The overall objective of this project is to study shock waves of the solar terrestrial medium in coronal and interplanetary space. This research will enhance our understanding on the propagation of large amplitude disturbances from the solar corona through the interplanetary space. The work accomplished during the past three years includes:

(a) a demonstrating example showing the formation of slow shock pairs associated with CMEs in a coronal environment;
(b) a parametric study of slow shocks in the entire domain of a three-dimensional parameter space, the $A, \theta, \beta$-space;
(c) the large scale geometry of traveling interplanetary shocks;
(d) the transition of slow shocks to fast shocks in the inner solar wind; and
(e) the evolution of CME associated shocks and their interplanetary manifestations.
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Final report

For Research project Entitled

MHD SLOW SHOCKS IN CORONAL AND INTERPLANETARY SPACE

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1. Summary

The overall objective of this project is to study shock waves of the solar terrestrial medium in coronal and interplanetary space. These shocks are magnetohydrodynamic (MHD) slow shocks and fast shocks. Our primary interests are to study dynamic problems related to shocks associated with coronal mass ejections (CMEs), including the formation of shocks in coronal environment, the transition of slow shocks to fast shocks, their evolution and their interaction with the solar wind in coronal and interplanetary space.

During the past three years of this grant, we have produced the following publications:


In the following sections, we summarize some highlights of these studies.

2. Formation of Slow Shock Pairs Associated With CMEs

In order to understand the basic physics involved in the shock formation process, we carry out a series of MHD simulations to show that MHD shocks formed in low-beta plasmas in the coronal environment are slow shocks. The simulation model assumes that flow properties are functions of x and t only. The x-direction is normal to the wave front in the forward direction of the solar wind flow and the magnetic field vector is parallel to the xy coordinate plane. The time-dependent MHD flow governed by a system of hyperbolic, nonlinear equations is studied using the method of characteristics. Shocks are treated as surfaces of zero thickness. The Rankine-Hugoniot solution is used to calculate the jumps in flow properties at all shock crossings.

The numerical solution shown in Figure 1 demonstrates the formation of a forward-reverse slow shock pair in a coronal environment. The initial condition represents the impact of a high-speed (600 km/s) mass ejecta on a low-speed (100 km/s) ambient solar wind. At t = 0 the flow velocity changes smoothly over a distance of about 200,000 km. On the upstream (mass ejecta) side \( U_1 = 600 \text{ km/s} \) and \( n_1 = 8.8 \times 10^6 \text{ protons/cm}^3 \). On the downstream (ambient solar wind) side, \( U_0 = 100 \text{ km/s} \) and \( n_0 = 6.0 \times 10^6 \text{ protons/cm}^3 \). The flow is field aligned in the rest frame of reference, \( \beta = 0.1 \), \( B_x = 0.8 \text{ Gauss} \), and \( \theta = 15^\circ \).
The simulation demonstrates that the difference in momentum flux is the driving force for the formation of shock pairs. The momentum impact compresses the plasma near the front of the CME. Large pressure disturbances propagate in both the forward direction relative to the ambient solar wind and the reverse direction relative to the ejecta flow. The pressure fronts steepen to form forward and reverse MHD shocks. The flow speed profiles calculated at a time interval of 30 seconds (Figure 1) show the gradual formation of the two shock fronts. The resulting shocks consist of a forward slow shock and a reverse slow shock. No fast shocks. The shock pair takes about 10 minutes to grow into a fully developed state.

The disturbances generated by the momentum impact also disturb the flow field outside the interaction region bounded by the forward-reverse slow shock pair. But their influence is limited to the region bounded by a forward fast mode characteristic on the downstream side and by a reverse fast mode characteristic on the upstream side. The amplitudes of disturbances outside the slow shocks are negligibly small compared with jumps in flow properties across the slow shocks.

\[ U_1 = 600 \text{ km/s} \quad U_0 = 100 \text{ km/s} \quad \frac{N_1}{N_0} = 1.46 \quad \beta = 0.1 \quad \Theta = 15^\circ \]

![Flow speed profiles](image)

Fig. 1. The flow speed profiles calculated at a time interval of 30 seconds showing the gradual formation of the two shock fronts.
3. A Parametric Survey of MHD Slow Shocks

We have an exact analytical method to calculate the solutions of MHD shocks as functions of three dimensionless upstream parameters: the shock Alfven number \( A = U_n/(a \cos \theta) \), the shock angle \( \theta \), and the plasma \( \beta \) value. (Here \( U_n \) is the normal component of the relative shock speed, \( a \) the Alfven speed, \( \theta \) the acute angle between the shock normal and the magnetic field, and \( \beta \) the ratio of the thermal pressure \( p \) to the magnetic pressure \( B^2/(8\pi) \).) A shock is a slow shock if the shock Alfven number \( A \) is less than 1 and is a fast shock if \( A \) is greater than 1. The magnetic field and the shock angle decrease across a slow shock, they increase across a fast shock.

The parametric survey of slow shock solutions are presented in a three dimensional \( A, \theta, \beta \)-space. The domain of slow shock solutions in the \( A,\theta \)-parameter space shrinks as the plasma \( \beta \) value decreases. A drastic change in the domain of solution takes place when \( \beta \) is between 0.1 and 1. The change becomes very small at very large or very small \( \beta \). When the shock Alfven number approaches one, slow shocks exist at all shock angles and at all \( \beta \) values. At any given value of \( \theta \), a whole range of changes in \( B_2/B_1 \) from 0 to 1 may take place. On the other hand the range of change in thermodynamic properties strongly depends on the \( \beta \) value. In Figure 2 of Paper 2 shows the density ratio, \( \rho_2/\rho_1 \), in the three dimensional \( A,\theta,\beta \)-parameter space. (A similar plot has been made for the pressure ratio.) Slow shocks covering a wide range of density jumps exist in the low \( \beta \) region (where \( \beta \leq 0.1 \)). On the other hand, only slow shocks with weak density jumps exist in the high \( \beta \) region (where \( \beta \geq 1 \)). Therefore, in the coronal space where the \( \beta \) value of the solar wind is in the order of 0.1, all physical properties may jump across a slow shock over a wide range of magnitudes. Near 1 AU the plasma \( \beta \) value is in the order of 1, the jumps in thermodynamic properties across a slow shock must be small but the change in the magnetic field is not necessarily small.

4. Transition of Slow Shocks to Fast Shocks

Whang [Paper 1] first studied the possible existence of forward slow shocks preceding some CMEs and their global geometry. When the speed of ejected CME material relative to the ambient solar wind exceeds the local magnetoacoustic speed, an MHD shock front forms at the leading edge of the compressed ambient plasma shell. In coronal space, the Alfven speed is of the order of 1000 km/s. If a forward MHD shock forms preceding the compressed ambient plasma shell associated with the CME, the shock Alfven number can be less than 1 and the shock can be a forward slow shock. The large-scale global surface of a forward slow shock should have a bow-shaped surface with its nose facing the sun because the slow-mode MHD waves and MHD shocks are upstream-inclined [Sears and Resler, 1961]. The relative shock speed varies from point to point on the curved surface of an MHD shock. The slow shock is relatively stronger at the nose. The shock becomes weaker on the flank and asymptotically approaches slow-mode MHD waves.

Sheeley et al. [1985] have demonstrated a close association between interplanetary shocks and CMEs. They reported that with very few exceptions interplanetary shocks detected at Helios A are produced by CMEs observed from Solwind coronagraph. Richter et al. [1985] reported a very certain identification of a forward slow shock at 0.31 AU. 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. The observed speeds for the outward motion of CMEs show that the speed at which a CME is overtaking the ambient coronal plasma is less than the Alfven speed but greater than the sound speed for many (probably most) observed CMEs. This supports the possible existence of forward slow shocks.

