FORWARD-REVERSE SHOCK PAIRS ASSOCIATED WITH CORONAL MASS EJECTIONS

Y. C. Whang

Department of Mechanical Engineering, Catholic University of America, Washington, D. C.

Abstract. For some coronal mass ejections (CMEs), their interaction with the ambient solar wind can produce a forward-reverse shock pair. The high-speed mass ejecta compresses the plasma near the top of the CME on both sides of the tangential discontinuity which separates the CME plasma from the ambient solar wind plasma. The front of the compressed CME plasma propagates in the reverse direction relative to the ejecta flow, it may steepen to from a reverse slow shock. The front of the compressed solar wind plasma also propagates in the forward direction relative to the ambient solar wind and it may steepen to form a forward shock. The forward-reverse shock pair associated with CMEs moves outward in interplanetary space and evolves into a pair of fast shocks. The interplanetary manifestation of some CMEs is pictured as a magnetic cloud accompanied by a shock pair: a forward shock precedes the cloud and a reverse shock either within or behind the cloud.

1. Introduction

The possible existence of forward slow shocks preceding some coronal mass ejections (CMEs) has been suggested by Whang [1987] and by Hundhausen et al. [1987]. Whang [1987] reported a very certain identification of a forward slow shock. The front of the CME. This causes a sudden increase in the magnetic field ratio $B_2/B_1$ changes over a whole range, from 0 to 1, and the deflection angle also changes over a whole range, $0 \leq \theta \leq 90^\circ$. A shock may be called a weak shock wave only when the discontinuity in every quantity is small. A slow shock with small discontinuity in thermodynamic properties is not necessarily a weak shock. However, when the discontinuities in thermodynamic properties are small, the identification of a slow shock from plasma observations becomes difficult.

2. Forward-Reverse Shock Pairs

We would like to investigate the dynamic interaction between the coronal mass ejecta and the ambient solar wind. Reference should be made to an excellent review of recent work on CMEs by Kahler [1987]. The association between interplanetary shocks and CMEs has been clearly demonstrated using shocks detected at Helios 1 and CMEs observed from Solwind coronagraph [Sheeley et al., 1985]. With very few exceptions, interplanetary shocks are produced by major CMEs and are confined in latitude to within 15° of the angular extents of the CMEs measured at 10 R_S. The number of slow shocks observed in interplanetary space is very small. Chao and Olbert [1970] have identified two forward slow shocks, Burlaga and Chao [1971] found a reverse and a forward slow shock, Richter et al. [1985] reported a very certain identification of a forward slow shock.

We may call the ejected material the CME plasma which is separated from the solar wind plasma in the background corona by a tangential discontinuity. The large momentum of the high-speed mass ejecta exerts an excessive pressure on the ambient plasma shell in a narrow region in front of the CME. This causes a sudden increase in the magnetic field ratio $B_2/B_1$ changes over a whole range, from 0 to 1, and the deflection angle also changes over a whole range, $0 \leq \theta \leq 90^\circ$. A shock may be called a weak shock wave only when the discontinuity in every quantity is small. A slow shock with small discontinuity in thermodynamic properties is not necessarily a weak shock. However, when the discontinuities in thermodynamic properties are small, the identification of a slow shock from plasma observations becomes difficult.
Fig. 1. The direct impact of high-speed mass ejecta on the ambient solar wind compress the plasma near the top of CME on both sides of the tangential discontinuity. This interaction produces a forward shock preceding the CME and a reverse shock in the CME plasma closely behind the leading edge.

in the pressure of the plasma shell. When the velocity at the front of the CME relative to the ambient solar wind exceeds the local magnetoacoustic speed, a forward MHD shock may form preceding the compressed ambient plasma shell. The nose of the shock should be at some standoff distance from the top of the CME. The shock is a forward slow shock if the normal component of the relative shock velocity $U_n$ is greater than the slow mode magnetoacoustic speed but less than a $\cos \theta$. The shock is a fast shock if $U_n$ is greater than both the fast-mode magnetoacoustic speed and a $\cos \theta$.

Recently, Hundhausen et al. [1987] studied CMEs observed from the coronagraphs aboard Skylab and on the Solar Maximum Mission satellite. The observed flattening of the tops of some mass ejection loops suggests the possible existence of traveling forward slow shocks immediately in front of some CMEs. Their study of the observed speeds for the outward motion of CMEs shows that the speed at which a CME is overtaking the ambient coronal plasma is less than the Alfvén speed but greater than the sound speed for many (probably most) observed CMEs. This also supports the possible existence of forward slow shocks.

