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Liping Yang
Peking University

Lei Zhang
Chinese Academy of Sciences

Linghua Wang
Peking University

Xueshang Feng
National Space Science

Excitation Of Magnetohydrodynamic Waves By Plasmoids Ejection In The Solar Corona

Liping Yang[1,2,a)], Lei Zhang[2], Jiansen He[2], Hardi Peter[3], Chuanyi Tu[2], Linghua Wang[2] and Xueshang Feng[1]

[1]*SIGMA Weather Group, State Key Laboratory for Space Weather, National Space Science Center, Chinese Academy of Sciences, 100190 Beijing, China.*
[2]*School of Earth and Space Sciences, Peking University, 100871 Beijing, China.*
[3]*Max-Planck-Institut für Aeronomie, Max-Planck-Strasse, 37191 Katlenburg-Lindau, Germany.*

[a)]Corresponding author: lpyang@spaceweather.ac.cn

Abstract. In this study, we numerically investigate the excitation of MHD waves in the interchange reconnection scenario in the solar corona. The modeling results show that as a result of tearing instability, the magnetic reconnection occurs, accompanying the creation of plasmoids. The created plasmoids are quickly shot, and strongly collide with the magnetic field in the outflow regions, which consecutively triggers the perturbations of velocity component V_x, V_y, and V_z. The perturbations of V_y satisfy the polarity relations of slow-mode wave, and their propagating speed approaches the sonic speed in the model, while the perturbations of V_z satisfy the polarity relations of Alfvén wave, and their propagating speed is about the Alfvén speed, thus verifying that they are slow-mode waves and Alfvén waves, respectively. These simulation results indicate that not only fast-mode wave but also slow-mode wave and Alfvén wave can be simultaneously excited by plasmoid ejections and releases.

INTRODUCTION

In the last decade, the observations from polarimetric, spectroscopic, and imaging instruments are revealing that the solar atmosphere is permeated with various modes of magnetohydrodynamic (MHD) waves, such as slow-mode waves, Alfvén waves, and fast-mode waves. These MHD waves are thought to play an important role in the solar atmospheres energy budge.

By analysis of EUV Imaging Telescope images from the Solar and Heliospheric Observatory spacecraft, DeForest and Gurman [1] reported the coherent quasi-periodic perturbations in the plume. These perturbations are considered to be compressive waves like sound waves or slow-mode magnetosonic waves. De Moortel, Ireland, and Walsh [2] used TRACE observations to conduct a wavelet analysis of motion at a bright loop-footpoint, and found outward propagating perturbations, suggested as slow-mode waves. From observations of the Hinode/SOT, De Pontieu *et al.* [3] reported transversal displacements of spicules. They interpreted these sway as a result of upward propagating Alfvén waves. With observations of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) satellite, McIntosh *et al.* [4] reported the ubiquitous outward-propagating Alfvénic motions. Using AIA EUV observations, Liu *et al.* [5] found that the fast-mode waves are driven quasi-periodically at the base of the flaring region and propagate outward along open funnels with a phase speed of up to $\sim$ 2200 km s^{-1}.

Meanwhile great theoretical modeling efforts have been devoted to understand the physics of MHD waves in the solar magneto-atmospheres. By conducting the first nonlinear, two-dimensional (2D), MHD simulation of the magnetosonic waves in plumes, Ofman, Nakariakov, and DeForest [6] found that outward-propagating slow magnetosonic waves are trapped, and nonlinearly steepen in the polar plumes. To investigate slow and fast wave propagation, transformation and interaction in the solar atmosphere, Bogdan *et al.* [7] presented isothermal MHD simulations. According to the observation results presented by Liu *et al.* [5], Ofman *et al.* [8] performed a 3D numerical simulation to study the fast-mode wave generation, propagation, and trapping. Khomenko and Cally [9] studied the conversion of fast magnetoacoustic waves to Alfvén waves by means of 2.5D numerical simulations in a sunspot-like magnetic configuration.

Provoked by fast-mode wave observations, Yang *et al.* [10] have simulated the interchange flare scenario, and found that the plasmoid ejections and releases could arose the fast-mode waves. Here, we will continue this study and demonstrate that not only fast-mode wave but also slow-mode wave and Alfvén wave are simultaneously excited.

NUMERICAL MHD MODEL

The details of the 2.5 dimensional (2.5D) numerical MHD model used here have been described in [11, 12, 10]. This section only gives the basic features and specifies parameters for this study. The solved equations are the resistive MHD equations in the Cartesian coordinates (x, y, z) with y axis directed vertically.

The simulation region spans 0 Mm $\leq x \leq$ 80 Mm in the horizontal dimension and 0 Mm $\leq y \leq$ 75 Mm in the vertical dimension. Initially, the domain is resolved with a nonuniform grid both in the x and y dimensions, with the grid spacing being $\delta x = \delta y =$ 25 km for 0 Mm $\leq y \leq$ 4 Mm, $\delta x = \delta y =$ 50 km for 4 Mm $\leq y \leq$ 6 Mm, and $\delta x = \delta y =$ 100 km for $y \geq$ 6 Mm. During the computation, AMR is executed the finest grid cells are set in the region with the strongest current density, with $\delta x = \delta y =$ 12.5 km. To solve the equations we use a splitting-based finite-volume scheme with the fluid part solved by the second-order Godunov-type central scheme and the magnetic part by the constrained transport approach [13].