The Alfven speed of the interplanetary plasma decreases at increasing heliocentric distance in the inner solar wind. As a forward slow shock travels outwards from the sun, the decrease in the Alfven speed causes the shock Alfven number of a forward slow shock to become greater than 1 at increasing heliocentric distances and the shock evolves from a slow shock into a fast shock. The large-scale global surface of a traveling forward fast shock has a bow-shaped surface with its nose facing away from the sun.

Whang [Paper 1] has a theory to explain the transition of traveling slow shocks into traveling fast shocks as shown in Figure 6 of Paper 1. The Alfven speed of the interplanetary plasma decreases at increasing heliocentric distance in the inner solar wind. As the forward slow shock moves outwards from the sun, the decrease in the Alfven speed causes the shock Alfven number to reach 1 near the nose of the shock surface, the transition from a forward slow shock to a forward fast shock begins to take place at a point of the shock surface where the shock angle equals 0°. The onset of transition must occur in the region of interplanetary space where \( \gamma < 2/\gamma \) or 1.2. At the onset of the transition the forward slow shock smoothly converts to a system consisting of a forward slow shock, a very weak forward rotational discontinuity (an Alfven wave), and a very weak forward fast shock (a fast MHD wave).

During the transition, the system consists of a slow shock, a fast shock, and a 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 slow shock diminishes and the entire system evolves into a forward fast shock. Such a system may have been observed from ISEE 1 and 3. Kennel et al. [1984a, b] reported that on November 12, 1978, ISEE 1 and 3 observed a forward fast shock associated with a pair of flares which occurred some 48 hours earlier. The shock was followed by a strong rotational discontinuity at approximately 40 Re downstream of the shock. This sequence of events resembles the forward transition system.

5. Evolution of CME Associated Shock Pairs

Recently, Whang [Paper 3] suggests that for some CMEs their interaction with the ambient solar wind can produce a forward-reverse shock pair as shown in Figure 1 of Paper 3. We may call the ejected material the CME plasma which is separated from the solar wind plasma in the background corona by an interface. 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. The high-speed mass ejecta causes a sudden increase in the pressure of the plasma near the top of the CME on both sides of the interface.
In response to the large pressure in the compressed ambient plasma shell, the CME plasma immediately behind the interface is decelerated, compressed and heated. This compressed CME plasma is confined in a narrow region bounded by the interface on the forward side and by a pressure front on the reverse side. The front of the compressed CME plasma propagates in the reverse direction relative to the ejecta flow, it may steepen to from a reverse shock.

The ejected CME plasma carrying a strong magnetic field is a low-β plasma in which the slow mode magnetoacoustic speed $C_s$ is much less than the Alfven 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 $a \cos \theta$. Whang estimated that the reverse shock can be a slow shock whether the forward one is a slow-mode or a fast-mode shock. As a slow shock pair travels outward from the Sun, the decrease in the Alfven speed with increasing heliocentric distance causes the slow shocks to evolve into fast shocks.

MacQueen [1980] suggested that CMEs do not carry out distended field very far to interplanetary space, 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.

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. Klein and Burlaga [1982] identified 45 clouds in interplanetary data obtained near 1 AU between 1967 and 1978. 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. They identified a magnetic cloud as an interplanetary structure in which the magnetic field strength is higher than average, the magnetic field direction rotates monotonically through a large angle, the temperature is low, and the plasma β is significantly lower than 1. A good case of an association between a CME observed by Solwind and a magnetic cloud observed at 0.54 AU by Helios 1 two days later was presented by Burlaga et al. [1982].

In summary, two important evolutions of the shock pairs associated with CMEs may occur in interplanetary space. First, a CME loop eventually disconnect from the sun to form a closed magnetic structure. The disconnected bubble manifests as a magnetic cloud in interplanetary space. Second, as the CME associated forward-reverse shock pair moves outwards in interplanetary space, they evolve into a pair of fast shocks. The reverse shock first propagates within the magnetic cloud, but eventually the reverse shock must exit the cloud to became detached from the magnetic cloud. Then both the forward and the reverse shocks propagate in the ambient solar wind. Therefore, the interplanetary consequence of some CMEs should consist of a magnetic cloud accompanied by a fast shock pair. The forward fast shock propagates preceding the cloud and the reverse fast shock is either within or behind the cloud.

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 several examples involving the observation of a shock pair associated with a CME or magnetic cloud. Lepping et al. [1988] reported that a large magnetic cloud accompanied by a shock pair was observed on October 31 and November 1 of 1972 from IMP 7. The event was associated with a unusually longlasting solar flare.
which occurred some 49 hours earlier. Gosling et al. [1988] have identified two CME associated shock pairs at 1 AU from ISEE 3. Another event involving a shock pair and a magnetic cloud was observed on August, 1982, from Voyager 2 at 10.3 AU [Burlaga et al., 1985]. This observation shows 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.
Abstract. The jump conditions of MHD shocks may be directly calculated as functions of three upstream conditions: the shock Alfven number based on the normal component of the relative shock speed, the shock angle, and the plasma $\beta$ value. The shock Alfven number is less than 1 for a slow shock and greater than 1 for a fast shock. A traveling, forward shock can be a slow shock in coronal space, where the Alfven speed is of the order of 1000 km/s. The surface of a forward slow shock has a bow-shaped geometry with its nose facing toward the sun. The decrease in the Alfven speed at increasing heliocentric distance causes the shock Alfven number of a forward slow shock to become greater than 1 and the shock eventually evolves from a slow shock into a fast shock. A theoretical prediction for the global geometry of traveling slow shocks and their transition to fast shocks was first presented at 1986 Spring Meeting of the American Geophysical Union (Whang, 1986a). Recently, we have carried out a numerical solution to demonstrate the transition process. This paper contains a formal presentation of these researches.

Theoretical investigations of MHD slow shocks in space plasma have been reported by Scherer (1976), Rosenau and Suss (1977), Whang (1982, 1986a, b), Hada and Kennel (1985), and Edmiston and Kennel (1986). Very few of the observed interplanetary shocks are slow shocks. Observations of interplanetary slow shocks near 1 AU have been reported by Chao and Obert (1976) and by Burlaga and Chao (1971). However, observations of slow shocks by HELIOS at a heliocentric distance of 0.31 AU (Richter et al., 1985) and by ISEE 3 beyond 100 earth's radii in the geomagnetic tail (Feldman et al., 1986) greatly increase our interest in slow shocks. A better understanding of the MHD slow shock process may have direct applications to the magnetic field reconnection process and to shock processes in coronal space, in interplanetary space, and in geomagnetic tails.

Recently, A. J. Hundhausen et al. (On slow shocks precede some coronal mass ejection?, submitted to Journal of Geophysical Research, 1986) hereafter referred to as HHX) studied the outward motion for coronal mass ejections observed by the Skylab coronagraph and the SMM coronagraph. The measured speeds of coronal mass ejections indicate that many mass ejections move into the background 'solar wind' faster than the gasdynamic sound speed but slower than the Alfven speed. This has been interpreted as a support for the possible formation of slow MHD shocks immediately in front of some coronal mass ejections.

1. Introduction

Interplanetary traveling shocks are associated with corona mass ejections and flares (Driver 1975; Hildner, 1977; MacQueen, 1980; Sheeley et al., 1985). If the speed of the ejected material relative to the ambient solar wind exceeds the local magnetosonic speed, a magnetohydrodynamic (MHD) shock front forms at the leading edge of the compressed ambient plasma (Cowley, 1973). The MHD shock process plays an important role in influencing solar terrestrial relations.

