New Astronomy 14 (2009) 238–248

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Attenuation of small-amplitude oscillations in a prominence–corona model with a transverse magnetic field

R. Soler, R. Oliver, J.L. Ballester *

Departament de Física, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain

ARTICLE INFO

Article history:
Received 16 June 2008
Received in revised form 14 August 2008
Accepted 18 August 2008
Available online 26 August 2008
Communicated by W. Soon

PACS:
52.35.Bj
96.60.–P

Keywords:
Sun: oscillations
Sun: magnetic fields
Sun: corona
Sun: prominences

ABSTRACT

Observations show that small-amplitude prominence oscillations are usually damped after a few periods. This phenomenon has been theoretically investigated in terms of non-ideal magnetoacoustic waves, non-adiabatic effects being the best candidates to explain the damping in the case of slow modes. We study the attenuation of non-adiabatic magnetoacoustic waves in a slab prominence embedded in the coronal medium. We assume an equilibrium configuration with a transverse magnetic field to the slab axis and investigate wave damping by thermal conduction and radiative losses. The magnetohydrodynamic equations are considered in their linearised form and terms representing thermal conduction, radiation and heating are included in the energy equation. The differential equations that govern linear slow and fast modes are numerically solved to obtain the complex oscillatory frequency and the corresponding eigenfunctions. We find that coronal thermal conduction and radiative losses from the prominence plasma reveal as the most relevant damping mechanisms. Both mechanisms govern together the attenuation of hybrid modes, whereas prominence radiation is responsible for the damping of internal modes and coronal conduction essentially dominates the attenuation of external modes. In addition, the energy transfer between the prominence and the corona caused by thermal conduction has a noticeable effect on the wave stability, radiative losses from the prominence plasma being of paramount importance for the thermal stability of fast modes. We conclude that slow modes are efficiently damped, with damping times compatible with observations. On the contrary, fast modes are less attenuated by non-adiabatic effects and their damping times are several orders of magnitude larger than those observed. The presence of the corona causes a decrease of the damping times with respect to those of an isolated prominence slab, but its effect is still insufficient to obtain damping times of the order of the period in the case of fast modes.

1. Introduction

Solar prominences are large-scale coronal magnetic structures whose material, cooler and denser than the typical coronal medium, is in plasma state. Prominences are supported against gravity by the coronal magnetic field, which also maintains the prominence material thermally isolated from the corona. Small-amplitude oscillations in solar prominences were detected almost 40 years ago (Harvey, 1969). These oscillatory motions seem to be of local nature and their velocity amplitude is typically less than 2–3 $\mathrm{km\,s^{-1}}$. Observations have also allowed to measure a wide range of periods between 30 s (Balthasar et al., 1993) and 12 h (Foullon et al., 2004). More recently, some high-resolution observations of prominence oscillations by the Hinode/SOT instrument have been reported (Okamoto et al., 2007; Berger, 2008; Ofman and Wang, 2008). From the theoretical point of view, the oscillations have been interpreted by means of the magnetoacoustic eigenmodes supported by the prominence body. A recent example is the work by Terradas et al. (2008) in which the observations of Okamoto et al. (2007) are interpreted as fast kink waves. The reader is referred to Oliver and Ballester (2002), Ballester (2006), and Banerjee et al. (2007) for extensive reviews of both observational and theoretical studies.

Evidence of the attenuation of small-amplitude prominence oscillations has been reported in some works (Molowny-Horas et al., 1999; Terradas et al., 2002; Lin, 2004). A typical feature of these observations is that the oscillatory motions disappear after a few periods, hence they are quickly damped by one or several mechanisms. The theoretical investigation of this phenomenon in terms of magnetohydrodynamic (MHD) waves has been broached by some authors by removing the ideal assumption and by including dissipative terms in the basic equations. Non-adiabatic effects appear to be very efficient damping mechanisms and have been investigated with the help of simple prominence models (Ballai,

---

* Corresponding author. Tel.: +34 971173426.
E-mail addresses: roberto.soler@uib.es (R. Soler), ramon.oliver@uib.es (R. Oliver), joseluis.ballester@uib.es (J.L. Ballester).

1384-1076/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.newast.2008.08.008

2003; Carbonell et al., 2004; Carbonell et al., 2006; Terradas et al., 2005). Nevertheless, other damping mechanisms have been also proposed, like wave leakage (Schutgens, 1997a; Schutgens, 1997b; Schutgens and Tóth, 1999), dissipation by ion–neutral collisions (Forteza et al., 2007) and resonant absorption (Arregui et al., 2008).

In a previous work (Soler et al., 2007, hereafter Paper I), we have studied for the first time the wave attenuation by non-adiabatic effects of a prominence slab embedded in the corona. In that work the magnetic field is parallel to the slab axis and it is found that the corona has no influence on the internal slow modes, but it is of paramount importance to explain the damping of fast modes, which are more attenuated than in simple models that do not consider the coronal medium. Following the path initiated in Paper I, here we investigate the wave damping due to non-adiabatic mechanisms (radiative losses and thermal conduction) in an equilibrium made of a prominence slab embedded in a coronal medium, but now we consider a magnetic field transverse to the slab axis. This configuration and that studied in Paper I correspond to limit cases, since measurements with Zeeman and Hanle effects indicate that the magnetic field lines are skewed to the long axis of prominences. On average, the prominence axis and the magnetic field form an angle of about 20°. Thus, the skewed case is relegated to a future investigation.

