Spanish Ministerio de Educación y Ciencia) and PCTIB2005GC3-03 (Conselleria d'Economia, Hisenda i Innovació of the Government of the Balearic Islands). The authors also acknowledge the International Space Science Institute for their financial support of the meetings of the teams responsible for "Coronal Waves and Oscillations" and "Imaging of Quiescent and Eruptive Solar Prominences from Space" in Bern, Switzerland, where some of the ideas relevant to this work were discussed.

#### REFERENCES

- Arregui, I., Andries, J., Van Doorselaere, T., Goossens, M., & Poedts, S. 2007, *A&A*, 463, 333
- Aschwanden, M. J., Fletcher, L., Schrijver, C. J., & Alexander, D. 1999, *ApJ*, 520, 880
- Ballester, J. L. 2005, *Space Sci. Rev.*, 121, 105
- . 2006, *Philos. Trans. R. Soc. London*, A364, 405
- Bommier, V., Landi Degl'Innocenti, E., Leroy, J.-L., & Sahal-Brechot, S. 1994, *Sol. Phys.*, 154, 231
- Bommier, V., & Leroy, J. L. 1998, in *IAU Colloq. 167, New Perspectives on Solar Prominences*, ed. D. F. Webb, B. Schmieder, & D. M. Rust (ASP Conf. Ser. 150; San Francisco: ASP), 434
- Carbonell, M., Oliver, R., & Ballester, J. L. 2004, *A&A*, 415, 739
- Díaz, A. J., Oliver, R., & Ballester, J. L. 2002, *ApJ*, 580, 550
- Edwin, P. M., & Roberts, B. 1983, *Sol. Phys.*, 88, 179
- Engvold, O. 1998, in *IAU Colloq. 167, New Perspectives on Solar Prominences*, ed. D. F. Webb, B. Schmieder, & D. M. Rust (ASP Conf. Ser. 150; San Francisco: ASP), 23
- Forteza, P., Oliver, R., Ballester, J. L., & Khodachenko, M. L. 2007, *A&A*, 461, 731
- Goossens, M. 2008, in *IAU Symp. 247, Waves & Oscillations in the Solar Atmosphere: Heating and Magneto-Seismology*, ed. R. Erdélyi & C. A. Mendoza-Briceño (Cambridge: Cambridge Univ. Press), 228
- Goossens, M., Andries, J., & Arregui, I. 2006, *Philos. Trans. R. Soc. London*, A364, 433
- Goossens, M., Arregui, I., Ballester, J. L., & Wang, T. J. 2008, *A&A*, 484, 851
- Goossens, M., Hollweg, J. V., & Sakurai, T. 1992, *Sol. Phys.*, 138, 233
- Goossens, M., Ruderman, M. S., & Hollweg, J. V. 1995, *Sol. Phys.*, 157, 75
- Hollweg, J. V. & Yang, G. 1988, *J. Geophys. Res.*, 93, 5423
- Leroy, J. L. 1980, in *Proc. Japan-France Seminar on Solar Physics*, ed. F. Moriyama & J. C. Henoux, 155
- Lin, Y. 2004, Ph.D. thesis, Univ. Oslo
- Lin, Y., Engvold, O., Rouppe van der Voort, L. H. M., & van Noort, M. 2007, *Sol. Phys.*, 246, 65
- Lin, Y., Engvold, O., Rouppe van der Voort, L., Wiik, J. E., & Berger, T. E. 2005, *Sol. Phys.*, 226, 239
- Martin, S. F., Lin, Y., & Engvold, O. 2008, *Sol. Phys.*, in press, DOI: 10.1007/s11207-008-9194-8
- Molowny-Horas, R., Wiehr, E., Balthasar, H., Oliver, R., & Ballester, J. L. 1999, in *JOSO Annu. Rep.*, 1998, 126
- Nakariakov, V. M., Ofman, L., DeLuca, E. E., Roberts, B., & Davila, J. M. 1999, *Science*, 285, 862
- Oliver, R., & Ballester, J. L. 2002, *Sol. Phys.*, 206, 45
- Ruderman, M. S., & Roberts, B. 2002, *ApJ*, 577, 475
- Sakurai, T., Goossens, M., & Hollweg, J. V. 1991, *Sol. Phys.*, 133, 227
- Sewell, G. 2005, *The Numerical Solution of Ordinary and Partial Differential Equations* (Hoboken: Wiley & Sons)
- Soler, R., Oliver, R., & Ballester, J. L. 2007, *A&A*, 471, 1023
- . 2008, *ApJ*, in press (astro-ph/0803.2600)
- Terradas, J., Carbonell, M., Oliver, R., & Ballester, J. L. 2005, *A&A*, 434, 741
- Terradas, J., Molowny-Horas, R., Wiehr, E., Balthasar, H., Oliver, R., & Ballester, J. L. 2002, *A&A*, 393, 637
- Terradas, J., Oliver, R., & Ballester, J. L. 2001, *A&A*, 378, 635
- . 2006, *ApJ*, 642, 533
- Van Doorselaere, T., Andries, J., Poedts, S., & Goossens, M. 2004, *ApJ*, 606, 1223
- Yi, Z., & Engvold, O. 1991, *Sol. Phys.*, 134, 275
- Yi, Z., Engvold, O., & Keil, S. L. 1991, *Sol. Phys.*, 132, 63