The solutions of MHD shocks may be expressed as functions of three upstream conditions: the shock Alfven number based on the relative shock speed $A = U_p/\sqrt{\alpha \cos \phi}$, the shock angle $\phi$, and the plasma $\beta$ value. (Here $U_p$ is the normal component of the relative shock speed, $\alpha$ the angle between the shock normal and the magnetic field, and $\beta$ the ratio of the thermal pressure $p$ to the magnetic pressure $B^2/8\pi$.) Two kinds of MHD shocks, the fast and the slow shocks, may exist. A shock is a slow shock if the shock Alfven number $A$ is less than 1 and is a fast shock if $A$ is greater than 1.

A traveling, forward MHD shock can be a slow shock in coronal space where the Alfven speed is of the order of 1000 km/s. The Alfven speed decreases at increasing heliocentric distance in the inner solar wind. The decrease in the Alfven speed causes the shock Alfven number of a forward slow shock to become greater than 1 at increasing heliocentric distances, and the shock eventually evolves from a slow shock into a fast shock. A theoretical prediction for the global geometry of traveling slow shocks and their transition to fast shocks was first presented at 1986 Spring Meeting of the American Geophysical Union (Whang, 1986a). Recently, we have carried out a numerical solution to demonstrate the transition process. This paper contains a formal presentation of these researches.

2. Interplanetary Slow Shock and Its Transition to Fast Shock

Two kinds of MHD shocks, the fast and the slow shocks, may exist in coronal and interplanetary space. The plasma density, the thermal pressure, and the total pressure (the sum of the thermal and the magnetic pressures) all increase across an MHD shock. The magnetic field and the shock angle decrease across a slow shock and increase across a fast shock. The density ratio $\rho_f/\rho_i$ is often used as a measure of the shock strength. Here the subscript $i$ denotes the flow condition upstream of a shock, and $f$ denotes the flow condition downstream. Figures 1 and 2 show the constant contours for the density ratio and the magnetic field ratio for slow and fast shocks, respectively, as functions of three dimensional.
The transition from a slow shock to shocks. The magnitude of the magnetic field decrease across a slow shock. The constant contours for the density surface with its nose facing the sun. The sketch of a forward slow shock should have a bow-shaped surface with its nose facing away from the sun as shown in the right panel of Figure 3. The deflection angle of the magnetic field represents the increase of the shock angle across a fast shock. During the transition the shock system consists of a slow shock, a fast shock, and a rotational discontinuity which may be referred to as a slow-fast shock system. We will continue to discuss the slow-fast shock system.

3. Jump Conditions of MHD Shocks

We obtain a direct and simple solution for the jump conditions of MHD oblique shocks. The jump conditions of MHD oblique shocks are downstream-tilted. Thus the large-scale global surface of a traveling forward fast shock has a bow-shaped surface with its nose facing away from the sun as shown in the right panel of Figure 3. The deflection angle of the magnetic field represents the increase of the shock angle across a fast shock.
conditions of MHD shocks can be calculated in terms of shock parameters, which are sometimes defined in terms of physical properties on both sides of the shock. This method of solution has all shock parameters defined in terms of the upstream conditions only.

It is convenient to formulate the shock solution using an n,p,r-coordinate system attached to the shock surface. Let n be the unit vector normal to the shock surface and pointing in the direction of mass flow. Since the shock normal n and the magnetic field vectors on both sides of a shock, $B_n$ and $B_p$, are coplanar, this coplanarity plane is chosen as the n-pr-coordinate plane. This means that $B_r = 0$ on both sides of the shock.

We use a pair of brackets to denote the jump of a physical quantity $Q$ across the shock, e.g.,

$$[Q] = Q_n - Q_p$$

Let $U$ be the flow velocity in a frame of reference attached to the shock surface. At any instant the jumps in plasma and magnetic fields across an MHD shock must satisfy the following jump equations [Heiles, 1963]:

$$B_n |_{n} = 0$$

$$[B_p] = 0$$

$$[\rho U] = 0$$

$$[p] = (1/8\pi)\left[B_p^2\right]$$

$$[\rho U B_p] = -B_n |_{n} B_p |_{p}$$

$$[U] = 0$$

$$[\rho U^2/2 + (p/\rho)/(\gamma - 1)]$$

$$= \left(1 - \frac{1}{\gamma - 1}\right)\left(B_{n} |_{n} B_{n} |_{p}\right)$$

and

$$B_{n} |_{n} B_{n} |_{p} = \frac{1}{\gamma - 1}\left[B_{p}^2\right].$$

From equations (4) and (7), we can obtain

$$4\pi n U_p B_n B_p = B_{n}^2 |_{p} B_{n} |_{p}.$$  

Making use of equations (5), (8), and (9), we write the energy equation (6) as

$$\left[1 + B_{n}^2/B_{n}^2\right] U_{n}^2 |_{p} = (p/\rho)/(\gamma - 1) = \eta.$$  

We shall show that for given upstream conditions, from (2), (7), (8), and (9) we can obtain the exact solution of the MHD shock equations for $p_1$, $B_{n1}$, $B_{p1}$, and $U_{n1}$ as functions of three dimensionless upstream parameters: the shock Alfvén number $A$, the shock angle $\theta$, and $\beta$. Note that these solutions are independent of the velocity components $U_p$ and $U_{n1}$. $U_{n1}$ can be directly calculated from (4). The shock solution remains unchanged if an arbitrary $U_{n1}$ is added to both sides of the shock.

It is convenient to denote the density ratio by

$$\eta = \frac{p_1}{p} = \frac{U_{n1}}{U_{n}}.$$  

Then from (10) and (11) we obtain

$$\eta = A^2 B_{n1} / (A^2 - 1) B_{p1} + B_{t1}.$$  

and

$$\eta - 1 = (A^2 - 1) (B_{p1} - B_{t1}) / (A^2 - 1) B_{n1} + B_{t1}.$$  

In terms of $A$ and $\eta$, we can write (1) and (9), respectively, as

$$p_2/p_1 = 1 - (\beta_{t2} - \beta_{t1})$$

$$\times \left(B_{t2} + B_{t2} - (A^2 - 1) B_{n1}^2 / B_{t1}^2 / 8 \pi p_1 \right)$$

and

$$p_2/p_1 = \eta \left(\gamma - 1\right) / \left(\gamma - 1\right) (A^2 - 1) B_{t1} + B_{t2}$$

$$\times \left(\eta - 1\right) (B_{n1}^2 + B_{t1}^2) + B_{t1}^2 - (A^2 - 1) B_{n1}^2 / 8 \pi p_1.$$  

Subtracting (13) from (14), we obtain

$$\eta - 1 = \left(\gamma - 1\right) / \left(\gamma - 1\right) (A^2 - 1) B_{t1} + B_{t2}$$

$$\times \left(\eta - 1\right) (B_{n1}^2 + B_{t1}^2) + B_{t1}^2 - (A^2 - 1) B_{n1}^2 / 8 \pi p_1.$$  

Dividing equation (15) by $\eta - 1$, making use of (12) and rearranging the result as a cubic equation in $B_{t1}$, we have

$$B_{t1}^3 + D_2 B_{t1}^2 + D_1 B_{t1} + D_0 = 0.$$  

The coefficients $D_1$ are functions of upstream conditions.
Fig. 4. For each given value of $\beta_1$ the jump conditions of flow properties such as the total pressure ratio $p_2^*/p_1^*$ and the deflection angle $\delta$ for slow shocks can be plotted as functions of $A$ and $\theta_1$. At the lower limit of $A$ the deflection angle $\delta = 0$ and there are no jumps in $p$, $T$, $B$, and $p^*$. At the upper limit, the shocks are known as the switch-off shocks. Slow shocks exist for all finite values of $\beta_1$. When $\beta_1 > 1$, slow shocks exist in a very small domain in the $A$, $\theta_1$-parameter space, and these shocks are very weak.