The equilibrium configuration assumed here was analysed in detail by Joarder and Roberts (1992) and Oliver et al. (1993) in the case of ideal, adiabatic perturbations. The main difference between both works is in the treatment of gravity. Joarder and Roberts (1992) neglected the effect of gravity and so straight field lines were considered. On the other hand, Oliver et al. (1993) took gravity into account and assumed curved field lines according to the Kippenhahn and Schülter (1957) model modified to include the surrounding coronal plasma (Poland and Anzer, 1971). Despite this difference, both studies agree in establishing a distinction between different normal modes depending on the dominant medium supporting the oscillation. Hence, internal modes are essentially supported by the prominence slab whereas external modes arise from the presence of the corona. In addition, hybrid (or string) modes appear due to the combined effect of both media.

The investigation of the thermal attenuation of oscillations supported by such equilibrium is unsettled to date and, indeed, this is the main motivation for the present study. However, two works (Terradas et al., 2001; Terradas et al., 2005) studied the wave damping in an isolated prominence slab. Terradas et al. (2001) considered radiative losses given by the Newtonian law of cooling as damping mechanism and studied the attenuation in the Kippenhahn and Schülter (1957) and Menzel (1951) prominence models. Subsequently, Terradas et al. (2005) considered a more complete energy equation including optically thin radiation, plasma heating and parallel thermal conduction, and assumed straight field lines since gravity was neglected. The main conclusion of both works is that non-adiabatic mechanisms are only efficient in damping slow modes whereas fast modes remain almost undamped. Nevertheless, in the light of the results of Paper I, the presence of the coronal medium can have an important repercussion on the wave damping. The investigation of this effect is the main aim of the present work. Therefore, we extend here the work of Terradas et al. (2005) by considering the presence of the corona and neglect the effect of gravity as in Joarder and Roberts (1992) for simplicity.

This paper is organised as follows. Section 2 contains a description of the equilibrium configuration and the basic equations which govern non-adiabatic magnetoacoustic waves. Then, the results of this work are extensively discussed in Section 3. Finally, our conclusions are given in Section 4.

2. Equilibrium and basic equations

The equilibrium configuration (see Fig. 1) is made of a homogeneous plasma slab with prominence conditions (density ρ_{p} and temperature T_{p}), whose axis is orientated along the z-direction, embedded in a coronal environment (density ρ_{c} and temperature T_{c}). The system is bounded in the x-direction due to the presence of two rigid walls representing the solar photosphere, but it is unlimited in the y- and z-directions. The width of the prominence slab is $2x_{\mathrm{p}}$ and the total width of the system is $2x_{\mathrm{c}}$. The magnetic field is transverse to the prominence slab, $\vec{B}_0 = B_0\hat{e}_x$, with B_0 everywhere constant.

In order to find the basic equations that govern non-adiabatic magnetoacoustic waves we follow the same process as in Terradas et al. (2005). We consider the usual MHD equations (Eqs. (1)–(6) of Terradas et al., 2005) in which non-adiabatic terms have been included in the energy equation,

$$\frac{\mathrm{D}p}{\mathrm{D}t} - \frac{\gamma p}{\rho}\frac{\mathrm{D}\rho}{\mathrm{D}t} + (\gamma - 1)[\rho L(\rho, T) - \nabla \cdot (\vec{\kappa} \cdot \nabla T)] = 0, \qquad (1)$$

where p, ρ and T are the gas pressure, density and temperature, respectively. The quantity γ is the adiabatic ratio, here taken $\gamma = 5/3$. The non-ideal terms in Eq. (1) are explained in detail in Carbonell et al. (2004). Thermal conduction is represented by $\nabla \cdot (\vec{\kappa} \cdot \nabla T)$, where $\vec{\kappa}$ is the conductivity tensor which in coronal and prominence applications is usually approximated by its parallel component to the magnetic field, $\kappa_{\parallel} = 10^{-11} T^{5/2}$ W m^{-1} K^{-1}. Radiative losses and heating are evaluated together through the heat-loss function, $L(\rho, T) = \chi^* \rho T^{\alpha} - h\rho^a T^b$, where radiation is parametrised with χ^* and α (see Table I of Paper I) and the heating scenario is given by exponents a and b (Rosner et al., 1978; Dahlburg and Mariska, 1988).

Regarding our equilibrium configuration, the reader must be aware that, although there have been some attempts to construct a self-consistent prominence model including both magnetostatics and thermodynamics (e.g. Milne et al., 1979; Low and Wu, 1981; Anzer and Heinzel, 1999), to date this task remains to be done. Here, we consider a simplified prominence–corona configuration, but it includes the two basic ingredients observed in real prominences. First, the existence of a steep temperature gradient between the prominence and the corona and, second, the apparent thermal isolation of the prominence material from the much hotter corona. The first point is addressed by considering that the

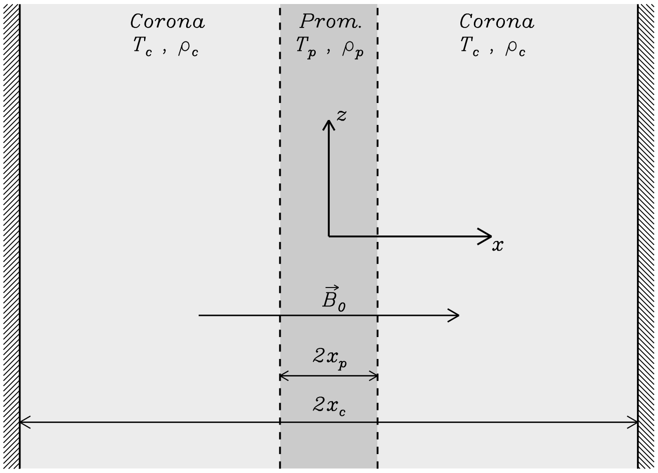

Fig. 1. Sketch of the equilibrium. The dark region represents the prominence slab while the light region corresponds to the corona. The photospheric walls are the two hatched areas on both sides of the corona.