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SLOW MAGNETOACOUSTIC WAVES IN TWO-RIBBON FLARES

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ABSTRACT

We demonstrate that disturbances observed to propagate along the axis of the arcade in two-ribbon solar flares at the speed of a few tens of km s^{-1}, well below the Alfvén and sound speeds, can be interpreted in terms of slow magnetoacoustic waves. The waves can propagate across the magnetic field, parallel to the magnetic neutral line, because of the wave-guiding effect due to the reflection from the footpoints. The perpendicular group speed of the perturbation is found to be a fraction of the sound speed, which is consistent with observations. The highest value of the group speed grows with the increase in the ratio of the sound and Alfvén speeds. For a broad range of parameters, the highest value of the group speed corresponds to the propagation angle of 25°–28° to the magnetic field. This effect can explain the temporal and spatial structure of quasi-periodic pulsations observed in two-ribbon flares.

Key words: Sun: flares – Sun: oscillations – Sun: X-rays, gamma rays

Online-only material: color figure

1. INTRODUCTION

The understanding of three-dimensional morphology and dynamics of large, two-ribbon flares can shed light on the physical processes operating in solar energy releases. In a number of observations, the spatial separation of the ribbons does not seem to change with time, while the energy release is seen to move along the axis of the flaring arcade, parallel to the magnetic neutral line. For example, such a behavior was found in 35% of the flares observed with the Hard X-ray Telescope on *Yohkoh*, analyzed by Bogachev et al. (2005). The typical speeds are several times lower than the sound speed of the coronal plasma. Krucker et al. (2003) estimated the average speed of the motion along an arcade to be about 50 km s^{-1}. Krucker et al. (2005) measured the footpoint motion speed as 20–100 km s^{-1}. Similar analysis has been carried out by several authors with similar results. In particular, Li & Zhang (2009) investigated the propagation of brightening along the neutral lines in 124 two-ribbons X-class and M-class flares observed with *Transition Region and Coronal Explorer*, and found the typical speeds to range from 3 to 39 km s^{-1}. Likewise, Tripathi et al. (2006) considered the brightening propagation along arcades of two-ribbon flares observed with *SOHO*/EIT and found the speed to be essentially sub-sonic in the vast majority of cases. Very recently, analysis of the microwave and hard X-ray imaging information gave the speed of the brightening progression along a flaring arcade as 8 km s^{-1} (Reznikova et al. 2010).

Often, flaring energy releases are seen as sequences of quasi-periodic pulsations (QPPs; see, e.g., Nakariakov & Melnikov 2009, for a recent review). In two-ribbon flares, individual bursts often appear at different spatial locations, gradually progressing along the arcade. For example, Grigis & Benz (2005) analyzed hard X-ray data obtained with *RHESSI* and showed that the position of footpoint-like paired sources of individual bursts moved along the arcade at the speed of about 50–60 km s^{-1}. The duration of the individual bursts was about 8–30 s. Recently, Zimovets & Struminsky (2009) observed QPPs in two different two-ribbon flares, with the periods of 1–3 minutes. The hard X-ray sources progressed along the arcade at the average speeds of about 90 and 60 km s^{-1}, respectively. It was shown that each individual pulsation was emitted from footpoints of different magnetic loops of the flaring arcades. Acceleration (or injection) of the non-thermal electrons apparently occurred near the tops of those loops.

Thus, there should be a continuously moving trigger of the individual acts of energy releases, propagating along flaring arcades. A fast magnetoacoustic wave, which can propagate across the magnetic field, should be ruled out as its speed is super-sonic and super-Alfvénic (see, e.g., Vorpahl 1976, for a discussion). A slow magnetoacoustic wave has been previously excluded too, as in a uniform medium it does not propagate across the magnetic field. One possibility, explaining the progressing of the brightening along the axis of a flaring arcade, is connected with an asymmetric eruption of a prominence or a filament (e.g., Grigis & Benz 2005; Tripathi et al. 2006; Liu et al. 2010). There is some observational evidence of the correlation of the eruption speed and the speed of the progressing brightening. However, it is not clear yet whether the eruption causes the energy releases or it is the other way around. Also, some other observed features of this phenomenon, in particular, the quasi-periodic bursts, are not easily explained by this mechanism.