When the upstream conditions are given, we first solve (15) for $B_{\beta_2}$. Next, we can calculate all other jump conditions. The solutions with the shock Alfen number $A$ greater than 1 represent fast shocks, and the solutions with $A$ less than 1 represent slow shocks. The cubic equation (16) may have one or three real roots. However, for any given upstream conditions, no more than one root produces a shock solution with density ratio $\eta$ greater than 1.

Algebraic solutions of MHD shocks have been extensively studied by many authors using two general methods of approach. We take the same approach as Lui (1958) using only the upstream conditions of a shock as the input for the calculation. His method involves the solution of a cubic equation in density ratio. The coefficients of the cubic equation in $B_{\beta_2}$ obtained in (16) are much simpler than their counterparts obtained by Lui. The second method involves the introduction of a shock parameter which is a function of some flow conditions on both sides of the shock (Helfer, 1957; Bazer and Ericson, 1959; Kulikovskii and Lyubimov, 1962; Lynn, 1966). Insofar as the downstream conditions of a shock are completely unknown, as in the example shown in the next section for the slow-fast shock system, the present solution is believed to be a more direct and simple method of solution for MHD shocks.

As shown in Figures 4 and 5 for each given value of $\beta_1$, the jump conditions can be plotted as functions of $A$ and $\theta_1$. For varying values of $\beta_1$ we plot the constant contours of the total pressure ratio $p_2^*/p_1^*$ and the deflection angle $\delta$ in Figures 4 and 5 for slow shocks and fast shocks, respectively. The existence of shock solutions requires that

$$U_{1l} - C_g$$
for slow shocks and

\[
U_{nl} > C_f \beta_1
\]

for fast shocks, where \( C_s \) and \( C_f \) are the normal speed (the phase speed) of the slow and fast magnetoacoustic wave

\[
C_s^2 = (a^2 + c^2)/2 - 1(a^2 + c^2) - 4a^2c^2\cos^2 \theta_1/2 \]

(17)

and

\[
C_f^2 = (a^2 + c^2)/2 + 1(a^2 + c^2) - 4a^2c^2\cos^2 \theta_1/2 \]

(18)

where \( c \) is the gasdynamic sound speed, \( c^2 = \gamma p/\rho \).

From (17) we obtain that for given \( \beta_1 \) and \( \theta_1 \), slow shocks exist in the interval

\[
1 + \gamma \beta_1/2 - 1(1 + \gamma \beta_1/2)^2 - 2\gamma \beta_1 \cos^2 \theta_1/2
\]

\[
2 \cos^2 \theta_1
\]

(19)

\[
A^2 < 1
\]

These limits are shown in Figure 4 for various values of \( \beta_1 \). At the lower limit the deflection angle \( \delta = 0 \), and there is no jump in \( \rho, T, \rho, \rho \), or \( p \). At the upper limit the deflection angle \( \delta \) equals \( \theta_1 \) (i.e., \( \theta_2 = 0 \) and \( \theta_1 = 0 \)), and the shocks are known as the switch-off shocks. When \( \delta_1 = 0 \), the lower limit equals \( \gamma \beta_1/2 \) for \( \beta_1 < 2/\gamma \) and equals \( 1 \) for \( \beta_1 > 2/\gamma \). The lower limit equals \( (1 + 2/\gamma \beta_1)^{-1} \). Note that this limiting value of \( \delta \) is less than 1 for all finite values of \( \beta_1 \). Thus, slow shocks exist for all finite values of \( \beta_1 \). When \( \beta_1 > 1 \), slow shocks exist in a very small domain in the \( A, \theta_1 \) parameter space, and these shocks are very weak.

At the lower limit of \( A^2 = 1 + \gamma \beta_1/2 - 1(1 + \gamma \beta_1/2)^2 - 2\gamma \beta_1 \cos^2 \theta_1/2 \)

which is the magnetoacoustic cusp speed.

From (18) we find that for given \( \beta_1 \) and \( \theta_1 \), the shock Alfven number of fast shocks has a lower limit

\[
A^2 > \frac{1 + \gamma \beta_1/2 + 1(1 + \gamma \beta_1/2)^2 - 2\gamma \beta_1 \cos^2 \theta_1/2}{2 \cos^2 \theta_1}
\]

At the lower limit the fast shock approaches a fast magnetoacoustic wave, the deflection angle \( \delta \) equals 0, and there is no jump in any fluid property. When \( \delta_1 = 0 \), the lower limit equals 1 for \( \beta_1 < 2/\gamma \) and equals \( \gamma \beta_1/2 \) for \( \beta_1 > 2/\gamma \). The onset of transition from slow shock to fast shock can take place only when the lower limit of \( A^2 \) is unity at \( \delta_1 = 0 \). For this reason the onset of transition must occur in the region of interplanetary space where \( \delta < 2/\gamma \) or 1.7.

Let us now examine the constant contour for the deflection angle \( \delta \) in Figure 5 for \( \delta_1 = 0 \).
The proposed slow-fast shock system shown in Figure 6 which may represent a physical process for the transition of slow shocks to fast shocks in the inner solar wind requires that the flow properties in the immediate neighborhood of the transition line satisfy all jump conditions of MHD discontinuity surfaces. The method of solution is to treat the normal directions of the four shock waves and the rotational angles of the two rotational discontinuities as six unknown variables. In order to analyze the flow conditions in the immediate neighborhood of the transition line it is convenient to introduce a coordinate system attached to the transition line $T$ as shown in Figure 7. We choose the $z$ axis tangential to the transition line and the $x,z$ plane parallel to the magnetic field vector $B$ upstream of the shock system. The normal directions of all surfaces of discontinuity are parallel to the $x,y$ plane.

We present a simple numerical example in which the upstream solar wind velocity relative to the shock system $V$ is parallel to the $x,y$ plane. The direction of the $x$ axis is chosen such that $U_x$ is positive upstream of the shock system. To have the shock Alfven number for the slow shock $S2$ less than $1$ and that for the fast shock $F1$ greater than $1$, $U_x$ must be positive. The example is carried out here using the following upstream conditions:

$$ \beta = 0.2 $$

$$ U/a = 1.2 $$

$$ \arctan(U_y/U_x) = 30^\circ $$

$$ \arctan(U_z/U_x) = 0^\circ $$

$$ \arctan(B_y/B_x) = 0^\circ $$

$$ \arctan(B_z/B_x) = 10^\circ $$

Let us first identify the three upstream parameters for the slow shock $S2$: $\beta$ is given; $U/a$ a shock Alfven number and the shock angle can be calculated once the normal direction of $S2$ is given. This means that for a given normal direction of $S2$ we can solve the cubic equation (16) for $B_{z2}$ and calculate the magnetic field vector downstream of $S2$. Then we use (7) to calculate $[U_t]$ and the flow velocity vector downstream of $S2$. $B_{y2}$ and $U_{x2}$ downstream of $S2$ are not zero any more. The next step is to calculate $p_2$ and $p_2$ using (11) and (13). Therefore, once the normal direction of $S2$ is given, we can determine all flow conditions downstream of $S2$ by solving a system of nonlinear algebraic equations. Following the same procedure, once the normal direction of $F1$ is given, we can determine all flow conditions downstream of $F1$.