For the initial conditions, the plasma is in hydrostatic equilibrium with temperature ranging from 2×10^4 K to 1×10^6 K. The initial magnetic field is constructed via the vector potential for a uniform background field and an infinite series of line dipoles. For the boundary conditions, we use the same form as defined by [10].

NUMERICAL RESULTS

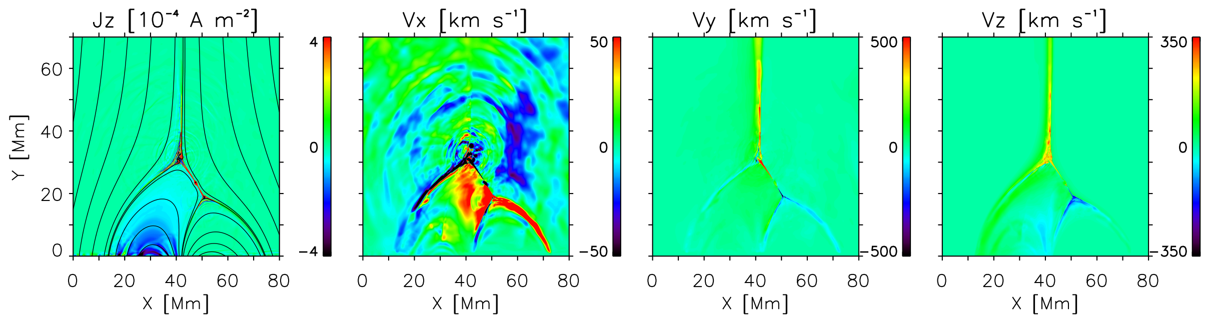

FIGURE 1. Calculated distributions of current density J_z, velocity component V_x, velocity component V_y, and velocity component V_z at t = 7.13 minutes, where streamlines show the magnetic field lines.

Figure 1 shows that the shearing of the loop causes its field lines to advance towards the initial null point, and current sheet along it develops. As a result, the magnetic reconnection with the creation of plasmoids due to tearing instability takes place. Then, the initially closed sheared-loop opens, and the initially open field is tied to the bottom. Meanwhile, the plasma in the current sheet is heated up to ~ 10 MK, and is ejected to develop a pair of hot outflows.

Accompanying the driven outflows, wave-like features are visible. In the distribution of V_x, the multiple arc-shaped wave trains, propagating across the magnetic fields, are launched from the reconnection region. These wave trains are identified as fast-mode MHD waves [10]. The distribution of both V_y and V_z show that the waves, propagating along the magnetic fields, also emanate from the reconnection site.

To see what patterns the waves propagating along the magnetic fields are, Figure 2 shows temporal evolution of the perturbed quantities on the path of the waves. At this point, the launched waves in the distribution of both V_y and V_z propagate in the upright direction, while the magnetic field also aligns to this direction. Under this situation, polarity relations of slow-mode MHD waves predicts dV_y and dN are in positive correlation, and they are correlated as $dV_y/Cs = dN/N_0$, where Cs and N_0 are sonic speed and background number density, respectively. Polarity relations of Alfvén waves predicts dV_z and dB_z are in negative correlation, and they are correlated as $dV_z = -dB_z/\sqrt{\mu\rho}$, where ρ is density. These features are clearly presented in Figure 2, and thus the perturbations in the distribution of V_y and V_z satisfy the polarity relations of slow-mode and Alfvén waves, respectively.

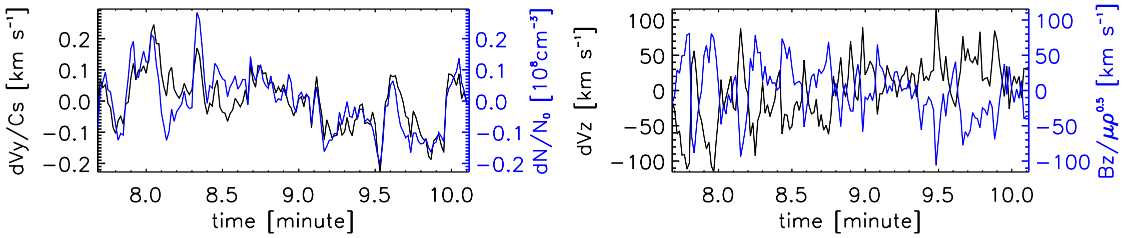

FIGURE 2. Temporal evolution of the perturbed velocity component dV_y/Cs (black line), density dN/N_0 (blue line), the perturbed velocity component dV_z (black line), and the perturbed magnetic field $B_z/\sqrt{\mu\rho}$ (blue line) at the point (x = 45 Mm, y = 45 Mm) on the path of the waves.

