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Theoretical aspects of prominence oscillations

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Abstract. The theoretical modelling of prominence vibrations has been performed mainly through the analysis of the magnetohydrodynamic normal modes of oscillation of simple equilibrium structures. Research on this topic has concentrated mostly on the oscillatory properties of prominence slabs (i.e. without taking into account the internal thread structure) and prominence fibrils (i.e. introducing some of this inherent internal complexity of prominences, although in a simplified manner). In an attempt to understand the observed strong damping of prominence oscillations, work has also been done on the attenuation of waves in these objects. The achievements in this particular research area are reviewed and some trends for possible future investigations are given.

Keywords. waves, MHD, Sun: prominences, Sun: filaments, Sun: atmosphere, Sun: Corona, Sun: oscillations

1. Introduction

There are several issues about prominence oscillations that have been investigated theoretically. Most of the first works were concerned with the normal modes of a prominence treated as a plasma slab with different magnetic field orientations: for example, in Joarder & Roberts (1992a) the magnetic field is along the slab axis, while in Joarder & Roberts (1992b), Oliver et al. (1993) and Oliver & Ballester (1996) it is perpendicular to the slab. On the other hand, the more realistic case of a magnetic field skewed to the main axis of the filament was investigated by Joarder & Roberts (1993).

Prompted by the observations of Yi & Engvold (1991) and Yi et al. (1991), that indicate that prominence threads may oscillate either individually or in groups of neighbours, these analyses were later followed by studies of the normal modes of oscillation of prominence fibrils. Such theoretical works were first performed for a single thread under the approximation of Cartesian geometry, see Joarder et al. (1997), Díaz et al. (2001), Díaz et al. (2003) and Díaz et al. (2005). The more realistic cylindrical tube partially filled with prominence plasma was also considered by Díaz et al. (2002) and also by Dymova & Ruderman (2005) in the thin tube approximation.

These and other works have been examined in detail in previous review papers, e.g. Oliver & Ballester (2002) and Erdélyi et al. (2008), and so they are not treated here. The purpose of this paper is to revise the theoretical investigations of the attenuation of prominence oscillations, a research area that has also received considerable attention. There are some observational works, e.g. those by Tsubaki & Takeuchi (1986) and Wiehr et al. (1989), revealing that the oscillatory amplitude decreases in time, which suggests that prominence oscillations are attenuated in time. A very clear example of this phenomenon can be found in Figure 5a of Landman et al. (1977). Here the integrated line intensity of the He D_3 line displays oscillations with a period around 25 min and with an amplitude that decreases in time. These oscillations are present for a few cycles but, unfortunately, a precise value of the attenuation rate is not computed in this case. More detailed observational analyses of damped prominence oscillations can be found in Molowny-Horas et al. (1999) and Terradas et al. (2002), who studied the spatial and temporal features of Doppler velocity oscillations in limb prominences. The second of these works contains a comprehensive study of the spatial distribution of oscillations and shows that, in this particular observation, they are concentrated in a restricted area (54,000 $\times$ 40,000 km in size) of the prominence. Both propagating waves and standing oscillations are detected in this region and their wavelength and phase speed are determined. Moreover, by fitting a sinusoidal function multiplied by a factor $\exp(-t/\tau)$ to the Doppler series, these authors obtained values of the damping time, τ, which are usually between 1 and 3 times the corresponding oscillatory period. In spite of the lack of similar studies, the existing evidence suggests that small-amplitude oscillations in prominences are excited locally and are damped in a few periods by an unknown mechanism. The plausible theoretical explanations of this effect are reviewed here and the relevance of different mechanisms is assessed on the basis of the ratio of the damping time to the period (τ/P), that must be in the range 1–10 to agree with the observational results. This work is organised as follows: Section 2 describes the works in which wave leakage from the prominence is invoked as the cause for the observed damping and Section 3 describes attenuation caused by non-ideal effects. Finally, Section 4 contains the concluding remarks.

