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MHD Waves in Coronal Structures: Observations & Modelling

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Abstract

A review of MHD waves in the solar corona over the last three decades is presented, covering both observations and theoretical aspects. Observations indicate that waves are ubiquitous in many coronal structures, being transverse kink waves in coronal loops the most clear example. Theoretical models have been developed to explain these waves in terms of magnetohydrodynamic (MHD) modes. The models have evolved from simple idealised systems to complex configurations. In this review we show how the comparison between observations and theory has allowed the growth of coronal seismology as a tool to probe the plasma conditions in the solar corona.

1 Introduction

Observations show that waves and oscillations are ubiquitous in the solar corona. One of the most clear examples of propagating disturbances on a global scale are coronal EIT waves. These propagating wave-like fronts are usually triggered by flares or CMEs (Coronal Mass Ejections). Examples of such phenomena can be found in [44, 56, 58], and more recently in [16]. The theoretical modelling of such phenomena was first attempted by [57] using magnetic field extrapolations from photospheric magnetograms. It was shown that fast magnetoacoustic disturbances might correspond to the EIT waves found in the observations. Nevertheless, the model did not take into account the density structure of active regions which might strongly affect the transmission and reflection of fast MHD waves.

Waves in the solar corona are also present on smaller spatial scales. For example, there is abundant literature on oscillations reported in solar prominences and filaments. The reader is referred to the reviews of [25], [5], and [4] for details about observations and the corresponding theoretical interpretation. In particular two families of MHD waves have been reported in these structures, the fast magnetoacoustic mode and the slow MHD mode.

Coronal loops and plumes are magnetic structures that also show oscillatory phenomena. Standing acoustic oscillations have been reported in hot coronal loops, e.g., [54], [53], and [52]. Propagating longitudinal waves involving compression have been found in coronal plumes (see [10, 23, 24]). Propagating intensity fluctuations are routinely observed at the footpoints of coronal loops (e.g., [9], [8], [42] and [7]), and are associated to driven slow modes from the photosphere.

More recently, it has been also shown that transverse propagating waves can be found in almost any coronal loop of the corona (see [46] and [45]). The propagating speed of these waves is of the order of the Alfvén speed (around $1000\,\mathrm{km\,s^{-1}}$ in the solar corona) while the amplitude is rather small, a few $\mathrm{km\,s^{-1}}$. These waves are also driven by photospheric motions, since they have dominant periods around 5 min. The theoretical interpretation of these waves has been given in terms of propagating transverse kink modes, see for example [27],[40] and [35]. It has been shown that a periodic driver excites upward propagating waves which are almost incompressible and producing a transverse displacement of the loop. The damping length of the reported waves has been also explained in terms of resonantly damped modes. Nevertheless, one of the most analysed types of waves in coronal loops are transverse kink oscillations, which are the main topic of this work.

2 Observations of standing transverse oscillations

Standing transverse oscillations are generated in flares and CME events, and in many cases they have been linked to the occurrence of blast waves or EIT waves. Transverse kink oscillations, producing a lateral displacement of the tube axis, have been reported using different instruments onboard different satellites such as TRACE, STEREO, EIS, and SDO/AIA (see the review of [1]). The most clear examples of such oscillations have been reported using the imaging telescope TRACE. However, although is not well known, there are also evidences of such waves in two-dimensional Dopplergrams. In [15] the instrument NOGIS (Norikura Solar Observatory, Japan) was used to study with an unprecedent detail the propagation and excitation of transverse waves in a magnetic arcade produced by an eruptive filament. This kind of observations (see also [46] and [45]) are quite promising since they have been performed using green coronal lines such as Fe XIV. Ground-based telescopes open new and interesting possibilities using this and other spectral lines.

The transverse displacements observed in loops have amplitudes of $80\,\mathrm{km\,s^{-1}}$ at most, and they show a fast attenuation that has been reported by both space and also ground-based observations. Typically the ratio between the damping time and the period of oscillation, τ_D/P, is in the range $2-5$. In this paper we do not focus on the attenuation process, which is and interesting problem by its own, but we rather prefer to explain the basics of coronal seismology.