The aim of this Letter is to investigate an alternative mechanism, connected with the propagation of a slow magnetoacoustic wave. The presence of plasma non-uniformities is known to modify the MHD wave propagation significantly, causing wave dispersion, appearance of cutoffs, and modification of the direction of wave propagation (see, e.g., Roberts 2000; Ruderman & Erdélyi 2009, for a review). In particular, one of the cornerstones of MHD coronal seismology is the propagation of fast magnetoacoustic waves along the magnetic field, which is impossible in a uniform medium (Van Doorsselaere et al. 2008; Verwichte et al. 2009). For the slow waves in two-ribbon arcades, the wave-guiding effect is connected with the reflection of the waves from the footpoints, on the sharp gradient, in comparison with the wave length, gradients of the sound speed, and the plasma density. We demonstrate that the wave-guiding effect allows slow waves to propagate across the magnetic field, at the group speed significantly lower than both the sound and Alfvén speeds in a low-β plasma. We show that this effect can explain the observed evolution of two-ribbon flares.

2. PERPENDICULAR MAGNETOACOUSTIC WAVES IN CORONAL ARCADES

Usually, in typical coronal conditions, slow magnetoacoustic waves are considered as non-propagating across the magnetic field. Indeed, according to the dispersion relations for MHD waves in a low-β uniform plasma, slow waves propagate weakly obliquely, in a rather narrow cone along the magnetic field. However, in the presence of plasma non-uniformities slow waves can bounce between two reflecting or refracting boundaries positioned across the field, and hence move gradually in the direction perpendicular to the guiding field. A magnetic arcade, typical for two-ribbon flares, can act as such a wave guide. A slow magnetoacoustic perturbation excited by an energy release somewhere at the top of the arcade propagates toward the arcade footpoints. There it experiences reflection on the sharp gradient of the sound speed and climbs up the arcade. This is accompanied by a slow motion along the arcade axis, across the field.

Consider a magnetic arcade as a box with the straight and uniform magnetic field B_0 in the x-direction, aligned perpendicularly to the axis of the arcade, which is directed along the z-axis (see Figure 1). The field lines begin at one ribbon and end at the other, which correspond in our model to the lines $x = \pm L/2$, where L is the length of the field lines. The dependence on the third coordinate is ignored. Taking the equilibrium plasma density ρ_0 and the plasma temperature to be constant everywhere, we obtain the characteristic MHD speeds, the sound speed C_s, and the Alfvén speed C_A to be constant too. The plasma β is less than unity, $C_s < C_A$.

Considering linear MHD perturbations of the equilibrium, we obtain the magnetoacoustic wave equation,

$$\left\{\left(\frac{\partial^2}{\partial t^2} - C_s^2\frac{\partial^2}{\partial x^2}\right)\left[\frac{\partial^2}{\partial t^2} - C_A^2\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}\right)\right] - C_s^2\frac{\partial^4}{\partial t^2 \partial z^2}\right\} \times V_z = 0, \quad (1)$$

where V_z is the plasma flow in the z-direction along the axis of the arcade. The wave equation is of the fourth order, and describes both fast and slow magnetoacoustic waves propagating in the positive and negative directions. Assuming the harmonic dependence upon time and the spatial coordinates, $\propto \exp(i\omega t - ik_x x - ik_z z)$, we readily obtain the standard dispersion relation for the magnetoacoustic waves,

$$\omega^2 = \frac{1}{2}\Big[\left(C_A^2 + C_s^2\right)\left(k_x^2 + k_z^2\right) \pm \sqrt{\left(C_A^2 + C_s^2\right)^2\left(k_x^2 + k_z^2\right)^2 - 4C_s^2 C_A^2 k_x^2\left(k_x^2 + k_z^2\right)}\Big], \quad (2)$$