In response to the large pressure in the compressed ambient plasma shell, the CME plasma immediately behind the tangential discontinuity is also decelerated, compressed and heated. This compressed CME plasma is confined in a narrow leading edge region bounded by the tangential discontinuity on the forward side and by a pressure front on the reverse side. The pressure front propagates in the reverse direction relative to the motion of the ejected material. Due to greater wave propagation speed on the side of the compressed CME plasma at the pressure front, the pressure profile and the flow speed profile steepen to form a reverse MHD shock as the CME moves outward from the Sun.

The ejected CME plasma carrying a strong magnetic field is a low-$\beta$ plasma in which the slow mode magnetoacoustic speed $C_s$ is much less than the Alfvén speed $a$. The reverse shock associated with CME can be a slow shock if the normal component of the relative shock speed $U_n$ is greater than $C_s$ but less than a $\cos \theta$. Since $U$ is the relative shock speed the above condition does not imply that the absolute velocity of the ejecta is low. We do not yet have a theory to explain why the pressure front steepens to form a slow shock rather than a fast shock in a low-$\beta$ plasma in the coronal environment. The possible observation of forward slow shocks associated with CME by Hundhausen et al. [1987] provides an observational support for such a hypothesis. On this basis we estimate that the reverse shock can be a slow shock whether the forward one is a slow-mode or a fast-mode shock.

Figure 1 shows a sketch of the forward-reverse shock pair associated with CMEs in the early phase of the shock pair. A large portion of the shock surface inside the ejecta is quasi-perpendicular shock with the shock angle $\theta$ slightly less than or equal 90°. Edmiston and Kennel [1986] and Whang [1987, 1988] showed that slow shocks with large shock angle $\theta$ exist at all $\beta$ values. In the limit of $\theta = 90^\circ$, the deflection angle $\delta$ approaches zero and the ratio of the total pressure $p^*/p^+_1$ approaches unity. The thermal pressure always increases and the magnetic pressure always decreases across a slow shock, but the two effects cancel out in the limiting case of $\theta = 90^\circ$. Because the total pressure $p^*$ must be continuous at every point across a tangential discontinuity, the jump in $p^*$ across the reverse slow shock must be maintained across the boundary surface of the CME plasma as the shock intersects with the boundary. This requires that the reverse shock must extend to the solar wind outside of the tangential discontinuity. The dynamical equilibrium of the solar wind flow field in the neighborhood of the ejecta has to be maintained in such a way that this boundary condition be satisfied. In Figure 2, we use an r,ct diagram to demonstrate the forward-reverse shock pair near the top of a CME. As mass ejections sweep through the corona, a tangential discontinuity separates the CME plasma from the solar wind in the background corona, a reverse slow shock propagates in the region of CME plasma, while a forward shock propagates in the solar wind ahead of the CME. The dotted lines indicate the paths of fluid elements.

Numerical simulations have been used to demonstrate the possible existence of forward shock in association with flares by Hundhausen and Gentry [1969] and the possible existence of forward-reverse MHD shock pairs by Steinolfson et al. [1975] and Whang [1984]. The evolution of a corotating streams also leads to the formation of a corotating forward-reverse shock pair [Dessler and Fejer, 1963; Sonnett and Colburn, 1965; Whang and Chien, 1981]. The region behind a corotating shock pair is known as a corotating interaction region (CIR). Evolution of corotating shock pairs and CIR has been very well studied in the literature (see a review by Burlaga [1988] and references therein). Corotating shock pairs begin to form at near 1 AU in interplanetary space. The shocks are weak near 1 AU and they become quite strong in the outer heliosphere. The direction of a corotating stream makes a spiral angle with the heliocentric radial direction. This effect substantially reduces the normal impact of the momentum of a high-speed stream on preceding solar wind streams. In contrast, the coronal mass ejecta can exert a direct impact on
As mass ejections sweep through the corona, a tangential discontinuity separates the CME plasma from the solar wind in the background corona, a reverse slow shock propagates in the region of CME plasma, while a forward shock propagates in the solar wind ahead of the CME. The dotted lines indicate the paths of fluid elements.

The plasma pressure can build up very rapidly near the top of a CME on both sides of the tangential discontinuity which separates the CME plasma from the ambient solar wind plasma. Thus the forward-reverse shock pairs associated with CMEs can form very rapidly in coronal space.

3. Interplanetary Evolution of CME-Associated Shock Pairs

Two important evolutions of the shock pairs associated with CMEs may occur in interplanetary space. First, a CME loop may disconnect from the Sun to form a closed magnetic structure. The disconnected bubble is believed to manifest as a magnetic cloud in interplanetary space. Second, slow shocks may convert to fast shocks. As a result, we picture the interplanetary consequence of some CMEs as a magnetic cloud accompanied by a shock pair: a forward fast shock precedes the cloud and a reverse fast shock either within or behind the cloud.