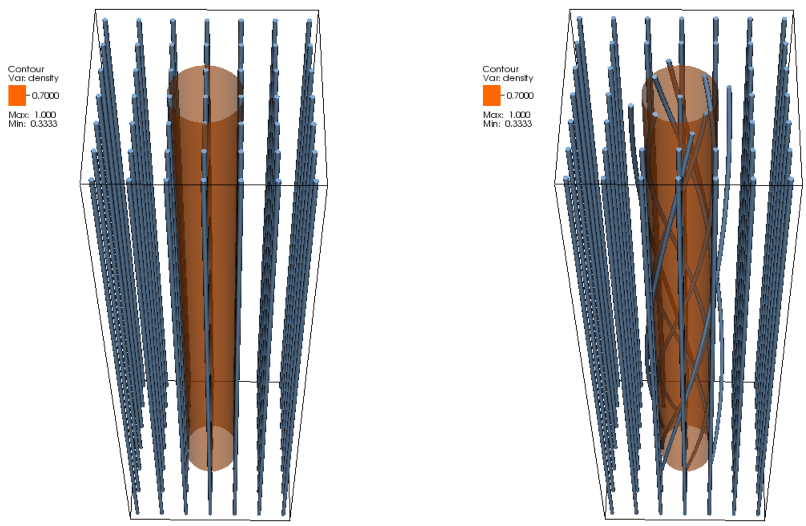

Figure 1: Idealised equilibrium models representing a coronal loop. On the left panel the magnetic field is straight, while on the right panel the density enhancement, representing the loop, is embedded in a twisted magnetic field.

3 Theoretical interpretation of standing transverse oscillations

3.1 Basic model and MHD waves

The simplest equilibrium model that represents a coronal loop is a straight magnetic tube of enhanced density. An example of such an idealised model is found in the left panel of Fig. 1. The magnetic field, pointing in the $z-$direction, permeates the cylindrically symmetric loop and the external environment. In this model we also assume that the gas pressure is negligible in front of the magnetic field, i.e., we adopt the zero-β approximation commonly used in the solar corona.

We use the equations of the magnetohydrodynamics to analyse the modes of oscillation of our idealised loop model. Since the reported amplitudes of oscillation are in general small we consider the linearised version of the MHD equations. The main aim is the determination of the eigenmodes of oscillation because they are the building blocks to understand the stationary state but are also necessary to understand the time-dependent behaviour of the system. Perturbations to the equilibrium are assumed to have a harmonic dependence with time, $e^{i\omega t}$. A Fourier analysis is assumed along the $z-$direction, i.e., $e^{ik_z z}$. The effect of the photospheric line-tying is incorporated to the model by selecting a particular value for the wavenumber k_z. For the fundamental mode $k_z = \pi/L$, being the L loop length. A Fourier analysis is also performed in the azimuthal direction, $e^{im\theta}$, since the equilibrium is invariant in this direction. The transverse oscillation of the whole tube corresponds to the $m = \pm 1$ mode, i.e., the kink mode. The dispersion relation has been studied in detail by many authors, being the most representative works by [36], [12], [6], [14], and [13]. It is known that the nature of the modes of oscillation is either trapped, with real frequency and evanescent for $r \to \infty$, or leaky, with complex frequency and representing radiating waves. Our main interest is on trapped transverse kink modes. For these modes the frequency of oscillation is given by

$$\omega_k = k_z v_{Ai} \sqrt{\frac{2}{1 + \rho_e/\rho_i}}, \tag{1}$$

where $v_{Ai} = B_0/\sqrt{\mu_0 \rho_i}$ is the internal Alfvén speed and ρ_e/ρ_i is the density contrast. This expression is valid in the thin tube approximation, i.e., for the situation when the loop radius is small in comparison with the wavelength of oscillation ($Rk_z \ll 1$). Interestingly, Eq. (1) has been used for seismological purposes. In [21] the period of oscillation, P, the length of the loop, L, and the densities were used for the first time to infer the magnetic field using Eq. (1)

$$B_0 \approx \frac{\sqrt{2\mu_0} L}{P} \sqrt{\rho_i \left(1 + \rho_e/\rho_i\right)}. \tag{2}$$

It was found that $B_0 \approx (13 \pm 9)$ G. The error is essentially due to the uncertainties in the determination of the densities. This inferred value for the magnetic field is of the same order as the magnetic field derived using photospheric extrapolations. More recently the same approach based on the combination of observational information and the theoretical expressions has been used by many authors to estimate the magnetic field in different coronal loops.