where the positive and negative signs correspond to the fast and slow waves, respectively (e.g., Goedbloed & Poedts 2004). Applying the rigid-wall ($V_z = 0$) boundary conditions at the footpoints, we determine the wave number k_x. In particular, for the second spatial harmonic mode it is $k_x = 2\pi/L$. This parameter is the characteristic spatial scale of the problem, responsible for the wave dispersion. Such a model is a two-dimensional generalization of the standard model used in theoretical studies of slow magnetoacoustic oscillations in coronal loops and arcades (see, e.g., Tsiklauri et al. 2004; Selwa et al. 2005). Results of this approach have been found to be qualitatively consistent with the two-dimensional results of Selwa et al. (2007), who studied the effect of vertical structuring on slow magnetoacoustic waves.

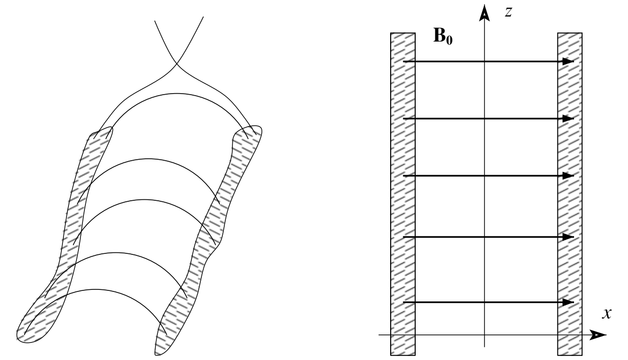

Figure 1. Magnetic arcade of a two-ribbon flare (on the left) and its model (on the right). The thick lines show the magnetic field lines. The hatched regions show the flare ribbons.

Figure 2 shows a typical dispersion plane for the magnetoacoustic waves propagating along an arcade. The frequency of a fast wave has a typical hyperbolic dependence upon the wave number. For slow waves, this dependence is more peculiar: the frequency decreases with the growth of the perpendicular wave number k_z. From those dependences it is obvious that the perpendicular phase speeds ω/k_z of both guided waves, fast and slow, tend to infinity in the limit $k_z \to 0$. The phase speeds gradually decrease with the growth in k_z to the fast speed $\sqrt{C_A^2 + C_s^2}$ and zero, for the fast and slow modes, respectively.

The perpendicular group speed $d\omega/dk_z$ of the fast wave grows from zero at $k_z = 0$ to the fast speed in the limit $k_z \to \infty$. Thus, in principle, the fast wave group speed can be much slower than the Alfvén speed. However, this occurs for the perpendicular wave lengths much larger than the parallel wavelength $2\pi/k_z$.

The behavior of the perpendicular group speed of the slow wave is more peculiar (see the right panel of Figure 2). First of all, its sign is opposite to the sign of the perpendicular phase speed. In both $k_z = 0$ and $k_z \to \infty$ limits it goes to zero. Its absolute value reaches the maximum somewhere in the vicinity of $k_z \approx k_x$. This maximum value is well below the sound speed in the arcade, and depends upon the ratio of the sound and Alfvén speeds (see Figure 3). For a broad range of the ratios, the maximum value of the perpendicular group speed is reached for the perpendicular wave numbers $k_z \approx (0.3–0.5)k_x$. This corresponds to the propagation angle of about 25°–28° to the magnetic field. This value is consistent with the observed geometry of two-ribbon flare arcades. Their spatial extent along the magnetic neutral line is typically comparable or larger than the length of the loops, which form the arcade (see, e.g., images of the flaring arcades in Grigis & Benz 2005; Zimovets & Struminsky 2009). Hence, the propagation angle of 25°–28° to the field allows slow waves to make several bounces, progressing along the arcade axis. In the majority of cases, QPPs are indeed present in flaring light curves as short wave trains of a few pulses only (e.g., Nakariakov & Melnikov 2009, and references therein).