MacQueen [1980] studied the average CME occurrence rate and the magnetic flux present in each CME. He suggested that CMEs do not carry out a distended field any further than the circular separation, but rather are subject to a reconnection process. He proposed that CME loops must magnetically disconnect from the Sun and form a closed magnetic structure. The disconnected bubble continues outward into interplanetary space.

Burlaga et al. [1981] analyzed the magnetic field configuration behind three shocks. They found a systematic configuration of the magnetic field and called it the magnetic cloud. A magnetic cloud is identified as an interplanetary structure in which the magnetic field strength is significantly lower than 1. Burlaga and Behannon [1982] showed that clouds persisted to the distances of 2 to 4 AU and estimated that the front and rear of a cloud expand at a speed of the order of half the Alfvén speed. Klein and Burlaga [1982] identified 45 clouds in interplanetary data obtained near 1 AU between 1967 and 1978. About one third of them are preceded by a shock, and these clouds appear to be moving faster than the ambient solar wind ahead. They compared the physical properties of magnetic clouds with those of CMEs and suggested an association of some clouds with disconnected magnetic structures of CMEs. A good case of an association between a CME observed by Solwind and a magnetic cloud observed at 0.5 AU by Helios 1 two days later was presented by Burlaga et al. [1982].

The Alfvén speed decreases at increasing heliocentric distance in the inner solar wind. As a forward or reverse slow shock travels outward from the Sun, the decrease in the Alfvén speed causes the shock Alfvén number to become greater than 1 at increasing heliocentric distances and the shock evolves from a slow shock into a fast shock. The transition of a forward slow shock which precedes a CME to a forward fast shock has been discussed by Whang [1987]. The reverse slow shock may also evolve into a reverse fast shock. The onset for the transition of reverse slow shocks may take place at the tangential discontinuity which is the boundary between the CME plasma and the ambient solar wind, inside the boundary, or outside the boundary.

Occurrence of Transition Inside or Outside of CMEs

If the onset of transition of reverse shocks occurs either inside or outside of the boundary tangential surface, the process should be similar to that for the transition of forward shocks.
Transition of a reverse slow shock to a reverse fast shock

Figure 3. This figure depicts the process for the transition of a reverse slow shock into a reverse fast shock. The normal vectors n point in the direction of plasma flow relative to the shock surface.

Figure 3 depicts the transition of a reverse slow shock to a reverse fast shock. The vector n denotes the normal direction pointing in the direction of plasma flow relative to the shock surface. The solar wind plasma enters a shock from its front side. The front side (the upstream side) of a reverse shock is the side closer to the Sun and the back side (the downstream side) is the side further away from the Sun. The surface of a reverse slow shock has a bow-shaped surface with its nose facing away from the Sun and the surface of a reverse fast shock has a bow-shaped surface with its nose facing the Sun.

As the reverse slow shock moves outwards from the Sun, the decrease in the Alfvén speed causes the shock Alfvén number to reach 1 near the nose of the shock surface. The transition from a reverse slow shock to a reverse fast shock begins to take place at a point of the shock surface where the shock angle equals 0°. At the onset of the transition process the reverse slow shock smoothly converts to a system consisting of a reverse slow shock, a very weak reverse rotational discontinuity (an Alfvén wave), and a very weak reverse fast shock (a fast MHD wave). A smooth conversion requires that at the onset of transition the three discontinuity surfaces (the slow shock, the weak rotational discontinuity and the weak fast shock) move at the same speed. Whang [1987, 1988] shows that the onset of transition must occur in the region of interplanetary space where \( \beta < \frac{2}{1} \) or 1.2.

During the transition, the system consists of a reverse slow shock, a reverse fast shock, and a reverse rotational discontinuity. The three surfaces of discontinuity intersect along a closed transition line. As the system moves outward from the Sun, the transition line moves laterally across the field lines, the area enclosed by the closed loop of the transition line expands continuously, the fast shock grows stronger, and the slow shock becomes weaker. Eventually, the reverse slow shock diminishes and the entire system evolves into a reverse fast shock.

The fast shock of a forward or reverse transition system is a near switch-on shock, across which small random fluctuations in plasma flow and magnetic fields on the front side of the shock are considerably ampliﬁed. The flow becomes very turbulent behind nearly switch-on shocks. Therefore during the transition, the amplitude of fluctuations in ﬂow velocity and magnetic ﬁelds are large in the turbulent region behind the fast shock [Whang, 1988].

