A UNIFIED MODEL OF CME-RELATED TYPE II RADIO BURSTS

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We present a theoretical model for the shock formation related to coronal and interplanetary type II radio bursts associated with coronal mass ejections (CMEs) on the basis of the magnetic reconnection model of eruptive solar flares. Coronal type II bursts are usually observed in metric wavelength range (metric type II bursts) and interplanetary type II bursts are in decametric-hectometric wavelength range (decametric-hectometric type II bursts). Our researches show that the decametric-hectometric type II radio bursts are produced by the piston-driven fast-mode MHD shock formed in front of an eruptive plasmoid (a magnetic island in 2-dimensional sense or a magnetic flux rope in 3-dimensional sense), while the metric radio bursts are by the reverse fast-mode MHD shock formed through the collision of a strong reconnection jet to the bottom of the plasmoid. This reverse shock moves apparently upward as long as the reconnection jet is sufficiently strong, and dies away when the energy release by the reconnection stops or weakens significantly. On the other hand, the piston-driven fast shock continues to travel upward. Our model succeeds in explaining such observational results that the piston-driven fast shock producing decametric-hectometric type II bursts moves faster and survives longer than the other shock.

Subject headings: MHD – Sun: corona – Sun: radio radiation – Sun: magnetic fields
1. INTRODUCTION

CMEs are one of the most prominent phenomena observed in the solar atmosphere. The spatial size of these events is very large and their influence on the interplanetary space is very strong. For example, when a big CME occurs on the sun a lump of plasmoid sometimes travels toward the earth at several hundred kilometers per second to cause a severe magnetostorm.

CMEs are characterized not only by their largeness in size but also by the number of phenomena associated with CMEs. In fact, many solar phenomena are believed to have a direct or indirect relationship to CMEs, such as solar flares, prominence eruptions, helmet streamers, high-speed solar winds, coronal and interplanetary traveling shock waves, and so on. These CME-related phenomena can be observed in various kinds of electromagnetic waves so that detailed studies have so far been done on this subject by many researchers (Gosling et al. 1976; Low, Munro, & Fisher 1982; Kahler et al. 1985; Priest 1988; Steele & Priest 1989; Forbes 1990; Gopalswamy & Kundu 1992; Feynman & Hundhausen 1994; Feynman & Martin 1995; Low 1996; Rust & Kumar 1996; Gibson & Low 1998; Hundhausen 1999; Klassen et al. 2000).

The CME-related phenomena we discuss here is coronal and interplanetary traveling shock waves. Observationally, these two kinds of shocks are recognized as coronal and interplanetary type II radio bursts, because these shocks accelerate plasma particles to emit radiowaves whose frequency is above the plasma frequency. The plasma frequency is proportional to a square root of the gas density...
so that the coronal type II bursts are observed in high frequency (small wavelength) compared to the interplanetary bursts. So far, it is well established by analyzing kilometric type II radio sources that the interplanetary shock is formed in front of a traveling plasmoid through its piston-driven effect. However, the formation process of the coronal shock which produces type II radio bursts in metric wavelength range has not been fully understood yet. One idea is that this shock is also produced by a plasmoid traveling in the corona through the same piston-driven effect as in the interplanetary space (Cliver et al. 1999) and another is that it is not produced by a plasmoid but a solar flare associated with the CME (Reiner et al. 2000).

Recently, Reiner et al. (2000) provided an interesting result on these CME-related shocks, which clearly shows two evolutionary lines of coronal and interplanetary type II radio bursts by using data from the Wind spacecraft and the Culgoora radio spectrograph. One of these evolutionary lines implies that a long-lasting emission source travels in the interplanetary space at high speed (1000 km s\(^{-1}\)). This evolutionary line is well coincident with that of the leading edge of a white-light CME observed simultaneously from the Solar and Heliospheric Observatory (SOHO)/Large-Angle and Spectrometric Coronagraph (LASCO). On the other hand, the second evolutionary line implies that there is another source traveling in the corona at lower speed than the other one (400 km s\(^{-1}\)).

Prompted by their results, we, in this paper, try to provide a theoretical
explanation for the properties of two kinds of shocks, one of which moves in the interplanetary space at high speed, emitting long-lasting decametric-hectometric type II radio bursts and the other moves slowly in the corona, emitting short-lived metric type II radio bursts. We performed 2-dimensional MHD numerical simulations based on the reconnection model of eruptive solar flares, called CSHKP (Carmichael-Sturrock-Hirayama-Kopp-Pneuman) model (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), to investigate the eruptive process of plasmoid with a special attention paid to the shock formation. The aim of this paper is to unify the formation processes of two kinds of shocks in the CME evolution.

The next section gives the description of our model. Our results and discussion are presented in § 3 and 4, respectively.

2. MODEL

The basic equations are 2-dimensional nonlinear, time-dependent, resistive, and compressive MHD equations, which are solved by the multistep implicit scheme (Hu 1989). The details of this method can be found in Chen et al. (1999).

