The Astrophysical Journal, 676: L73–L75, 2008 March 20

DETECTION OF WAVES IN THE SOLAR CORONA: KINK OR ALFVÉN?

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Received 2007 November 14; accepted 2008 February 1; published 2008 March 6

ABSTRACT

Recently, the omnipresence of waves has been discovered in the corona using the CoMP instrument. We demonstrate that the observational findings can be explained in terms of guided kink magnetoacoustic modes. The interpretation of the observations in terms of Alfvén waves is shown to be inconsistent with MHD wave theory. The implications of the interpretation in terms of kink waves are discussed.

Subject headings: MHD — Sun: corona — Sun: oscillations

1. INTRODUCTION

In the last decade, the progress in the spatial and time resolution of solar coronal instruments brought up abundant evidence of the magnetohydrodynamic (MHD) wave activity of the corona (Nakariakov & Verwichte 2005). In uniform plasmas there are three basic types of MHD waves: Alfvén waves and the fast and slow magnetoacoustic waves. The solar corona is highly structured across the magnetic field into loops, plumes, filaments, etc. For the MHD waves detected there, theory allows for a rich variety of modes. Within the range of frequencies currently observed by solar instruments there can be four main kinds of MHD modes of cylindrical plasma structures: kink, sausage, longitudinal, and torsional. The first three modes are magnetoacoustic and hence compressible. The last one, torsional, is the true (incompressible) Alfvén mode. All three magnetoacoustic modes have recently been identified in the corona. As yet, there has not been direct evidence of the (torsional) Alfvén mode found. The torsional mode attracts great interest as it can carry significant energy from subphotospheric regions to the corona, potentially supplying the energy required for coronal heating. This is possible because the torsional mode can propagate through the highly stratified layers of the solar atmosphere without reflection (Ofman 2002).

One of the intensively studied coronal wave phenomena are kink modes which are fast magnetoacoustic modes modified by coronal structures. Standing kink modes were discovered as flare-induced quickly decaying periodic transverse displacements of active region loops with the EUV imager *TRACE* (Aschwanden et al. 1999; Nakariakov et al. 1999), and created a foundation for MHD coronal seismology. Propagating kink modes were discovered by Verwichte et al. (2005) in the supra-arcade dark channels also with *TRACE*. Both kinds of the kink modes have been identified unambiguously because of the sufficient spatial resolution of the instrument.

Recently, ubiquitous waves have been observed in the corona by Tomczyk et al. (2007) using the Coronal Multi-Channel Polarimeter (CoMP). The revelation that the waves are omnipresent in the corona is an important development. Although many uncertainties (such as instrumental sources of systematic error, uncertainties on the field inclination and atomic polarization, 3D geometry) will have to be resolved in the future, it is already clear that the discovery has major implication for coronal physics, e.g., in the context of coronal heating and coronal seismology (e.g., Van Doorsselaere et al. 2007).

The observed oscillations only had a significant contribution in the Fourier power spectrum of the velocity signal. No oscillations were observed in the intensity or line width. Tomczyk et al. interpreted their observations in terms of Alfvén waves. This was based on the facts that

1. the observed phase speeds are much larger than the sound speed,
2. the waves propagate along the field lines,
3. the waves are seen to be incompressible.

In this Letter, we do not question these observational findings, but show that an interpretation in terms of fast kink waves is more appropriate.

It was already stated by Parker (1991) that, “In the absence of an ignorable coordinate, the Alfvén-type waves … are coupled together into a single coordinated fast mode …”, concluding that, in the solar corona, pure, plane, long wavelength Alfvén waves require special physical conditions to exist. Moreover, even in the presence of an ignorable coordinate (e.g., torsional modes of a straight cylinder), Alfvén waves do not show coherent behavior, being subject to phase mixing; i.e., Alfvén waves associated with neighboring flux surfaces propagate with different speeds and rapidly get out of phase. This affects their observability. In contrast, kink modes are genuinely collective modes. Furthermore, the kink and Alfvén waves fundamentally differ in many respects; e.g., their phase speeds, propagation, compressibility, nonlinear evolution, damping mechanisms, and excitation are essentially different.