3. IMPLICATIONS FOR QUASI-PERIODIC PULSATIONS IN FLARES

According to the right panel of Figure 2, the perpendicular group speed has a rather sharp maximum in the vicinity of

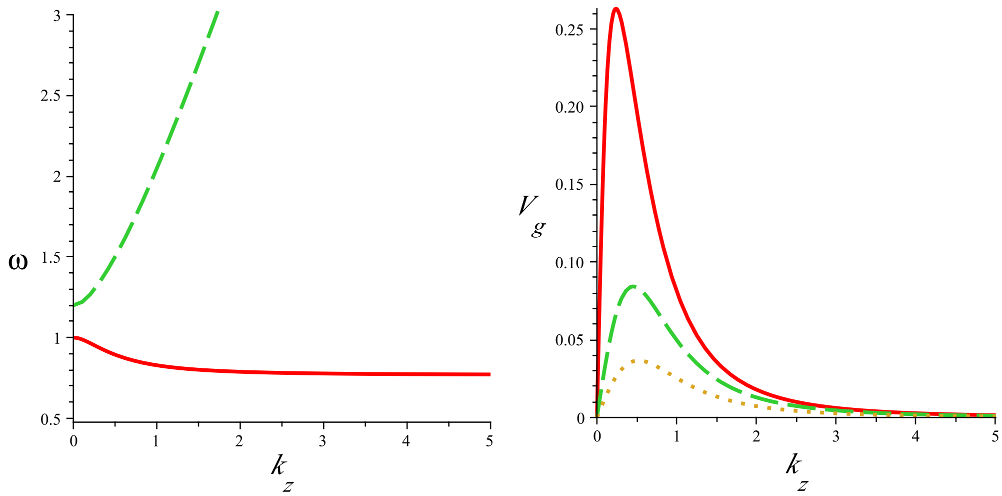

Figure 2. Left panel: the dispersion plot of magnetoacoustic waves propagating along the axis of a magnetic arcade, across the field, in the case $C_A = 1.2C_s$. The dashed (green) line shows the fast waves; the solid (red) line shows the slow wave. The frequency is measured in $C_s k_x$ and the perpendicular wave number in k_x. Right panel: dependences of the absolute value of the perpendicular group speeds of slow magnetoacoustic speed upon the perpendicular wave number: the solid (red) line corresponds to $C_A = 1.2C_s$, the dashed (green) line to $C_A = 2C_s$, and the dotted (brown) line to $C_A = 3C_s$. The group speeds are measured in the units of the sound speed C_s.

(A color version of this figure is available in the online journal.)

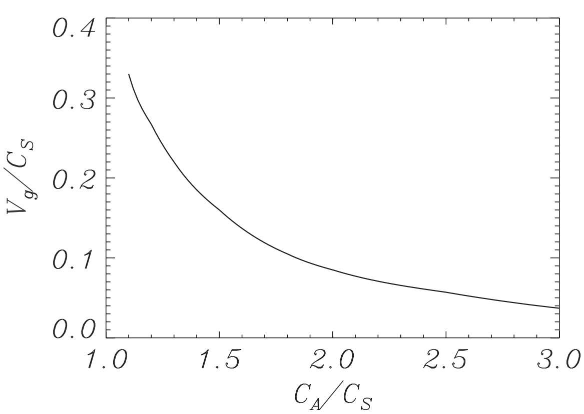

Figure 3. Dependence of the maximum value of the perpendicular groups speed of a slow magnetoacoustic wave guided by a magnetic arcade, on the ratio of the Alfvén and sound speeds.

the propagation angle to the magnetic field of about 25°–28°. Hence, the corresponding angular spectral components, excited by an elementary burst at the top of an arcade, are the fastest to propagate down the footpoints, get reflected and reach the top of the arcade again. There they can trigger another elementary burst by several different mechanisms, reinforcing the slow wave and hence compensating the dissipative and scattering losses. The period of the generated QPP is then determined by the speed of the triggering slow magnetoacoustic wave and the travel path. Hence, it is similar to the period of the second harmonics of the longitudinal mode of a coronal loop, estimated in the range 10–300 s (Nakariakov et al. 2004).