2. Wave leakage

Wave leakage is a common event by which the energy imparted by a disturbance to a given structure (e.g. a coronal loop or a solar prominence) is not confined as standing oscillations of the structure, which emits waves carrying energy into the external medium. This situation has been studied at length in relation with coronal loop oscillations; see Cally (1986) and Cally (2003) and references therein. Most of the works described in this section make no mention about wave leakage, but our interpretation is that the obtained attenuation of oscillations is simply a consequence of the emission of waves from the prominence into the corona.

2.1. *Line-current filament models*

In the celebrated model of Kuperus & Raadu (1974) a prominence is treated as a horizontal line current suspended in the corona. Such an approximation is justified by the fact that if the prominence plasma is supported against gravity by the Lorentz force, then a current runs along the filament. In this work the photosphere is substituted by a rigid, perfectly conducting plane with a surface current distribution caused by the coronal magnetic field generated by the filament current. Such induced currents in turn give rise to a coronal magnetic field whose effect on the prominence is to provide the lifting force necessary to counteract gravity. The full magnetic field arrangement in the corona is determined by both the line current and the photospheric currents and can be of two types: either of normal polarity (NP) or of inverse polarity (IP); see Schutgens (1997b) and van den Oord et al. (1998) for more details.

This magnetic configuration was used by van den Oord & Kuperus (1992), Schutgens (1997a), Schutgens (1997b) and van den Oord et al. (1998) to study the oscillations of a filament. It is worth to remark that in these works the prominence is treated as an infinitely thin and long line, so that it has no internal structure, although the interplay of the filament current with the surrounding magnetic arcade and photosphere is taken into account. In addition, both NP and IP structures were considered; see Figure 2 of Schutgens (1997b), in which the poloidal magnetic field is displayed (the toroidal

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magnetic field component being zero). The fundamental ingredient of these papers is that if a disturbance causes a displacement of the whole line current, that remains parallel to the photosphere during its motion, then the coronal magnetic field is reshaped and the photospheric surface current is modified. This, in turn, influences the magnetic force acting on the filament current. Such a force can either strengthen the initial perturbation, so that the original equilibrium is unstable, or diminish it, so that the system is stable against the initial disturbance. This simple description becomes more complicated when one takes into account that perturbations travel at a finite speed (namely the Alfvén velocity) which causes time delays in the communication between the line current and the photosphere. van den Oord & Kuperus (1992), Schutgens (1997a), Schutgens (1997b) and van den Oord et al. (1998) investigated the effect of these time delays on the filament dynamics.

Exponentially growing or decaying solutions were found both for NP and IP prominence models; see Figure 4 of van den Oord & Kuperus (1992) and Figure 5 of Schutgens (1997a) as examples. An important conclusion that can be extracted here is that the attenuation is very efficient for many parameter values, and consequently the ratio of the damping time to the period is between 1 and 10 (i.e. in agreement with observations). This point is well illustrated by Figure 6 of Schutgens (1997b), in which the quality factor, $Q \equiv \pi\tau/P$, is depicted as a function of the Alfvén speed. Different curves in this diagram correspond to different sets of parameters, with solid and dashed lines used to distinguish between IP and NP configurations. All the IP curves and one of the NP curves in this figure take values below $Q = 30$, equivalent to $\tau/P \simeq 10$, which is an indication of the efficiency of the damping of oscillations.

2.2. *Finite-thickness filament model*

A magnetic configuration similar to that used by van den Oord & Kuperus (1992), Schutgens (1997a), Schutgens (1997b) and van den Oord et al. (1998) was taken by Schutgens & Tóth (1999), although in this study the prominence is not infinitely thin and instead is represented by a current-carrying cylinder. Schutgens & Tóth (1999) carried out numerical simulations of the isothermal magnetohydrodynamic (MHD) equations and this implies that the equilibrium temperature is set to a constant value (10^6 K) everywhere. The authors mention that, despite the large temperature difference between solar prominences and the corona, this isothermal assumption can only have a minor effect. In addition, the photosphere is described as a perfectly conducting boundary, as in the papers examined above. The inner part of the filament is disturbed by a perturbation with a velocity amplitude of 10 km s^{-1} and at an angle of 45$^{\text{o}}$ to the photosphere. This causes the prominence to move like a rigid body in the corona, both vertically and horizontally, and to undergo exponentially damped oscillations; see Figure 7 in Schutgens & Tóth (1999). It is found that the horizontal and vertical motions are decoupled from one another (and so can be investigated separately) and that the period and damping time of horizontal oscillations are much larger than their respective counterparts for vertical oscillations. Again, strong damping can be achieved for some parameter values; see Figure 12 of Schutgens & Tóth (1999). It turns out that vertical oscillations are very efficiently attenuated for all the parameters considered in this work and that the same happens with horizontal oscillations for coronal densities above $\simeq 5 \times 10^{-13}$ kg m^{-3}. These contrasting properties of damped horizontal and vertical oscillations contain some potential for performing seismology of prominences.