2. MHD MODES OF A STRAIGHT CYLINDER

To describe MHD oscillations in a fine-structured coronal plasma, we use the classical model (Edwin & Roberts 1983), i.e., a high density cylinder (a structure) with radius a, aligned with the homogeneous magnetic field ($\boldsymbol{B} = B\boldsymbol{e}_z$), embedded in a low density corona. The internal density is ρ_i, and the external density is ρ_e. We use linearized ideal MHD equations where the gas pressure is neglected. We Fourier analyze all quantities with respect to ϕ, z, and t (i.e., a normal mode analysis): $Q(r, \phi, z, t) = Q'(r) \exp i(m\phi + kz - \omega t)$.

The cylindrical model has proven to be a robust and successful tool for identification of coronal modes. Obviously, as with any model, it neglects some potentially important effects. However, critical assessment of the effects of, e.g., curvature (Van Doorsselaere et al. 2004), stratification (Andries et al. 2005), and departure from the circular cross section (Ruderman 2003) has shown to be of secondary importance.

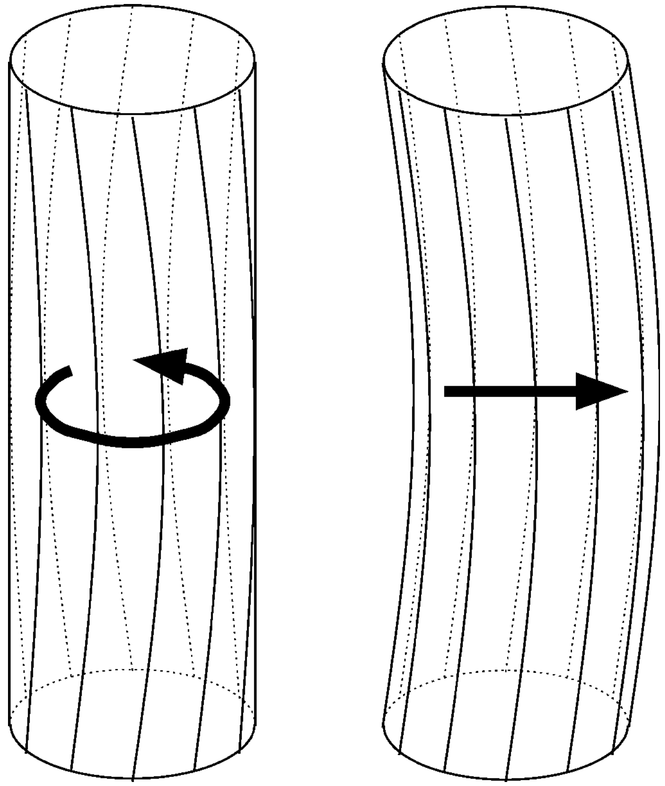

FIG. 1.—*Left*: Schematic view of a torsional Alfvén mode. The mode is a propagating twisting of magnetic field lines forming a concentric flux shell. Neighboring shells can oscillate with different phases. *Right*: Schematic view of a fast magnetoacoustic kink mode. This mode is the collective phenomenon. All field lines experience a coherent periodic displacement. The structure oscillates as a whole.

Using the above assumptions, the linearized ideal MHD equations are reduced to one governing wave equation:

$$(\omega^2 - \omega^2_{\mathrm{A}i,e})\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{dP'}{dr}\right) - \left(\kappa^2_{i,e} + \frac{m^2}{r^2}\right)P'\right] = 0, \qquad (1)$$

where $\omega^2_{\mathrm{A}i,e} = k^2B^2/\mu\rho_{i,e} = k^2V_\mathrm{A}^2$ is the square of the Alfvén frequency in respectively the internal and external region, P' is the magnetic pressure perturbation, and $\kappa^2_{i,e} = -(\omega^2 - \omega^2_{\mathrm{A}i,e})/V^2_{\mathrm{A}i,e}$. The two terms of the equation describe the torsional Alfvén waves and magnetoacoustic waves, respectively.

2.1. *Torsional Alfvén Modes*

For the torsional Alfvén modes inside the coronal loop, $\omega^2 = \omega^2_{\mathrm{A}i}$ and the magnetic pressure perturbation P' is equal to zero. Because the compressibility of the mode is directly linked with P' ($\rho' \sim P'$), the Alfvén wave is incompressible and hence does not manifest intensity variations. The Alfvén wave is transversely polarized, hence $V_z' = 0$. Together with the incompressibility, this leads to the relation $\partial rV_r'/\partial r = -imV_\phi'$, where V_r' and V_ϕ' are the radial and poloidal velocity, respectively.