Slow magnetoacoustic waves can trigger magnetic reconnection directly, by the variation of plasma density in the vicinity of the potential site of magnetic reconnection (Chen & Priest 2006). The density variation results into a variation of the electron drift speed. Depending upon the ratio of electron and proton temperatures, the value of the speed controls the onset of the Buneman or ion-acoustic instabilities and hence anomalous resistivity. Observational evidence of the ability of slow waves to trigger flaring energy releases has recently been found in the analysis of microwave and EUV data (Sych et al. 2009).

Also, in the vicinity of magnetic X-points, slow magnetoacoustic waves can be linearly coupled with fast waves, which in turn generate sharp spikes of the electric current density (McLaughlin & Hood 2004). The plasma in the spikes is subject to rapidly developing micro-instabilities, causing the onset of micro-turbulence. The enhanced resistivity caused by the turbulence triggers magnetic reconnection and hence the energy release (Foullon et al. 2005; Nakariakov et al. 2006).

Moreover, the discussed scenario can easily explain another frequently observed feature of flaring QPP, the presence of double maxima in the elementary bursts (e.g., Tajima et al. 1987; Zimovets & Struminsky 2009). This can occur due to some asymmetry in the positioning of the wave source or in the arcade. In this case, the slow pulses, reflected from the opposite footpoint ribbons, arrive at the arcade top and trigger the next elementary bursts at slightly different times and at slightly different locations.

4. DISCUSSION AND CONCLUSIONS

We demonstrated that slow magnetoacoustic waves can propagate along the axis of a coronal magnetic arcade, along the neutral line, in the direction perpendicular to the magnetic field. The group speed is a fraction of the sound speed in the plasma that is considered to have low β. The effect is connected with the ability of slow magnetoacoustic waves to propagate at some small angle to the magnetic field, and with the reflection of the waves from the footpoints of the magnetic field lines forming the arcade. The ratio of the perpendicular group speed to the sound speed grows with the increase in the ratio of the sound speed to the Alfvén speed. For example, for $C_A/C_s = 2$, the maximum value of the perpendicular group speed is about 10% of the sound speed. In a hot and dense plasma of a flaring arcade, with the temperature of 10^7 K and the Alfvén speed of about $1000\,\mathrm{km\,s^{-1}}$, the perpendicular group speed of the slow waves is about $40\,\mathrm{km\,s^{-1}}$. This value is well consistent with the observations of the brightening progressing along the neutral line in two-ribbon flares. For smaller values of the Alfvén speed, the perpendicular group speed is higher, but always remains sub-sonic.

This result does not change qualitatively in the presence of a magnetic shear, i.e., when the magnetic field is not perpendicular to the neutral line. As, locally, slow magnetoacoustic waves propagate with a small oblique angle to the magnetic field, after the reflection from the footpoints they come back to the top of the arcade at almost the same distance from the initial position in both cases, with and without the shear. In the case with the shear, the travel path of the slow wave is slightly longer, by factor equal to the reciprocal of the shear angle cosine.

The highest value of the perpendicular group speed corresponds to the propagation angle of about 25°–28° to the magnetic field. This may explain the observed spatial and temporal structures of flaring QPP: the next elementary act of the energy release can be triggered at the locations where the oblique slow waves, generated by the previous burst, return to the top of the arcade. The period of the generated QPP is then determined by their travel times.