The initial condition of the simulation is almost in equilibrium, similar to that in Chen & Shibata (in preparation). The configuration of magnetic field is that a magnetic island centered at \((x, y) = (0, h_0) = (0, 2)\) overlies three magnetic arcades (see the left panel in Figure 1). Here \(x\) and \(y\) define the
horizontal and vertical coordinates, respectively. The flux function of magnetic field is given by

\[ \psi = \begin{cases} \frac{B_0 r_0}{2} \left( \frac{x}{r_0} \right)^2 + f(x, y) & r \leq r_0 \\ \frac{B_0 r_0}{2} \left[ \ln \left( \frac{r}{r_0} \right)^2 + 1 \right] + f(x, y) & r > r_0 \end{cases} \]

where \( r \equiv [x^2 + (y - h_0)^2]^{1/2} \) and

\[ f(x, y) = \psi_0 \ln \left\{ \frac{\left[ (x + x_1)^2 + (y + y_1)^2 \right] \left[ (x - x_1)^2 + (y + y_1)^2 \right]}{\left[ (x + x_2)^2 + (y + y_1)^2 \right] \left[ (x - x_2)^2 + (y + y_1)^2 \right]} \right\} \]

\[ - \frac{B_0 r_0}{2} \ln \left[ x^2 + (y + h_0)^2 \right] \]

In the present simulation, we adopt \( B_0 = 1, \psi_0 = 3.44, r_0 = 0.5, x_1 = 0.2, x_2 = 0.05, \) and \( y_1 = 0.05 \) so that we make the center of magnetic island keep stable for a sufficiently long time. A uniform current density is distributed in a circular region with \( r \leq r_0 \). As to the gas density, we enhance it inside the magnetic island in order to model a dense filament material. Accordingly, the density at the center of the magnetic island is about 70 times larger than outside it, that is, \( \rho = 1 + 2 / \beta (1 - 4 r^2) \) for \( r \leq r_0 \), and 1 for \( r > r_0 \), where \( \rho \) is the dimensionless density and \( \beta = 0.03 \) is the plasma beta. In addition, the temperature is uniformly distributed (dimensionless temperature \( T = 1 \)) and the specific heat ratio \( \gamma \) is set.
to be $5/3$. The units of length, velocity, and time are $L_0 = 2 \times 10^4$ km, $v_A = 1050$ km s$^{-1}$, and $t_0 = L_0/v_A \sim 20$ s, where $v_A$ is the Alfvén velocity measured just at the boundary of the magnetic island (at $r = r_0$). We also adopt typical coronal values as units of temperature and density, namely, $T_0 = 10^6$ K and $n_0 = 10^9$ cm$^{-3}$.

The initial perturbation is made by adding an artificial force near the center of the magnetic island, that is, $F/\rho = -0.2 \exp(-\psi) \text{sgn}(v_c - 0.14 v_A)$, where $F$ is a dimensionless volume force, ‘sgn’ is the sign function, and $v_c$ is the dimensionless velocity of the center of the magnetic island. In this simulation, this volume force makes the magnetic island start rising and keep its velocity around $0.14 v_A$, 150 km s$^{-1}$, after it is accelerated to this value. The resistivity $\eta = 0.02 \cos(6x) \cos[6(y - h_x)]$ is imposed in a local area of $|x| \leq 0.26$ and $|y - h_x| \leq 0.26$, where $\eta$ is the dimensionless resistivity and $h_x$ traces the location of a X-point below the magnetic island while it is rising.

The simulation is performed within the region of $0 \leq x \leq 8$, $0 \leq y \leq 16$ under the assumption of a symmetry with respect to the $y$-axis. We have $61 \times 181$ grids, which are distributed uniformly in the $y$-axis and nonuniformly in the $x$-axis, similar to Chen et al. (1999). The top ($y = 16$) and side ($x = 8$) boundaries are both free and the bottom boundary ($y = 0$) is a rigid boundary with line-tying effect.

3. RESULTS
Figure 1 shows the eruption of a magnetic island which is initially accelerated by a upward force. Although this force is an artificial force in this simulation, several studies so far suggests that a magnetic island rises under a net upward force in some environments (Forbes 1990; Chen, 1996; Wu, Guo, & Dryer, 1996; Gibson & Low 1998). After the magnetic island rises, it stretches magnetic field lines and a current sheet forms below the magnetic island. Those gases around this sheet flow toward a X-point in the sheet, causing the fast magnetic reconnection there because the resistivity is locally enhanced around this point (Magara & Shibata 1999). The resultant reconnection jets, one of which flows upward to collide the bottom of the magnetic island and the other flows downward to collide the top of a magnetic arcade, produce fast-mode MHD shocks in both cases (see the right panel in Fig. 1). Moreover, we also have a piston-driven fast shock in front of the ejecting magnetic island. All of these shocks can be seen clearly in Figure 2 indicating how the vertical component of fluid velocity is distributed along the y-axis at \( t = 30 \) and 50.