Now we turn our attention to the interpretation of the results presented so far. None of the works cited in the first part of this section, i.e. van den Oord & Kuperus (1992), Schutgens (1997a), Schutgens (1997b) and van den Oord et al. (1998), mention wave leakage

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as the cause of the attenuation, but instead these papers connect this behaviour with the effect of the distant photosphere and the presence of time delays in the communication of disturbances between the filament and the photosphere. On the other hand, Schutgens & Tóth (1999) link the damping of oscillations to the emission of waves by the prominence: the damping of horizontal motions is attributed to the emission of slow waves, whereas fast waves are invoked as the cause of the damping of vertical motions. Given that the main difference between this work and the other ones lies essentially in the cross section of the filament, there is no reason to believe that the physics involved are much different regardless of the prominence being modeled either as a straight and infinitely thin current or as a current-carrying cylinder. This issue must be examined in more detail to better understand the dynamics of solar prominences.

A final remark about the exact nature of the wave leakage found by Schutgens & Tóth (1999) must be made. In this work (see their Figure 6a) the plasma-β in the prominence ranges from $\beta > 1$ in its central part to $\beta < 0.1$ at its boundary. Hence, waves emitted by the prominence into the corona propagate in a $\beta \ll 1$ environment in which magnetic field lines are closed. Under these conditions, slow modes propagate along magnetic field lines and are unable to transfer energy from the prominence into the corona and so wave leakage in the system studied by Schutgens & Tóth (1999) is only possible by fast waves. Then, it is hard to understand how the prominence oscillations can be damped by the emission of slow waves in this particular model, in which the dense, cool plasma is only allowed to emit fast waves. It must be mentioned, however, that the plasma-β in the corona increases with the distance from the filament, which implies that the emitted fast waves can transform into slow waves when they traverse the $\beta \simeq 1$ region. This effect has been explored by McLaughlin & Hood (2006) and McDougall & Hood (2007), but see also references therein for similar studies.

3. Non-ideal effects

Ballai (2003) took into account some dissipative mechanisms and explored, through some order-of-magnitude calculations, their importance as possible damping agents. In this work we are warned about the simplicity of the calculations and about the neglect of the solar corona, whose role on the damping of prominence oscillations is beyond this simple study. Dissipative mechanisms are separated into isotropic and anisotropic. Amongst the first ones, viscosity and magnetic diffusion are found to be rather inefficient in attenuating perturbations in only a few periods, as demanded by observations. Moreover, radiative losses (here modeled by means of Newton's cooling law, that gives an extremely simplified account of radiation in a solar prominence), may be of some importance, although their effect is difficult to establish unambiguously because of the presence of the unknown radiative relaxation time-scale in Newton's cooling law. Therefore, radiation by the prominence plasma requires a more specific treatment to determine its significance. Regarding anisotropic mechanisms, in Ballai (2003) it is determined that, because of the very large density and very low temperature of prominences, viscosity can be considered isotropic and thus irrelevant as the cause of the observed damping of oscillations. In addition, thermal conduction is dominated by the presence of a magnetic field and is essentially parallel to the field direction. This mechanism is very efficient as a damping agent for very short wavelengths. Since Ballai's work has been extended in other papers discussed below, the meaning of "very short wavelengths" will become clear later. Although other dissipative mechanisms are not contemplated in Ballai (2003), e.g. wave leakage, ion-neutral collisions or resonant absorption, this work is important since it allowed subsequent investigations to discard the irrelevant mechanisms and to concentrate only in the rest.

