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A REVERSE HYDROMAGNETIC SHOCK IN THE SOLAR WIND

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I. Introduction.

A hydromagnetic shock propagating away from the sun is seen by a fixed observer as a discontinuous increase in the plasma density, $n$, proton temperature, $T$, bulk speed, $V$, and the magnetic field intensity, $B$. It is possible that a similar shock may propagate toward the sun, relative to a frame moving with the solar wind, yet move outward relative to a fixed observer, the net outward motion being due to convection by the solar wind. In this case, one sees the rear of the shock first, so $n$, $T$ and $B$ are seen to decrease discontinuously, while the speed $V$ increases. Such a discontinuity is called a reverse shock. (e.g., see Razdan et al., 1965).

This paper presents quantitative evidence for such a shock in the solar wind. Using Ness's magnetic field data from three spacecraft, the shock is shown to be oriented along the spiral direction. It is also shown that the shock separates a high speed wind stream from a region of gas that appears to have been compressed and heated by the speed stream.

II. Description of the Discontinuity.

The discontinuity that we shall identify as a shock is shown by the dashed line in Figure 1, which is a plot of plasma and magnetic field data from Explorer 34. (For a description of the instruments, see Ogilvie et al., 1968, and Fairfield, 1969). The signature is clearly that of a reverse shock. Table I shows that $n$, $T$ and $B$ decrease by nearly a factor of 2 across the discontinuity. Higher time resolution data shows that the decrease in $B$ occurred in less than $\sim 5$ sec at $\sim 2243$ UT on 28 Sept., 1967. The change in the plasma parameters seems to occur over several minutes.
The gradualness may be illusory because of the relatively large fluctuations (see Figure 1). The energy density, defined by \( P = B^2/8\pi + nk(T_eT) \) with \( T_e = 1.5 \times 10^5 \)K (see Burlaga and Ogilvie, 1970 for a review of measurements of \( T_e \)) decreases by nearly a factor of 2 across the discontinuity, primarily because of the change in \( B \).

The magnetic field direction, \( \mathbf{B} \), did not change appreciably across the discontinuity. From 1.5 min. averages of components of \( \mathbf{B} \) measured before and after the discontinuity, we find \( \mathbf{B}_1 = (-.49, .59, .64) \), and \( \mathbf{B}_2 = (-.42, .59, .69) \) in solar ecliptic coordinates (\( X \) toward the sun, \( Z \) normal to the ecliptic). The magnitude of \( \mathbf{B} \) did change across the discontinuity while the direction did not, so the field has to be parallel to the surface of the discontinuity since \( [B_n] = 0 \).

The flow direction was not measured precisely, but the flow did change in less than 3 min from a direction >5.9\(^\circ\) west of the sun earth line in region 1 to <5.9\(^\circ\) W. in region 2 at the time of the discontinuity.

III. Identification of the Discontinuity as a Reverse Shock.

Basic Equations. To show that a discontinuity is a reverse shock, one must show (1) that it propagates relative to the plasma in the sunward direction, (2) that \( n \) decreases across the shock, and (3) that the changes in the fluid parameters satisfy the Rankine-Hugoniot equations which are as follows:

\[
\begin{align*}
[nv_n] &= 0 \\
[\phi v_n] - B_n B_p \gamma (4\pi n) &= 0 \\
[p v_n^2 + p] &= 0 \\
\left(\frac{v_n^2 + v_p^2}{2}\right) + \frac{\gamma nkT}{p} + \frac{B_p^2}{4\pi p} + \frac{B_p B_n v_p^2}{4\pi p v_n} &= 0
\end{align*}
\]
where \( v_n = V_n - U \).

The subscripts \( n \) and \( p \) denote components of vectors normal and parallel to the shock surface, respectively; \( U \) is the speed of the shock surface (assumed plane) in the direction of its normal, relative to a fixed observer; \( \rho \) is the mass density. Our method is to use (1) and (2) in the determination of \( U \) and the shock normal \( \hat{n} \), and then show that the data in Table I satisfy (3) and (4).