There are other ways to perform coronal seismology using the interpretation based on the transverse kink mode. In [38] the amplitude of oscillation from observations and the distance from the flare was used to estimate the energy released in the flare that triggered the loop motions. These authors found that the energy released was around 10^{25} J, which is a typical value in big flares.

3.2 Additional effects

Other effects have been added to the simple equilibrium model described above. For example, the inclusion of stratification along the tube, studied by [2], [11], [20], [51], and [3] has allowed to estimate the scale height in coronal loops from the comparison of the theoretical models and the observations. In particular, the estimations of the density scale heights are essentially due to the expected change in the ratio between the fundamental and first harmonic introduced by the effect of stratification. The effects of elliptical cross section on the frequencies of oscillation have been analysed by [29], who showed that the kink mode splits in two different modes. The role of small tube expansion has been investigated by [33] and [31] while the collective behaviour of a tube composed by many different strands has been analysed by [17], [18], [19], and [49]. More recently, [30] and [39] have investigated the effect of siphon flows on the frequencies of oscillation, and this has allowed to have indirect estimations of the flow speed in coronal loops. This is also a clear seismological application.

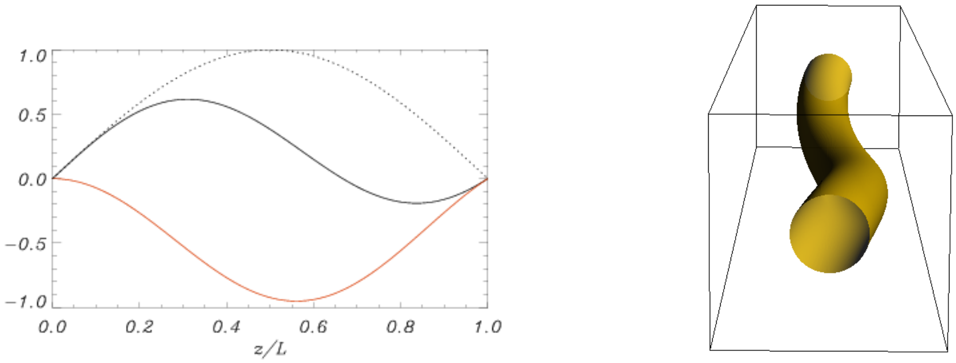

Figure 2: *Left panel:* Loop displacement of a twisted magnetic tube given by Eq.(3). The dotted line represents the displacement in the absence of twist, while the black and red lines correspond to the displacement in the x and y direction for a twisted tube. *Right panel:* three-dimensional representation of the displacement of the tube at a given time. In these plots $k_z = \frac{\pi}{L}$ and $k_T = 0.75k$.

Another relevant effect that has been considered in [41] is the presence of magnetic twist (see right panel of Fig. 1). It has been shown that for weak twist the displacement of the tube axis is given by the following expression

$$\begin{aligned} \xi_x &= A \sin(k_z z) \cos(k_T z + \theta_0) \sin(\omega t), \\ \xi_y &= A \sin(k_z z) \sin(k_T z + \theta_0) \sin(\omega t), \\ \xi_z &= 0, \end{aligned} \tag{3}$$

where θ_0 is an arbitrary phase. Again the external magnetic field points in the $z-$direction, and the x and y axis lie on the plane perpendicular to the tube axis. From Eq. (3) we see that the simple sinusoidal transverse oscillation for the untwisted case is recovered when $k_T = 0$ (see dotted line in the left panel of Fig. 2). However, for a twisted magnetic field $k_T \neq 0$, being k_T linearly proportional to the amount of twist. For example, the loop displacement as a function of the coordinate along the tube is plotted in Fig. 2 for $k_T = 0.75k_z$. These figure suggests that although the loop is oscillating with the fundamental mode (since $k_z = \frac{\pi}{L}$), the motion of the loop axis resembles the first harmonic. This is one of the fingerprints that we should look for in the observations. Note that if we have detailed observational information about the loop displacement, we might be able to determine the value of k_T, and indirectly the amount of twist. This is another example of the possible application of coronal seismology.