Since the shock Alfven number of $R1$ and $R2$ must be unity, this condition is used to determine the normal direction of the two rotational discontinuities. The strength of a rotational discontinuity may be measured by the rotational angle of the tangential magnetic field vector. We use the right-hand rule to determine the positive direction for the rotational angle. Now we can calculate all flow conditions downstream of $R1$ and $R2$, respectively, for given
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system (equations (16), (7), (11), and (13)) to determine the flow conditions downstream of the two shocks. In summary, the flow conditions downstream of S1 and F2 are functions of six parameters: the normal directions of the four shock waves and the rotational angles of the two rotational discontinuities. The six parameters are treated as six unknown variables to be determined by boundary conditions for the flows downstream of S1 and F2.

The flows downstream of S1 and F2 are separated by a contact discontinuity. Across the contact surface the flow must satisfy three conditions: (1) the magnetic field B be continuous, (2) the thermal pressure p be continuous, and (3) the velocity vectors be parallel. The three conditions are actually represented by six scalar equations. We can numerically solve the system of nonlinear equations for the six unknown variables. Note that since $U \times B$ is continuous across each of the MHD shocks and rotational discontinuities, conditions 1 and 3 guarantee that $U$ is also continuous across the contact discontinuity. Following the procedure outlined above, we have obtained a numerical solution which satisfies the jump conditions across the four shock waves, two rotational discontinuities, and one contact discontinuity. Important parameters of the solution identified with each shock and rotational discontinuity obtained from this example are listed in Table 1.

![Fig.7](image)

Fig.7. A coordinate system attached to the transition line T is used for the analysis of the flow conditions in the immediate neighborhood of T. The z axis is tangential to the transition line and the x,y plane is parallel to the magnetic field vector B upstream of the shock system. We study a simple case in which the upstream solar wind velocity relative to the shock system $U$ is parallel to the x,y plane. The direction of the x axis is chosen in such a way that $U_x$ is positive upstream of the shock system. S1, R1, and F1 denote the discontinuities inside the closed loop of the transition line. S2, R2, and F2 are outside the closed loop. The flow downstream of S1 and F2 is separated by a contact discontinuity.

Once the normal directions of F2 and S1 are given, we can calculate the three upstream shock parameters ($A$, $\beta$, and $\phi$) for each shock. Once again, we can solve the nonlinear algebraic system (equations (16), (7), (11), and (13)) to determine the flow conditions downstream of the two shocks. In summary, the flow conditions downstream of S1 and F2 are functions of six parameters: the normal directions of the four shock waves and the rotational angles of the two rotational discontinuities. The six parameters are treated as six unknown variables to be determined by boundary conditions for the flows downstream of S1 and F2.

The flows downstream of S1 and F2 are separated by a contact discontinuity. Across the contact surface the flow must satisfy three conditions: (1) the magnetic field $B$ be continuous, (2) the thermal pressure $p$ be continuous, and (3) the velocity vectors be parallel. The three conditions are actually represented by six scalar equations. We can numerically solve the system of nonlinear equations for the six unknown variables. Note that since $U \times B$ is continuous across each of the MHD shocks and rotational discontinuities, conditions 1 and 3 guarantee that $U$ is also continuous across the contact discontinuity. Following the procedure outlined above, we have obtained a numerical solution which satisfies the jump conditions across the four shock waves, two rotational discontinuities, and one contact discontinuity. Important parameters of the solution identified with each shock and rotational discontinuity obtained from this example are listed in Table 1.

If $B_z = 0$ upstream of the slow-fast shock system, $B_z = 0$ everywhere in the immediate neighborhood of $T$. The rotational angles are zero for both R1 and R2. The problem is reduced to solving a nonlinear system for four unknown directional angles of the shocks.

The analysis of the flow conditions in the immediate neighborhood of the transition line suggests that during the transition process the large-scale slow-fast shock system can have a configuration as shown in Figure 6. This model

### Table 1. An Illustrative Example for the Slow-Fast Shock System

<table>
<thead>
<tr>
<th>Discontinuity</th>
<th>S1</th>
<th>S2</th>
<th>F1</th>
<th>F2</th>
<th>R1</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Direction of Each Discontinuity</td>
<td>$\arctan(n_y/n_x)$</td>
<td>-48.8</td>
<td>-44.0</td>
<td>34.6</td>
<td>37.2</td>
<td>9.7</td>
</tr>
<tr>
<td>Direction of $U$ and $B$ Behind Each Discontinuity</td>
<td>$\arctan(U_y/U_x)$</td>
<td>21.2</td>
<td>32.3</td>
<td>18.2</td>
<td>21.2</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>$\arctan(U_y'/U_x')$</td>
<td>4.3</td>
<td>1.1</td>
<td>3.4</td>
<td>4.3</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>$\arctan(B_y'/B_x')$</td>
<td>-13.2</td>
<td>-1.7</td>
<td>-11.4</td>
<td>-13.2</td>
<td>-11.4</td>
</tr>
<tr>
<td></td>
<td>$\arctan(B_z'/B_x')$</td>
<td>12.4</td>
<td>9.7</td>
<td>12.8</td>
<td>12.4</td>
<td>12.9</td>
</tr>
<tr>
<td>Rotation Angle of $B_z$</td>
<td>-0.02</td>
<td>7.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jump Conditions of the Four Shocks</td>
<td>$\beta_1$</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.322</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
<td>0.474</td>
<td>0.467</td>
<td>1.476</td>
<td>1.663</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_1$</td>
<td>39.15</td>
<td>46.89</td>
<td>35.84</td>
<td>41.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B_z/B_1$</td>
<td>0.976</td>
<td>0.972</td>
<td>1.196</td>
<td>1.207</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\rho_2/\rho_1$</td>
<td>1.296</td>
<td>1.283</td>
<td>1.271</td>
<td>1.239</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_2/T_1$</td>
<td>1.195</td>
<td>1.186</td>
<td>1.173</td>
<td>1.174</td>
<td></td>
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<tr>
<td></td>
<td>$p_2/p_1$</td>
<td>1.548</td>
<td>1.521</td>
<td>1.432</td>
<td>1.455</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_2$</td>
<td>0.325</td>
<td>0.322</td>
<td>0.200</td>
<td>0.322</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_2$</td>
<td>0.416</td>
<td>0.412</td>
<td>1.336</td>
<td>1.493</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_2$</td>
<td>37.36</td>
<td>43.19</td>
<td>47.34</td>
<td>51.44</td>
<td></td>
</tr>
</tbody>
</table>
for the transition process infers that a traveling forward slow shock observed in the inner solar wind can be part of a single bow-shaped slow shock surface or of a complicated slow-fast shock system. It also infers that the transition process provides a mechanism which generates rotational discontinuities in interplanetary space. The presence of shock-rotational discontinuity sequences in the observational data (C. F. Kennel, private communication, 1986) possibly supports the existence of slow-fast shock systems predicted by this model.