3.1. *Uniform medium*

The efficiency of thermal conduction (parallel to the magnetic field) and radiation in transporting heat, and thus in causing the attenuation of oscillations, has been addressed in a number of papers; see Ibáñez & Escalona (1993), Carbonell et al. (2004), Terradas et al. (2005) and Carbonell et al. (2006). These works are concerned with the spatial and temporal damping of fast and slow waves propagating in a uniform medium. Radiative losses are simulated by Equation (7) of Hildner (1974), which contains two parameters that can be tuned to represent optically thin or thick radiation; see Carbonell et al. (2004). Different sources of plasma heating are also included, although this mechanism has a negligible consequence on the properties of the waves.

To understand the results of these studies it is worth to consider the characteristic time-scales of thermal conduction and radiative losses (τ_c and τ_r), that following De Moortel & Hood (2004) can be defined as

$$\tau_c = \frac{Lp}{(\gamma - 1)\kappa_{\parallel} T}, \tag{3.1}$$

$$\tau_r = \frac{\gamma p}{(\gamma - 1)\rho^2 \chi T^{\alpha}}. \tag{3.2}$$

In these expressions p, ρ and T are the plasma pressure, density and temperature, L is a characteristic length-scale (the wavelength of oscillations, for example) and χ and α are the two parameters in Hildner's radiative loss function. We see that τ_r is independent of L and so the rate at which the plasma looses energy through radiation does not vary with the wavelength or frequency of the waves. On the other hand, the conduction time-scale, τ_c, decreases with L and so conduction becomes more effective at transporting heat for short wavelengths, just as noticed by Ballai (2003), for example. In the limit of very short wavelengths conduction is so efficient that the isothermal regime is reached. The critical wavenumber, k_c, at which this transition occurs is given by Porter et al. (1994) as

$$k_c^2 = \frac{2nk_B}{\kappa_{\parallel}}, \tag{3.3}$$

with n the number density and k_B Boltzmann's constant. Now, let us consider a perturbation with tunable wavelength travelling in a magnetised, uniform medium in which thermal conduction and radiation can transport heat. Let us start with an extremely short wavelength, so that the wavenumber is larger than k_c and the perturbation is isothermal. Let us now increase the wavelength until the wavenumber becomes just smaller than k_c. Now thermal conduction is still more efficient than radiation because it works in a very short time-scale (i.e. τ_c is quite small), but perturbations are no longer isothermal. Next the wavelength is allowed to increase and consequently the conduction time-scale increases proportionally to L. Under these conditions, conduction becomes less and less efficient and there is eventually a wavenumber (or length-scale) at which the conduction and radiation time-scales become equal. This length-scale, L^*, is obtained by imposing $\tau_c = \tau_r$ and with the help of Equations (3.1) and (3.2) is

$$L^* = \frac{\gamma \kappa_{\parallel}}{\rho^2 \chi T^{\alpha - 1}}. \tag{3.4}$$

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Finally, for wavelengths larger than L^* radiative losses dominate the energy budget of the plasma.

These formulas are useful to explain some features of the damping time (in the case of temporal damping of oscillations) or the damping length (in the case of spatial damping) obtained by Ibáñez & Escalona (1993), Carbonell et al. (2004), Terradas et al. (2005) and Carbonell et al. (2006). Consider, for example, the bottom two panels of Figure 1 in Carbonell et al. (2004), where the damping per period ($D_p = 2\pi\tau/P$) is represented as a function of the wavenumber; we concentrate on the solid line of the left panel (fast mode), although the results described now are similar for the other line styles and for the right panel (slow mode). For the paramater values used in this work, we have $k_c = 1.82$ and $L^* = 4770$ m, that corresponds to the wavenumber $k^* = 2\pi/L^* = 1.32 \times 10^{-3}$ m^{-1}. The right-most maximum in this plot is around $\log k = 0.5$ and coincides roughly with the value of k_c, so it is caused by the transition between the isothermal and the conduction-dominated regimes. In addition, the minimum is around $\log k = -3$ and its agreement with k^* confirms that it corresponds to the transition from the conduction-dominated to the radiation-dominated regimes. Therefore, the shift from one regime to another leaves its imprint in the variation of τ/P with respect to the wavenumber.