Apart from the straight tube, curved tube models have been also considered in some detail. An example of such a model is shown in Fig. 3. The normal modes of this configuration were studied analytically by [48], and numerically by [43] (see also [50] for a review on this topic). It was shown that there are two modes of oscillation that produce transverse

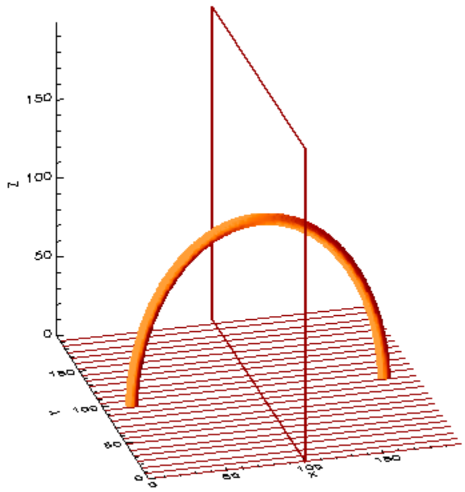

Figure 3: Idealised curved loop model. The toroidal tube intersects the photosphere at the plane $z = 0$ and has a semicircular shape. The eigenmodes of this configuration have been calculated in [48] and [43].

displacements of the tube. The fundamental mode displaces the tube mostly horizontally, while the second mode produces a vertical displacement. However, for long loops compared with the radius of the tube the two modes tend to the same frequency, given again by Eq. (1). Thus, differences in the frequency of oscillation should be investigated in short and fat loops where the split in frequencies is higher. The time-dependent problem has been analysed by [26] solving the MHD equations in three dimensions and using essentially the same model as in Fig. 3. These authors have studied the evolution of an impulse generated near the loop apex and exciting essentially the fundamental kink mode.

From the observational point of view it has been also shown that the identification of different kink modes due to curvature is difficult, since in general one expects the simultaneous excitation of the horizontal and vertical modes (see [55]). An extension to the previous models includes the effect of non-coplanar loops, recently investigated by [32] and [34] using a theoretical model. The information of the three-dimensional motion of loops is crucial to compare with the models, and in this regard STEREO observations might be very useful.

4 Discussion and conclusions

We have demonstrated that coronal seismology, originally proposed by [47] and [28], is a viable method to infer some parameters of the solar corona. We have described using simple models the main efforts that have been done to understand standing transverse kink oscillations in coronal loops. However, for a further development of this method much more realistic models need to be considered. Due to the nature of the structures in the solar corona a key point is the geometry in three dimensions that must be implemented in the models. It is important to remark that not only the time-dependent problem needs to be numerically studied (see [37] for a review), we also need to dispose of numerical tools that are able to calculate the eigenmodes of complex 3D configurations. Nowadays, observations are well ahead of theoretical models, for this reason a significant improvement of the theoretical part of the process is required. In this regard, computational MHD is a valuable tool that allows to study problems with more realistic geometries that are very difficult to solve analytically.

Finally, it is worth to mention that in this work we have deliberately avoided the topic of the strong damping of the transverse kink oscillations. However, a couple of comments deserve to be done. The first interpretations of the damping were based of the existence of an anomalous magnetic Reynolds number, see [22]. The Reynolds number was estimated to be around eight orders of magnitude smaller than classical value. It was shown later that other mechanisms can explain the damping without the need of using an anomalous resistivity. In particular, it was demonstrated that the process of resonant absorption is compatible with the reported damping times as long as the loop has an inhomogeneous transition between the internal density of the loop and the external density of the coronal medium. However, other damping mechanism cannot be fully discarded, for example, damping by wave leakage. This last mechanism needs to be understood using three-dimensional models by means of numerical simulations, and here we have to mention the overlooked problem of numerical dissipation in MHD simulations. It turns out that in many numerical studies the effect on the results of the intrinsic numerical dissipation of the numerical scheme is not taken into account. The issue of the dissipation is very important in numerical studies, since too much artificial dissipation can dominate the attenuation of the waves by a physical mechanism and lead to the wrong interpretation of the results.

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