Those fast shocks formed at the bottom and in front of the magnetic island move upward. Strictly speaking, the front shock is a forward shock, while the bottom shock is a reverse shock traveling downward, although the upward reconnection jet is so fast that the wavefront of this shock moves apparently upward. Figure 3 displays the time variations of the heights of these two kinds of fast shocks as well as the center of the magnetic island. From this figure, we find that the front shock moves upward at high speed \( (0.2 v_A) \) and the bottom
shock rises rather slowly ($0.09 \nu_\lambda$), so that the interval between these two shocks becomes large with time.

4. DISCUSSION

Let us now introduce the main result of Reiner et al. (2000) about traveling radio sources. Figure 4 reproduces their original height-time data in a simplified manner to show readers the essence of their result. This figure has three kinds of height-time data, that is, the white-light CME data, longer wavelength radio data (from decametric to hectometric range), and shorter ones (metric range). Firstly, we would like to focus attention on decametric-hectometric radio data. The height-time relation of them is fairly coincident with that of the leading edge of white-light CME data, which supports the well established idea that decametric-hectometric type II bursts originate from the piston-driven fast shock formed in front of an eruptive plasmoid, where the shock enhances the gas density so that it appears bright in white light. In addition, the radio source of decametric-hectometric type II bursts travels from the upper corona to the interplanetary space. These features are basically confirmed in our model. Figure 1 shows that a piston-driven fast shock is formed in front of an ejecting magnetic island and Figure 2 shows that this shock is traveling outwards. We then discuss metric type II bursts, the generator of which is unclear as opposed to decametric-hectometric type II bursts. Figure 4 gives us two important properties of metric type II bursts. One is that the source of metric type II bursts appears earlier and
occupies lower positions until its disappearance than the source of decametric-hectometric type II bursts. The other is that the source of metric type II bursts travels in the corona more slowly than the source of decametric-hectometric type II bursts and disappears in a short time. Our model can explain these two properties in the following way. The simultaneous existence of two radio sources at different positions means that they have distinct spatial origins in their formations, which is consistent with our result that the source of metric type II bursts is located in the fast shock formed at the bottom of the magnetic island, whereas the other source has its origin in the piston-driven fast shock formed in front of the same magnetic island. The speed and life-time of the radio sources depend directly on the properties of the fast shocks in our model. The piston-driven fast shock which produces decametric-hectometric type II bursts is the forward shock traveling in a free space while the shock producing metric type II bursts is the reverse shock formed through the collision of a high-speed reconnection jet to “the wall of magnetic field”. The reason why this reverse shock moves apparently upward is that the reconnection jet is so strong that it can move the magnetic wall upward, which implies that this reverse shock no longer goes upward and finally disappears when the energy release by the reconnection stops or weakens to reduce the speed of reconnection jet. Accordingly, our model suggests that the shock producing decametric-hectometric type II bursts can travel in the interplanetary space freely for a long time whereas the shock producing metric type II bursts travels in the corona at the same velocity as the magnetic wall
In summary, this is the first paper to apply a phenomenological model, the so-called CSHKP model, to understand two kinds of shocks systematically. This model describes the physical processes of plasmoid eruption (Shibata 1996) and as far as the coronal shock producing metric type II bursts is concerned, we strongly suggest that the essence of their formation is directly connected to the occurrence of a strong reconnection jet below an eruptive plasmoid. From this viewpoint, detailed studies on the shock formation around the bottom of plasmoid in more realistic environments will be needed in order to explain more precisely the properties of metric type II bursts and their related phenomena (Klassen et al. 2000). In our present study, we assume an artificial force to lift a magnetic island and the reverse shock formed at the bottom of the magnetic island seems to survive for a long time because the magnetic reconnection remains effective all through the simulation. These imperfect points will be improved in our following studies, where such realistic components as the gravitational force, time-dependent resistivity, and 3-dimensional effects are taken into considerations.
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FIGURE CAPTIONS

FIG. 1.—Evolution of plasmoid eruption. Contour lines, black arrows, and color map represent magnetic field lines, fluid velocity field, and temperature, respectively. Yellow arrows show the positions of piston-driven fast shock and reverse fast shock.

FIG. 2.—Spatial distributions of the vertical component of fluid velocity along the \( y \)-axis (symmetric axis). Broken line (\( time = 30 \)) and solid line (\( time = 50 \)) are shown. The positions of piston-driven fast shock and the reverse fast shock are indicated by arrows.

FIG. 3.—Height-time relations of piston-driven fast shock (solid line), flux rope center (dotted-broken line), and reverse fast shock (broken line). The time-variation of flux rope center represents the motion of a filament material inside the rope.

FIG. 4.—Height-time data of white-light CME (dots), decametric (light-gray solid line), hectometric (light-gray broken line), and metric (dark-gray solid line) type II radio bursts. Dotted horizontal line represents the level of the solar surface. This figure originates from Fig. 2 in Reiner et al. (2000), displayed in a simplified manner.