The main conclusions of Carbonell et al. (2004), Terradas et al. (2005) and Carbonell et al. (2006) regarding the damping of prominence oscillations are that the slow mode is strongly attenuated for wavenumbers within the range of observed values (i.e. for k in the range $10^{-8} - 10^{-6}$ m^{-1}). Moreover, the considered approximations for optically thin or thick plasmas can give very different attenuation properties and all the considered heating mechanisms are of no relevance.

3.2. *Structured medium*

The influence of the surrounding corona on the damping of these oscillations has been studied by Soler et al. (2007a). In this work the filament is taken as a plasma slab embedded in the solar corona and with a uniform magnetic field parallel to the filament axis. Both the prominence plasma and the coronal plasma are uniform and threaded by the same magnetic field; see Figure 1 of Soler et al. (2007a).

To understand the results of Soler et al. (2007a) it is necessary to describe the main properties of the linear, adiabatic normal modes of such a configuration, that have been studied by Edwin & Roberts (1982), Joarder & Roberts (1992a) and Soler et al. (2007b). In the latter work the solutions are classified in three types: fast, internal slow and external slow modes and it is concluded that the perturbations associated to internal slow modes are essentially confined to the prominence slab, so that these waves are hardly influenced by the coronal environment. On the other hand, fast modes have tails that penetrate in the corona and as a result coronal conditions are important in determining the features of these waves. Moreover, the confinement of fast modes becomes poorer for small values of the wavenumber in the direction of the filament axis. Regarding external slow modes, they produce almost negligible perturbed amplitudes inside the cold slab and thus seem uninteresting in the context of prominence oscillations.

Soler et al. (2007a) included the thermal conduction, radiative losses and plasma heating terms in the energy equation and studied the damping properties of the fast and internal and external slow modes. They obtained values of τ/P in agreement with observations both for the internal slow and the fast modes. Such as expected, the damping rate of the internal slow mode is not modified by the inclusion of the corona in the model and it only depends on the value of the wavenumber in the direction parallel to the magnetic field. The attenuation of this mode can be recovered by inserting the parallel wavenumber, $k_\parallel$, and a "modified sound speed" in the expression $\omega = k_\parallel c_s$; see

Appendix B in Soler et al. (2007a) for more details. The damping rate of the fast mode, however, is severely influenced by the addition of the coronal medium. Firstly, this mode couples with the external slow mode, whose properties are essentially dictated by the coronal plasma. But secondly, apart from this coupling the coronal medium has a direct influence because of the presence of coronal tails in the perturbed variables. In Soler et al. (2007a) a close examination of the role of the corona in the damping of the fast mode was done by removing one of the important non-adiabatic mechanisms (thermal conduction or radiation) either in the filament or in the corona. The conclusion of this study is that coronal mechanisms govern the attenuation of the fast modes for wavenumbers $k_\parallel \lesssim 10^{-7}$ m, whereas prominence mechanisms prevail for $k_\parallel \gtrsim 10^{-7}$ m. In each of these ranges radiation is dominant in the low-$k_\parallel$ range and thermal conduction is dominant in the high-$k_\parallel$ range. More specifically, coronal radiation controls the attenuation for $k_\parallel \lesssim 10^{-9}$ m, coronal conduction does so for 10^{-9} m $\lesssim k_\parallel \lesssim 10^{-7}$ m, while prominence radiation and conduction are the most important non-adiabatic mechanisms for 10^{-7} m $\lesssim k_\parallel \lesssim 10^{-3}$ m and $k_\parallel \gtrsim 10^{-3}$ m, respectively. Hence, in the range of observed wavelengths both thermal conduction in the corona and radiation from the prominence gas are important to explain the reported damping times.