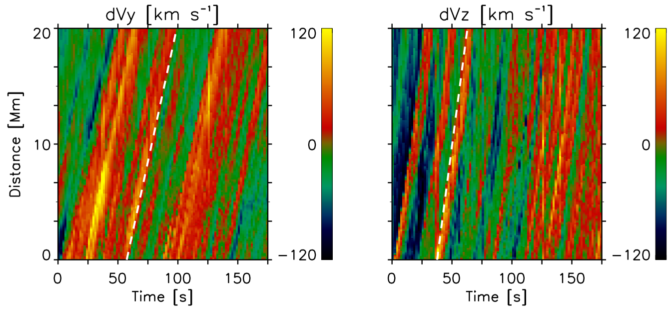

FIGURE 3. Time-distance diagrams of the perturbed velocity component dV_y, and the perturbed velocity component dV_z. The spatial direction is along the direction of wave propagation, and the white dashed line indicate the wave propagation speeds.

Figure 3 shows the steep, recurrent stripes resulting from the perturbation fronts. The slopes of these stripes correspond to the propagating speeds of the waves. By linearfitting with the wave fronts, we estimate the slope of each stripe. It is found that the average propagating speed of the wave trains in the distribution of V_y is about 430 km s^{-1}, which is the sonic speed in the model, and that in the distribution of V_z is about 800 km s^{-1}, which is the Alfvén speed in the model. Thus, it is verified that these wave trains in the distribution of V_y and in the distribution of V_z , emanated from the reconnection site, are indeed slow-mode and Alfvén waves, respectively.

To illustrate how the simulated slow-mode and Alfvén waves are driven, Figure 4 presents the distributions of component V_y and velocity component V_z, which displays that the collision between the ejected plasmoids and the field in the outflow region yields the slow-mode and Alfvén wave trains. At t = 6.20 minutes, one plasmoid appears in the current sheet, and move quickly upwards along the current sheet. At t = 6.35 minutes, it collides and reconnects with the magnetic fields existing in the outflow region, rapidly releasing its plasma with high thermal pressure. Meanwhile, velocity perturbations in V_y and V_z, appear in the outflow region. At t = 6.50 minutes, the velocity perturbations in V_y and V_z travel upwards along the magnetic field, and after the plasmoids coalesce into the outflow region, the waves disappear. When other plasmoids come into the outflow region, this processes will be repeated.

SUMMARY AND DISCUSSION

In this study, we performed a numerical investigation of the excitation of MHD waves in the interchange reconnection in solar corona. The footpoint-shearing flow is used here to energize the system and drive the reconnection. We find that plasmoid ejections and releases simultaneously initiate not only fast-mode wave but also slow-mode wave and Alfvén wave.

The modeling results show that as a result of the shearing of the loop, the null-point current sheet forms and magnetic reconnection between sheared-loop field lines and open funnel lines takes place. Due to tearing instability, the plasmoids are created, and are injected quickly. As a result of the collision between the impacting plasmoids and the fields in the outflow region, the perturbations are consecutively and alternately launched from the outflow region, quickly propagating outward. The perturbations seen in the distribution of the velocity component V_y satisfy the polarity relations of slow-mode wave, and their propagating speed is about the sonic speed in the model. Therefore, these

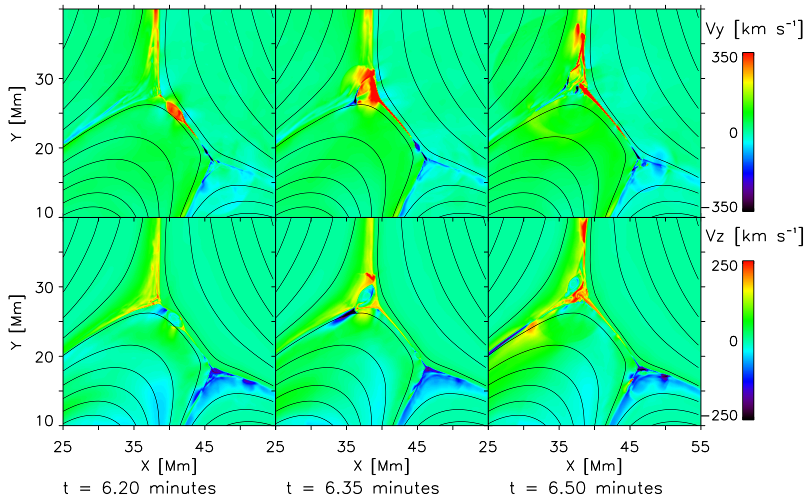

FIGURE 4. Distributions of velocity component V_y and velocity component V_z at $t = 6.20, 6.35$, and 6.50 minutes, respectively, zoomed into the area around the reconnection region. The white lines show magnetic field lines.

perturbations are slow-mode wave. Nevertheless, the perturbations seen in the distribution of the velocity component V_z satisfy the polarity relations of Alfvén wave, and their propagating speed is about the Alfvén speed in the model, thus verifying that they are Alfvén waves.

In this study, we note that this work is restricted into a 2.5D simulation. Although it gives a clear illustration of the processes at work, a loss of one degree of freedom may affect the energetics of the system and especially the excitation of the waves. In future, we may extend this work to a fully 3D simulation to see whether these waves are launched from the reconnection or not.

ACKNOWLEDGMENTS

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