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References


EVOLUTION OF INTERPLANETARY SLOW SHOCKS

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Abstract. The possible existence of traveling forward slow shocks, their global geometry and their transition to forward fast shocks have been discussed in a recent paper. The decrease in the Alfven speed at increasing heliocentric distance causes the evolution of a forward slow shock into a forward fast shock. During the transition the shock system consists of a slow shock, a fast shock, and a rotational discontinuity. This paper continues to discuss three aspects about the evolution of interplanetary slow shocks. We first present a survey of slow shock solutions in a three-dimensional $A, \beta, \theta$ parameter space. Here $A = U_n / (a \cos \theta)$ is the shock Alfven number, $U_n$ the normal component of the relative shock speed, $a$ the Alfven speed, $\theta$ the acute angle between the shock normal and the magnetic field, and $\beta$ the ratio of the thermal pressure $p$ to the magnetic pressure $B^2 / 8 \pi$. Two kinds of MHD shocks, their global geometry and total pressure (the sum of the thermal and the magnetic pressures) all increase across an MHD shock. The magnetic field and the shock angle decrease across a slow shock and increase across a fast shock. Observations of slow shocks have been reported by Chao and Olbert [1970], Burlaga and Chao [1971], Richter et al. [1985], and Feldman et al. [1985]. In a recent paper [Whang, 1987] (hereafter referred to as paper I), we studied traveling interplanetary forward slow shocks and their transition to forward fast shocks in the inner solar wind. In coronal space, the Alfven number of an MHD shock in the inner solar wind can be less than 1 and the shock can be a slow shock. An important characteristic of slow shocks (and slow MHD waves) is that they are upstream-inclined [Sears and Resler, 1961]. The large-scale global surface of a forward slow shock should have a bow-shaped surface with its nose facing the Sun. Recently, Hundhausen et al. [1987] studied the outward motion for coronal mass ejections observed by the Skylab coronagraph and the SMM coronagraph. Their conclusion supports the possible formation of forward slow MHD shocks immediately in front of some coronal mass ejections. They pointed out that in a diverging radial background field a large-scale traveling forward slow shock may have a rather flat configuration, because the upstream inclined nature of forward slow MHD shocks is relative to the magnetic field geometry. Thus, the observed flattening of the tops of some mass ejection loops support the possible existence of traveling forward slow shocks. The Alfven speed decreases at increasing heliocentric distance in the inner solar wind. The variation of the shock speed relative to the solar wind flow is not well understood. Presume that the Alfven speed decreases at a rate faster than the relative shock speed if the relative shock speed also decreases at increasing heliocentric distance. Then as a forward slow shock travels outwards from the Sun, the decrease in the Alfven speed causes the shock Alfven number of a forward slow shock to become greater than 1 at increasing heliocentric distances and the shock evolves from a forward slow shock into a forward fast shock. Because the fast-mode MHD waves and MHD shocks are downstream-inclined, the large-scale global surface of a traveling forward fast shock has a bow-shaped surface with its nose facing away from the Sun. Paper I suggested a possible process for the transition of a forward slow shock to a forward fast shock. During the transition, the system consists of a forward slow shock, a forward fast shock, and a forward rotational discontinuity. The three surfaces of discontinuity intersect along a closed transition line. At the onset of the transition process the fast shock and the rotational discontinuity are very weak. As the...
of the MHD shock equations as functions of three dimensionless upstream parameters: the shock Alfvén number \( A \), the shock angle \( \theta \), and \( \beta \). The subscript 1 denotes the flow condition on the front side (upstream) of a shock, and 2 denotes the flow condition on the back side (downstream). The plasma density \( \rho \), the thermal pressure \( p \), and the total pressure \( p^* \) (the sum of the thermal and the magnetic pressures) all increase across an MHD shock. The magnetic field and the shock angle decrease across a slow shock. The decrease in shock angles across a slow shock may be called the deflection angle \( \delta \). In this section, we present the solution of slow shocks in a three-dimensional parameter space, the \( A,\theta,\beta \)-space as shown in Figures 1-3. All calculations are carried out using the ratio of specific heats \( \gamma = 5/3 \) for fully ionized plasma. A parametric study of MHD slow shocks in different combinations of two-dimensional parameter space has also been reported by Edmiston and Kennel '1956'.

Let us first examine the domain in which slow shock solutions exist in the three dimensional parameter space (Figure 1). Slow shocks exist at all shock angles (from \( 0^\circ \) to \( 90^\circ \)) and at all values in a certain interval of the shock Alfvén number \( A \).
discontinuities in density, then from Figure 2 we can reach a conclusion that slow shocks covering a wide range of strength for the discontinuity in density (from very weak to moderately strong) exist in the low β region (where $\beta_1 < 0.1$). On the other hand, only weak discontinuities in density exist in the high β region (where $\beta_1 > 1$). Next, we study the discontinuities in pressure for slow shocks. From a plot of the pressure ratios in Figure 3 we can reach the same conclusion. In the coronal space where the β value of the solar wind is much less than 1, the jump in thermodynamic properties across a slow shock may vary over a wide range. On the other hand, near 1 AU where the average β value of the solar wind is on the order of 1, the jump in thermodynamic properties across a slow shock is always very weak.

The jumps in other physical properties offer different ways to measure the effect of an MHD slow shock on the plasma and fields. The constant contours for $B_y/B_1$ at $\beta = 0.2$ were plotted in Figure 1 of paper 1. A whole range of changes in $B_y/B_1$ from 0 to 1 may take place in the domain of slow shock solutions at $\beta = 0.2$. Across an MHD shock the magnetic field vector abruptly changes its direction by the deflection angle. The relative flow velocity also make a sudden change in its direction across an MHD shock by an angle approximately in the similar magnitude as the deflection angle. Constant contours for the deflection angle, $0 \leq \delta \leq 90^\circ$, were plotted in Figure 4 of paper 1. All field-related properties, such as $B_y/B_1$ and $\delta$, change over the same ranges in the domain of slow shock solutions for any given value of $\beta_1$.

The plasma β value is on the order of 0.1 in coronal space, it increases at increasing heliocentric distance. In the region where the plasma β value is on the order of 0.1 or less, all physical properties may jump across a slow shock over a wide range magnitudes. Near 1 AU where the plasma β value is on the order of 1 or greater, the jumps in thermodynamic properties across a slow shock must be small but the jumps in field-related properties are not necessarily small. Traditionally, we measure the strength of a shock by the jump in density or pressure across the shock ($\rho_2/\rho_1$ or $\rho_2/\rho_1$). Actually, 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 one. When the discontinuities in thermodynamic properties are small, the identification of a slow shock becomes difficult from plasma observations.

3. Onset of the Transition Process

It is convenient to discuss the onset of the transition process using an AB coordinate system as shown in Figure 4. Here A is the shock Alfven number and B stands for the ratio of the magnetic field $B_y/B_1$. We may call the region in which both $A$ and $B_y/B_1$ are greater than 0 and less than 1 a slow region, the quadrant in which both $A$ and $B_y/B_1$ are greater than 1 the fast quadrant, and the point at which both A and $B_y/B_1$ are unity the Alfven point. The domain of solutions for slow shocks is limited to the slow region in the AB plane. As discussed in the previous section, the domain shrinks as the plasma $\beta_1$ value increases. The domain of solutions for the fast shocks is
becomes weaker on the flank and asymptotically switch-on shocks. Switch-on shocks and near
should be relatively stronger at the nose. It neighborhood of the parameter space are near
Alfven number is less than
surface of the forward slow shock the shock space. The shocks
solar wind frame of reference. On the curved shocks in this neighborhood of the parameter
bounded by the discontinuity surface of the Figure 5 we can see that the deflection angles
nose facing the Sun. A large pressure jump than
solar wind having a bow-shaped surface with its fast shock near the nose are slightly g-eater
of the AB plane.

Rotational discontinuities and Alfven waves are When a forward transition system consisting of
located on the slow region of the AB plane.