Previous observational and theoretical studies demonstrated that coronal slow magnetoacoustic waves are subject to strong damping (see, e.g., Wang et al. 2003; Tsiklauri et al. 2004; Selwa et al. 2005, 2007). However, the typical damping time is usually longer than one period of the oscillation; hence, the waves are able to complete one bounce from the footpoints and reach the top of the arcade. There the waves can trigger another elementary burst, which will excite another slow magnetoacoustic pulse, repeating the cycle.

One important question to this scenario is why the same effect is not caused by the fast waves. It may be explained by the different efficiency of the excitation of fast and slow waves. Indeed, if in a low-β plasma a compressible perturbation is excited by a localized perturbation of the plasma temperature, the main energy goes into the almost field-aligned slow wave, as the displacement of the magnetic field lines by the total pressure gradient is rather small. Also, fast waves are subject to refraction, and hence are not necessarily channeled along the arcade.

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REFERENCES

Bogachev, S. A., Somov, B. V., Kosugi, T., & Sakao, T. 2005, ApJ, 630, 561
Chen, P. F., & Priest, E. R. 2006, Sol. Phys., 238, 313
Foullon, C., Verwichte, E., Nakariakov, V. M., & Fletcher, L. 2005, A&A, 440, L59
Goedbloed, J. P. H., & Poedts, S. (ed.) 2004, Principles of Magnetohydrodynamics (Cambridge: Cambridge Univ. Press)
Grigis, P. C., & Benz, A. O. 2005, ApJ, 625, L143
Krucker, S., Fivian, M. D., & Lin, R. P. 2005, Adv. Space Res., 35, 1707
Krucker, S., Hurford, G. J., & Lin, R. P. 2003, ApJ, 595, L103
Li, L., & Zhang, J. 2009, ApJ, 690, 347
Liu, C., Lee, J., Jing, J., Liu, R., Deng, N., & Wang, H. 2010, ApJ, 721, L193
McLaughlin, J. A., & Hood, A. W. 2004, A&A, 420, 1129
Nakariakov, V. M., Foullon, C., Verwichte, E., & Young, N. P. 2006, A&A, 452, 343
Nakariakov, V. M., & Melnikov, V. F. 2009, Space Sci. Rev., 149, 119
Nakariakov, V. M., Tsiklauri, D., Kelly, A., Arber, T. D., & Aschwanden, M. J. 2004, A&A, 414, L25
Reznikova, V. E., Melnikov, V. F., Ji, H., & Shibasaki, K. 2010, ApJ, 724, 171
Roberts, B. 2000, Sol. Phys., 193, 139
Ruderman, M. S., & Erdélyi, R. 2009, Space Sci. Rev., 149, 199
Selwa, M., Murawski, K., & Solanki, S. K. 2005, A&A, 436, 701
Selwa, M., Ofman, L., & Murawski, K. 2007, ApJ, 668, L83
Sych, R., Nakariakov, V. M., Karlicky, M., & Anfinogentov, S. 2009, A&A, 505, 791
Tajima, T., Sakai, J., Nakajima, H., Kosugi, T., Brunel, F., & Kundu, M. R. 1987, ApJ, 321, 1031
Tripathi, D., Isobe, H., & Mason, H. E. 2006, A&A, 453, 1111
Tsiklauri, D., Nakariakov, V. M., Arber, T. D., & Aschwanden, M. J. 2004, A&A, 422, 351
Van Doorsselaere, T., Brady, C. S., Verwichte, E., & Nakariakov, V. M. 2008, A&A, 491, L9
Verwichte, E., Foullon, C., Van Doorsselaere, T., Smith, H. M., & Nakariakov, V. M. 2009, Plasma Phys. Control. Fusion, 51, 124019
Vorpahl, J. A. 1976, ApJ, 205, 868
Wang, T. J., Solanki, S. K., Curdt, W., Innes, D. E., Dammasch, I. E., & Kliem, B. 2003, A&A, 406, 1105
Zimovets, I. V., & Struminsky, A. B. 2009, Sol. Phys., 258, 69