In the case $m = 0$, $V_r' = 0$ and there are no constraints on V_ϕ'. Physically, this means that each flux surface oscillates separately, and that no globally coherent oscillations occur. This behavior is depicted in the left-hand panel of Figure 1. Only a single magnetic shell oscillates with a velocity purely in the ϕ-direction, without being influenced by the neighboring concentric shells. The torsional Alfvén mode does not alter the geometry of the loop, i.e., no displacements of the loop axis or deformations of the loop width.

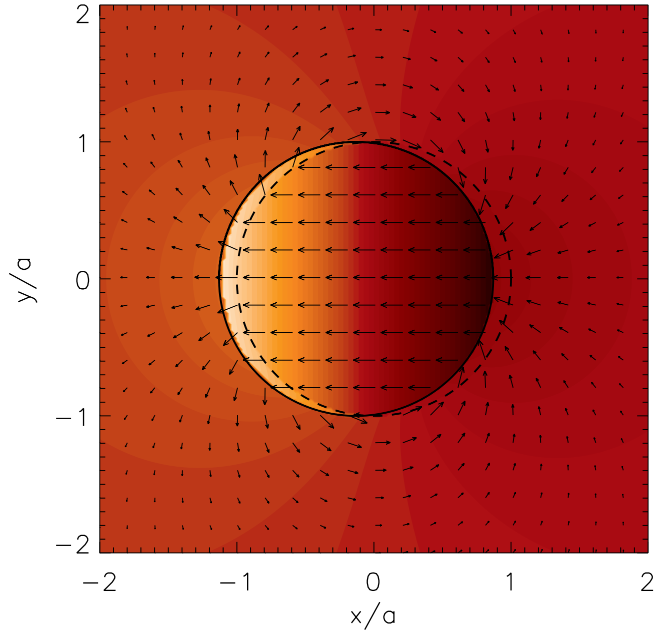

FIG. 2.—Transverse cut through the cylinder for a fast kink mode. The arrows indicate the velocity profile, and the color shade shows the relative density perturbation (ρ'/ρ): light colors show a high density perturbation, dark shows the low values.

If the Alfvén speed varies in the radial direction, neighboring magnetic shells oscillate at different frequencies. This mode does not show a collective behavior.

2.2. *Fast Kink Modes*

For the fast kink mode ($m = 1$), a bulk motion in the whole loop displaces the cylinder away from its original position (shown in the right hand panel of Fig. 1). The radial structure of the oscillation is shown in Figure 2. It is clear that the loop oscillates as a monolithic structure, with an almost constant velocity in the loop body. Outside the loop, the perturbation decreases steeper than exponential. Hence the fast kink mode is confined, and guided along the structure. We conclude that the fast kink mode propagates along the magnetic field lines. In the direction perpendicular to the axis of the structure (and the magnetic field), this mode cannot be planar.

In the long wavelength limit, it is found that $\omega^2 = \omega_k^2 = V_k^2k^2$, where $V_k = V_{\mathrm{A}i}[2/(1 + \rho_e/\rho_i)]^{1/2}$. This phase speed can be up to a factor of $\sqrt{2}$ larger than the internal Alfvén speed.

If the Alfvén speed varies in the radial direction, this still remains a collective mode and the whole structure oscillates with a single frequency and phase.

In the long wavelength limit, the internal mode structure is $P_i' = A|\kappa_i|r$, with an associated internal density perturbation

$$\rho_i'/\rho_i = \frac{P_i'}{\rho_i V^2_{\mathrm{A}i}}. \qquad (2)$$

We can thus relate the amplitude of the density perturbation $\mathbb{D}$ to the velocity amplitude $\mathbb{V} = \max |V'|/V_{Ai}$:

$$\mathbb{D} = \pi\sqrt{2}\left(\frac{a}{\lambda}\right)\frac{1-\rho_e/\rho_i}{\sqrt{1+\rho_e/\rho_i}}\mathbb{V}, \tag{3}$$

where λ is the wavelength.

3. OBSERVATIONAL MANIFESTATION OF KINK AND TORSIONAL MODES

As can be seen from the sketches in Figure 1, it is clear that the observational manifestation of the torsional Alfvén and the fast kink mode is entirely different.