Kennel et al. [1984a, b] reported a sequence of events observed from ISEE 1 and 3 that seems to resemble the forward transition system. On November 12, 1978, the passage over the ISEE spacecraft of a high-speed, quasi-parallel, interplanetary forward fast shock with \( U_{1} = 240 \text{ km s}^{-1}, \theta_{1} = 41°, a_{1} = 160 \text{ km s}^{-1} \) and \( \beta_{1} = 1.14 \). The shock is followed by a strong magnetic field rotation at approximately 40 R_E downstream of the shock, and an extended region of intense MHD turbulence between the shock and the magnetic field rotation. They reported that the shock was probably associated with the pair of flares beginning at 0048 and 0113 UT on November 10, 1978.

Occurrence of Transition at the Boundary of CMEs

Figure 1 shows that a reverse slow shock in the CME plasma extend to the ambient solar wind outside of the tangential discontinuity surface. If the relative flow velocity across the tangential discontinuity is less than the Alfvén speeds on both sides, the flow satisﬁes the criterion of Kelvin-Helmholtz stability. The flow velocity and the Alfvén speed are discontinuous across a tangential discontinuity. But the total pressure \( p^{*} \) must be continuous across a tangential discontinuity and the magnetic field vectors and the relative flow velocities on both sides must be parallel to the tangential discontinuity surface. As the shock angle decreases across the reverse slow shock inside the CME, the boundary surface must deflect by a small angle at the location where the reverse
slow shock intersects the tangential discontinuity. The flow pattern near the deflection point of the boundary in the ambient solar wind may consist of a reverse slow shock, a reverse rotational discontinuity, and a reverse fast shock. Depending on the physical properties outside the CME boundary, the slow (fast) shock can be replaced by a continuous centered slow (fast) expansion wave. As the cluster consisting of the cloud and the shock pair moves outward from the Sun, the decrease in the Alfvén speed can cause a possible conversion of the pattern for shocks and discontinuities near the deflection point of the boundary in the ambient solar wind from the pattern of a reverse slow followed by a reverse rotational discontinuity to that of a reverse fast shock preceded by a reverse rotational discontinuity.

4. Conclusions

For some coronal mass ejections (CMEs), the direct impact of the high-speed mass ejecta on the ambient solar wind can substantially compress the plasma near the leading edge of the CME on both sides of the tangential discontinuity which separates the CME plasma from the ambient solar wind plasma. This interaction can produce a forward shock preceding the CME and a reverse slow shock in the CME plasma closely behind the leading edge. As the forward-reverse shock pair moves outward in interplanetary space, it evolves into a pair of fast shocks. If the magnetic clouds are indeed the interplanetary manifestations of the disconnected magnetic structures of CMEs, then the reverse shock propagates within the magnetic cloud as the cloud moves outward from the Sun. Eventually, the reverse shock exits the cloud to become detached from the magnetic cloud. Then both the forward and the reverse shocks propagate in the ambient solar wind as shown in Figure 4. If this picture is correct, the interplanetary signature of some CMEs at large heliocentric distances may consist of a magnetic cloud wrapped around by an interaction region, which in turn is bounded by a pair of fast shocks. The solar wind plasma continuously adds to the interaction region across the shocks as the system moves away from the Sun.

Klein and Burlaga [1982] reported that about one third of clouds identified near 1 AU between 1967 and 1978 are preceded by a shock. There are two examples involving the observation of a reverse shock and a magnetic cloud. R. P. Lepping et al. (private communication, 1988) have observed one; their report will soon be ready for journal publication. Another event involving a reverse shock and a magnetic cloud was observed on August, 1982, from Voyager 2 [Burlaga et al., 1985]. The observed cloud remained stable out to 10.3 AU after a propagation time of approximately a month. The cloud had a dimension of the order of 1 AU and was preceded by two shocks and an interface and followed by a reverse fast shock at about 0.1 AU behind the cloud. This observation probably explains that for a long-lived cloud, the reverse shock had enough time to propagate through the cloud, exited the rear of the cloud, and appeared closely behind the cloud.

Acknowledgments. The author thanks K. W. Behannon, L. F. Burlaga, S. Kahler, and C. F. Kennel for useful discussions of this topic, and L. F. Burlaga for his comments on the manuscript. This work was supported by the Air Force Office of Scientific Research under contract 86-160, and by the Atmospheric Sciences Section of the National Science Foundation under grant ATM-8614990.

The Editor thanks R. S. Steinolfson and another referee for their assistance in evaluating this paper.

References


Y. C. Whang, Department of Mechanical Engineering, Catholic University of America, Washington, DC 20064.

(Received January 12, 1988; revised February 16, 1988; accepted February 25, 1988.)