In Section 3.1 the characteristic time-scales of thermal conduction and radiation in a uniform medium were invoked to explain the transition from the radiation-dominated wavenumber range to the conduction-dominated wavenumber range. The same idea can be applied to explain this transition in the present, structured configuration both for the prominence and for the corona. In the case of the prominence, the transition value is the same as before, namely $k^* = 1.32 \times 10^{-3}$ m^{-1}, whereas for the corona it is $k^* = 3.42 \times 10^{-9}$ m^{-1}. These numbers coincide well with the ones quoted in the previous paragraph. Moreover, the wavenumber at which the transition between the ranges of dominance of coronal conduction and prominence radiation takes place can be derived from the equality of τ_c in the corona and τ_r in the prominence. This calculation yields $k = 1.32 \times 10^{-7}$ m^{-1}, also in good agreement with the previous value. More details can be found in Soler et al. (2007a).

3.3. *Partial ionisation effects*

Chromospheric and prominence plasmas are not fully ionised and so several new effects are present in comparison to a fully ionised plasma. For example, electric charges are frozen to magnetic field lines, but neutrals are not and thus the neutral and ionised fractions of the plasma behave differently. Collisions between neutrals, on one hand, and electrons and ions, on the other hand, arise and consequently a modified Ohm's law is obtained. As a consequence, the main outcome of the interaction between neutrals and charged particles is the presence of enhanced Joule heating and enhanced magnetic diffusion. These ideas were presented by Piddington (1956) in connection with the heating of the solar chromosphere and corona and have also been invoked to explain the dynamics of chromospheric spicules, e.g. Haerendel (1992) and James & Erdélyi (2002), and of flux tubes emerging from the solar interior, Arber et al. (2007).

The influence of partial ionisation of the prominence plasma on the properties of the fast and slow modes has been investigated by Forteza et al. (2007). In this work the one-fluid MHD equations for a partially ionised plasma made of electrons, protons and neutral hydrogen are derived. Next, a uniform medium with a straight magnetic field is considered. The linear regime is assumed and this results in the vanishing of the Joule heating term in the energy equation, so that the corresponding physical effect is absent. One may conclude that in more realistic configurations dissipation may be stronger than that found by Forteza et al. (2007). The main result of this work is that the fast mode can be strongly damped (in agreement with observations) for small values of the ionisation fraction, whereas the slow mode is hardly attenuated. The mechanism responsible for the damping of the fast mode is Cowling's diffusion, that vanishes in a fully ionised plasma. An analytical approximation for the fast mode damping rate,

$$\frac{\tau}{P} = \frac{1-\xi_n}{\xi_n^2}\rho^{1/2}B^{-1}k^{-1}, \tag{3.5}$$

is derived by Forteza et al. (2007), with ξ_n the relative density of neutrals, ρ the gas density, B the magnetic field strength and k the modulus of the wavenumber. Such a simple expression can be of practical use in the interpretation of observations. It indicates that the damping is stronger, i.e. τ/P is smaller, for almost neutral plasmas with low density, strong magnetic field and for short wavelengths.

4. Conclusions

In this paper the possible role of several physical mechanisms in the attenuation of prominence oscillations has been reviewed. It has been shown that both the fast and slow waves can undergo strong damping under a variety of physical conditions and with the intervention of different effects. Nevertheless, the list of the presumably relevant mechanisms has not been totally explored and other effects should be investigated. In addition, the geometry of the models is too simplified, which implies that the results derived so far only give a rough guide to the damping features in actual prominences. The efficiency of wave leakage and coronal conduction in draining oscillatory energy from the prominence and transferring it to the corona calls for the study of complex configurations in which the structure of the full prominence-corona system is treated more realistically.

Most of the works are based on the linear approximation, whose validity seems quite robust in view of the small amplitude of prominence oscillations in many cases. Nevertheless, apart from the so-called small-amplitude prominence oscillations, that in general affect small regions of a prominence and have Doppler velocity peaks typically below 1–2 km s^{-1}, there is a different kind of phenomenon, the large-amplitude oscillations. They are characterised by a much higher amplitude (with oscillatory velocities up to 90 km s^{-1}) and disturb the whole filament; see Eto et al. (2002), Jing et al. (2003), Okamoto et al. (2004), Jing et al. (2006), Isobe & Tripathi (2006) and Vršnak et al. (2007). These prominence vibrations also damp very rapidly, in a few periods, so it is in order to ascertain whether the mechanisms at work in the damping of small-amplitude oscillations are also the main ones for the large-amplitude counterparts or whether non-linear effects can also cause the attenuation of the latter.

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