It varies from point
to point. The slow shock must occur in the region of interplqnetary spac-e A
limited to the fast quadrant of the AB plane. Rotational discontinuities and Alfven waves are represented by a single point, the Alfven point of the AB plane.

A forward slow shock can travel in the inner solar wind having a bow-shaped surface with its nose facing the Sun. A large pressure jump bounded by the discontinuity surface of the forward slow shock propagates forward in the solar wind frame of reference. On the curved surface of the forward slow shock the shock Alfven number is less than 1 everywhere, although it becomes weaker on the flank and asymptotically approaches slow mode MHD waves. Across all points of this single surface the shock solutions are located on the slow region of the AB plane.

As the forward slow shock travels outwards from the Sun, the decrease in the Alfven speed causes the shock Alfven number to reach 1 near the nose of the shock surface, the transition from a forward slow shock to a forward fast shock begins to take place. At the onset of the transition process the interplanetary forward slow shock smoothly converts to a system consisting of a forward slow shock, a very weak forward rotational discontinuity (an Alfven wave), and a very weak forward fast shock (a fast MHD wave). On the AB plane the mapping of the slow shock solutions near the nose lies in the immediate neighborhood of the Alfven point in the slow region. As shown in the lower panel of Figure 4 the shock angle approaches 0°. The limiting case of the shock is a gasdynaminc normal shock with finite strength. The slow shock continues to carry the finite jumps in pressure and density and propagates in the solar wind frame. The rotational discontinuity maps with the Alfven point. On the AB plane, the newly generated weak fast shock maps with points in the immediate neighborhood of the Alfven point in the fast quadrant.

A smooth conversion requires that at the onset of transition the three discontinuity surfaces (the slow shock, the weak rotational discontinuity, and the new fast shock) move at the same speed. In Figure 4, the upper panel plots the solution curves for MHD shocks on the AB plane with \( \beta > 2/\gamma \) and the lower panel plots the solution curves with \( \beta < 2/\gamma \). When \( \beta > 2/\gamma \), fast shock solutions do not exist near the Alfven point in the AB plane. Thus, a smooth conversion at the onset of transition is not possible when \( \beta > 2/\gamma \) or 1.2. The onset of transition must occur in the region of interplqnetary space where \( \beta < 2/\gamma \) or 1.2.

4. Turbulent Flow behind the Fast Shock

Figure 5 shows the constant contours of deflection angle and the pressure ratio in the domain of fast shock solutions in the AB plane at a given \( \beta \) value. The shock Alfven number of fast shocks has a lower limit

\[
A^2 > \frac{1 + \gamma \beta_1/2 + (1 + \gamma \beta_1/2)^2 - 2\gamma \beta_1 \cos^2 \theta_1}{2 \cos^2 \theta_1}
\]

At the lower limit the fast shock approaches a fast magnetoacoustic wave, the deflection angle \( \delta \) equals 0, and there is no jump in any physical property.

When a forward transition system consisting of a slow shock, a fast shock, and a rotational discontinuity propagates in interplanetary space with \( \beta < 1.2 \), the shock Alfven numbers of the fast shock near the nose are slightly greater than 1 and the shock angles are very small. From Figure 5 we can see that the deflection angles are quite significant and change rapidly for fast shocks in this neighborhood of the parameter space. The shocks significantly change the directions of the magnetic field and the relative flow velocity. The fast shocks in this neighborhood of the parameter space are near switch-on shocks. Switch-on shocks and near switch-on shocks may exist in the region where \( \beta < 1.2 \). Small random fluctuations in plasma flow and magnetic fields on the front side of the
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Fig. 5. When a transition system propagates in interplanetary space with $\beta < 1.2$, the shock Alfven numbers of the fast shock near the nose are slightly greater than 1 and the shock angles are very small. In this neighborhood of the parameter space, the fast shocks significantly change the directions of the magnetic field and the relative flow velocity. Small random fluctuations in plasma flow and magnetic fields on the front side of the shock are considerably amplified. The flow becomes very turbulent and the amplitude of fluctuations in flow velocity and magnetic fields are large in the turbulent region behind the fast shock.

shock are considerably amplified across the near switch-on shocks. The flow becomes very turbulent behind the 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. When ISEE-1 and -3 observed a possible forward transition system consisting of a forward fast shock ahead of a rotational discontinuity on November 12, 1978, an intense MHD turbulence was also observed in the region between the two discontinuity surfaces [Kennel et al., 1984b].

5. Summary

In this paper, we discuss three aspects of traveling interplanetary forward slow shocks: (1) A survey of slow shocks in a three-dimensional parameter space, (2) the onset of the transition process, and (3) the turbulent nature of the flow field behind the fast shock during the transition process.

The parametric study shows that in the region where the plasma $\beta$ value is of the order of 0.1 or less, the jumps of all physical properties across a slow shock may vary over a wide range of magnitudes. On the other hand, in a region where the plasma $\beta$ value is on the order of 1 or greater, the jumps in thermodynamic properties across a slow shock are small but the jumps in field-related properties are not necessarily small.

Next, we use a graphical demonstation to explain that the onset of the transition process can occur in the region of interplanetary space where $\beta < 2/\gamma$ or 1.2. At the onset of the transition process the interplanetary slow shock near the nose of the slow shock smoothly converts to a system consisting of a slow shock, a very weak rotational discontinuity (an Alfven wave), and a very weak fast shock (a fast MHD wave). The three surfaces of discontinuity move at nearly the same speed (the Alfven speed) in the solar wind frame of reference.

Finally, we show that during the transition, the amplitude of fluctuations in flow velocity and magnetic fields are large in the turbulent region behind the fast shock.

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References


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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 form 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 also showed that transition from traveling forward slow shock to a forward fast shock can take place in interplanetary space. This paper suggests that a reverse slow shock associated with CMEs can form under some circumstances, and it shows that when such a shock is present it will evolve into reverse fast shock.

The solutions of magnetohydrodynamic (MHD) shocks may be expressed as functions of three dimensionless upstream parameters: the shock Alfvén number based on the relative shock speed A = U/A (a cos θ), the shock angle θ, and the plasma β value. Here U is the normal component of the relative shock speed, A the Alfvén speed, θ the angle between the shock normal and the magnetic field, and ß the ratio of the thermal pressure p to the magnetic pressure B²/8π. Two kinds of MHD shocks, the fast and the slow shocks, may exist. A shock is a slow shock if the shock Alfvén number A is less than 1, a fast shock if A is greater than 1. In coronal space, the Alfvén speed is on the order of 1000 km/s. If a forward MHD shock forms preceding the compressed ambient plasma shell associated with the CME, the shock Alfvén number can be less than 1 and the shock can be a forward slow shock. The plasma density ρ, the thermal pressure p, and the total pressure p*(a sum of the thermal and the magnetic pressures) all increase across an MHD shock. The magnetic field and the shock angle decrease across a slow shock and increase across a fast shock. The change in shock angle across an MHD shock may be called the deflection angle. Edmiston and Kennel [1986] and Whang [1988] have studied the slow shock solutions for the jumps of physical properties as functions of various combinations of dimensionless parameters.

The plasma β value plays an interesting role in the jumps of thermodynamic properties across slow shocks. In coronal space where the β value of the solar wind is on the order of 10 or less, the discontinuity in thermodynamic properties across a slow shock may vary over a wide range of magnitudes. On the other hand, near 1 AU where the average β value of the solar wind is on the order of 1, the jump in thermodynamic properties across a slow shock becomes very small. The jumps in field-related properties behave quite differently. At any given values of β, in the domain of solutions for slow shocks the magnetic field ratio B²/B₀ changes over a whole range, from 0 to 1, and the deflection angle also changes over a whole range, 0 ≤ ð ≤ 90°. 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 150° of the angular extents of the CMEs measured at 1 AU.