In an imaging instrument, the fast kink modes are observed as transversal displacements of coronal loops (Aschwanden et al. 2002). The collective motion displaces the structure several radii from its equilibrium. On the other hand, the torsional Alfvén mode causes neither displacement of the structure boundary nor variations in the density, and hence cannot be observed with imaging instruments.

In spectrographs or polarimeters (such as CoMP), both of the modes are detectable. Because of their globally coherent structure, the kink mode will produce a *periodic Doppler shift* in the spectral lines, provided there is a significant line-of-sight component of the velocity. The Alfvén modes, on the other hand, do not have a collective behavior, and show both blue and redshifts simultaneously, and in different parts of the loop. Because of the spatial integration, both Doppler shifts are seen simultaneously, and a *periodic nonthermal line broadening* is created (as shown by Williams 2004).

The intensity variation is estimated using equation (3). The typical internal Alfvén speed is about 1000 km s^{-1} (see, e.g., Verwichte et al. 2004). For *TRACE* oscillations, the typical velocity amplitude is up to 50 km s^{-1}, resulting in $\mathbb{V} = 0.05$. For typical values of the density ratio $\rho_e/\rho_i \leq 0.5$ and $a/\lambda \leq 0.2$, it can be estimated that $\mathbb{D} < 4.5\%$. However, for the discussed CoMP observations, the velocity amplitude is 100 times smaller, implying a reduction in the intensity amplitude by the same amount.

Line-of-sight integration effects could cause intensity variations (Cooper et al. 2003). The highest possible amplification factor would be 2 and can only be achieved when $\lambda \approx a$. Hence, from an observational point of view, the kink mode can be considered incompressible.

4. IMPLICATIONS OF THE PROPOSED INTERPRETATION

The arguments used by Tomczyk et al. (2007) to conclude that the detected waves are Alfvén waves (see § 1) suggest the opposite: it is unlikely that the observed waves are Alfvén waves. Alfvén waves take a torsional character in the solar corona, and cannot be detected either as Doppler shifts or as intensity variations, but solely as periodic broadening of the spectral line.

Furthermore, because of the noncollective nature of coronal Alfvén waves, different field lines and flux surfaces can oscillate with different phases and frequencies. Hence, Alfvén waves are subject to phase mixing (Heyvaerts & Priest 1983), which has two observational implications. First, they do not produce coherent observational patterns, and second, they are subject to enhanced dissipation.

On the other hand, the interpretation we put forward, fast kink waves, complies with all the observational requirements. As shown in the above sections, kink waves have a phase speed much larger than the sound speed, they propagate along the magnetic field lines, and they are transverse and nearly incompressible.

Interpreting these observations as kink waves has implications for the conclusions in Tomczyk et al. (2007). First, the magnetic fields determined by doing coronal seismology are systematically overestimated. The phase speed of kink waves, the kink speed, is up to a factor of $\sqrt{2}$ larger than the Alfvén speed. This means that the inferred magnetic fields can be 40% lower than reported. Although the uncertainties on the measurements are currently too large for this to be significant, it has to be taken into account in future data analysis.

Second, the calculation of the energy budget reported in Tomczyk et al. (2007) has to be modified. Kink waves are heavily influenced by the filling factor. In Figure 2 it is clear that the kink waves are confined to the plasma nonuniformity and show a quickly evanescent behavior outside the structure. To calculate the energy flux, it cannot be assumed that the whole volume of the corona is oscillating with the wave, because it is not plane across the magnetic field. On the contrary, only the plasma very near the structure oscillates. For kink waves, the expression for F_W (eq. [3] in Tomczyk et al. 2007) thus has to be multiplied with the filling factor as the observed waves cannot be planar. The value of the filling factor is not known, but it is likely to be a few percent. This would drastically reduce the measured energy flux with at least an order of magnitude.

As a final remark, we wish to point out that the observations in Tomczyk et al. (2007) signify an important new development in coronal wave physics. They show that waves are truly ubiquitous in the solar corona.

Note added in manuscript.—After submission, the studies by De Pontieu et al. (2007) and Okamoto et al. (2007) came to our attention, to which the work presented here is of direct relevance.

T. V. D. would like to thank STFC for the support. E. V. acknowledges support from EPSRC.

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