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. [1978] 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
is greater than \( C_0 \) 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-\( B \) plasma in the coronal environment. The possible observation of forward slow shocks associated with CME by Hundhausen et al., 1987 provides 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 to \( 90^\circ \). Observation of forward slow shocks associated with CMEs observed from the coronagraphs aboard Skylab but less than a \( \cos \theta \). The deflection angle \( \delta \) approaches zero and the ratio of the total pressure \( p^* \) to \( p^0 \) 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 velocity 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.t-d 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 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 stream also leads to the formation of a corotating forward-reverse shock pair [Dessler and Fejer, 1961; Sonnett and Colburn, 1965; Whang and Chien, 1981]. The region bounded by 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
Coronal Mass Ejection

Background Corona

Heliocentric distance r

Fig. 2. 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 ambient solar wind. 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.

1. 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 very far into interplanetary space, 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 higher than average, the magnetic field direction rotates monotonically through a large angle, the temperature is low, and the plasma $\beta$ 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. Klim and Burlaga [1982] identified 42 clouds in interplanetary data obtained near 1 AU between 1981 and 1982. 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 0.3 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

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 1 that seems to resemble the forward transition system. On November 10, 1978, the passage over the ISCM spacecraft of a high-speed, quasi-parallel, interplanetary forward fast shock with \( V_A = 240 \) \( \text{km s}^{-1} \), \( \theta_1 = 41^\circ \), \( a_1 = 160 \) \( \text{km s}^{-1} \), and \( a_1 = 114 \). 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

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**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.

- The normal vectors \( n \) denote 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 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 \( \theta \approx \pi/q \) or \( \approx 1.2 \).

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 outwards from the Sun, the transition line moves laterally across the field lines. At the area enclosed by the closed loop of the transition line, 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 reverse 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 shock 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 one month. The cloud had a dimension of the order of 1 AU and was preceded by two shocks and an interface 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.

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CME ASSOCIATED FORWARD-REVERSE SHOCK PAIRS

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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 form 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 into 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.

INTRODUCTION

The solutions of MHD shocks /1/ may be expressed as functions of three dimensionless upstream conditions: the shock Alfven number based on the relative shock speed \( A = U_{sh}/(a_C \cos \theta) \), the shock angle \( \phi \), and the plasma \( \beta \) value. (Here \( U_{sh} \) is the normal component of the relative shock speed, \( a_C \) the Alfven speed, \( \theta \) the acute angle between the shock normal and the magnetic field, and \( \beta \) the ratio of the thermal pressure \( p \) to the magnetic pressure \( B^2/8\pi \)). A shock is a slow shock if the shock Alfven number \( A \) is less than 1 and is a fast shock if \( A \) is greater than 1. The magnetic field and the shock angle decrease across a slow shock, they increase across a fast shock.

The association between interplanetary shocks and CMEs has been clearly demonstrated using shocks detected at Helios 1 and CMEs observed from Solwind coronagraph /2/. In 1989, Whang first suggested the possible existence of forward slow shocks preceding some CMEs and the transition of slow shocks to fast shocks /1,3/. The theory was reported at the XXVI COSTAR Meeting at Toulouse in July 1986. Whang explained that when the speed of ejected CME material relative to the ambient solar wind exceeds the local magnetoacoustic speed, an MHD shock front forms at the leading edge of the compressed ambient plasma shell. In coronal space, the Alfven speed is of the order of 1000 km/s. If a forward MHD shock forms preceding the compressed ambient plasma shell associated with the CME, the shock Alfven number can be less than 1 and the shock can be a forward slow shock.

Whang also discovered the large scale geometries of forward slow and fast shocks, and the transition of slow shocks to fast shocks in the inner solar wind. The large scale global surface of a forward slow shock should have a bow-shaped surface with its nose facing the sun because the slow mode MHD waves and MHD shocks are upstream aligned. The relative shock speed varies from point to point on the curved surface of a slow shock. The slow shock is relatively stronger at the nose. The shock becomes weaker on the flank and asymptotically...
Fast shock of a 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.

Kennel et al. /6,7/ reported the observation of a rotational discontinuity preceded by a forward shock from ISEE 1 and 3. On 12 November 1978, the passage over the ISEE spacecraft of a high speed, quasi-parallel, interplanetary forward fast shock with \( V_{\parallel} = 260 \text{ km s}^{-1} \), \( \beta = 410 \), \( a_1 = 160 \text{ km s}^{-1} \) and \( \beta_1 = 1.14 \). The shock was probably associated with a pair of flares which occurred some 48 hours earlier. The shock is followed by a strong magnetic field rotation at approximately 40 RE downstream of the shock, and an extended region of intense MHD turbulence between the shock and the magnetic field rotation. This sequence of events observed from ISEE 1 and 3 seems to resemble a forward transition system.

INTERPLANETARY MANIFESTATION

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, for some coronal mass ejections (CMEs), the direct impact of the high-speed mass ejecta on the ambient solar wind 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 outwards in interplanetary space, they evolve into a pair of fast shocks.

MacQueen /8/ suggested that CMEs do not carry out distended field very far to interplanetary space, 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.

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 as shown in Figure 3. The cloud is now wrapped around by an interaction region which is itself bound by a pair of forward-reverse fast shocks.

Burlaga and his coworkers /9-11/ identified a magnetic cloud as an interplanetary structure in which the magnetic field strength is higher than average, the magnetic field direction rotates monotonically through a large angle, the temperature is low, and the plasma \( \beta \) is significantly lower than 1. Clouds may persisted to the heliocentric distances of 2 to 4 AU. They also suggested an association of some clouds with disconnected magnetic structures of

![Fig. 3](image-url) The reverse shock propagates within the cloud as it moves outward from the Sun. Eventually, the reverse shock exits the cloud to become detached from the magnetic cloud. The cloud is now wrapped around by an interaction region which is itself bound by a pair of fast shocks.
Two recent papers reported the observations of CME associated forward-reverse shock pairs at near 1 AU. Lepping, Ipavich and Burlaga (13) reported that a large magnetic cloud accompanied by a shock pair was observed on October 31 and November 1 of 1972 from IMP 7. The plasma, magnetic field and energetic particle data observed a forward shock wave followed by a large tangential discontinuity and a reverse shock. The tangential discontinuity was the forward boundary of the magnetic cloud. The reverse shock was within the cloud. The flow system was associated with a unusually long lasting solar flare which occurred some 49 hours earlier. Gosling et al. (14) reported that they have identified two CME associated forward-reverse shock pairs at 1 AU using plasma and magnetic field data from ISEE 3 for the interval from August 1978 through February 1980. The shock pairs were closely associated with the propagation of transient disturbances. Strong bidirectional electron heat flux events, which they identified as the CME driving the shocks, were detected during both of these disturbances. In the stronger of the two disturbances the reverse shock was found within the CME and was separated from the forward shock by 0.2 AU. In the weaker of the two disturbances the reverse shock had propagated entirely through the CME and trailed the forward shock by 0.3 - 0.4 AU.

Burlaga et al. (15) reported another event observed at 10.3 AU from Voyager 2 on August 1982 involving forward, reverse shock waves and a magnetic cloud on August 1982 from Voyager 2. The observed cloud remained stable out to 10.3 AU after a propagation time of approximately 1 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 indicates 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.

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