From (1) and (5), we get

\[
U = \frac{n_1 V_{1n} - n_2 V_{2n}}{n_1 - n_2} \quad (6)
\]

From (1) and (2), \( v_{1p} = v_{2p} \) (assuming \( B_n = 0 \)), which with (5) gives

\[
v_{1p} = v_{2p} \quad (7)
\]

Let \( \omega \) be the angle between \( V_2 \) and \( \hat{n} \), and let \( \omega + \epsilon \) be the angle between \( V_1 \) and \( \hat{n} \). Then

\[
v_{1p} = V_1 \sin(\omega + \epsilon) \quad (8)
\]

\[
v_{2p} = V_2 \sin \omega \quad (9)
\]

and (7) gives

\[
\epsilon \sim \frac{(V_2 - V_1) \tan \omega}{V_1} \quad (10)
\]

for small \( \epsilon \). From (6) one finds that \( U \) is given by

\[
U \sim \frac{n_1 V_1 (\cos \omega - \epsilon \sin \omega) - n_2 V_2 \cos \omega}{n_1 - n_2} \quad (11)
\]

In the next section it is shown that to determine \( \hat{n} \) we need \( V_s \equiv U/\cos \omega \), where \( \omega \) is the angle between \( \hat{n} \) and the radial direction. If \( V_2 \) is nearly radial, as it surely is, we may set \( \omega = \omega \); the consequent small error does not contribute significantly to the uncertainty in \( \hat{n} \).
Thus,
\[ V_s \approx \frac{V}{\cos \omega} = \frac{n_1 V_1(1-\epsilon \tan \omega) - n_2 V_2}{n_1 - n_2} \tag{12} \]

The quantities \( \epsilon \) and \( \omega \) can be determined by the following method of successive approximations. Assume \( \epsilon = 0 \) and compute \( V_s \) from (12). With this, compute \( \omega \) from (15), (16), and (17) below, and then get a better estimate of \( \epsilon \) from (10). Repeat the process until \( \epsilon \) and \( \omega \) have the desired accuracy.

**Surface Orientation.** The discontinuity in the 
was observed minutes apart at 3 spacecraft, Explorers 33, 34 and 35, separated by tens of earth radii, as shown in Table II. If the shock can be approximated by a plane on a scale of the spacecraft separations (<100RE), the measured time delays can be used to calculate the orientation as a function of the radial speed of the surface \( V_s \). Let \( \theta \) be the angle between the normal to the boundary surface and the ecliptic plane (\( \theta = 0 \) implies a boundary normal to the ecliptic, \( \theta > 0 \), if the normal is above the ecliptic). Let \( \varphi \) be the angle between the line determined by the intercept of the boundary surface with the ecliptic plane and a line in the ecliptic which is perpendicular to the earth-sun line. (\( \varphi = 45^\circ \) implies a plane along the spiral direction; \( \theta = 0 \), \( \varphi = 0 \) implies a plane normal to the earth-sun line). Then

\[ V_s = A + B \tan \theta \tag{13} \]
\[ \tan \varphi = C V_s + E \tan \theta + D, \tag{14} \]

where
\[ A = \frac{(X_2 Y_1 - X_1 Y_2)}{(t_1 Y_2 - t_2 Y_1)}, \]
\[ B = (Z_1 Y_2 - Z_2 Y_1)(t_1 Y_2 - t_2 Y_1), \]
\[ C = -\frac{t_2}{Y_2}, D = -\frac{X_2}{Y_2} \text{ and } E = \frac{Z_2}{Y_2}. \]

Here \((X,Y,Z)\) is the position of Explorer 34 (subscript 1) or Explorer 35 (subscript 2) relative to Explorer 33, in solar ecliptic coordinates, and the times \( t_1, t_2 \) are the time intervals during which the boundary
moves from Explorer 33 to Explorer 34 and 35, respectively.

The coordinates of Explorer 33 are (23.72, 36.73, 11.78). Using

the data in Table 2 we derive from (13) and (14) the following relations

\[
\tan \theta = (2.3 \pm 0.8) \times 10^{-3} V_s (\text{km/sec}) - (0.7 \pm 0.3) \quad (15)
\]

\[
\tan \varphi = (2.65 \pm 1.15) \times 10^{-3} V_s (\text{km/sec}) - (0.04 \pm 0.02) \quad (16)
\]

The components of the shock normal are

\[
\begin{align*}
    n_x &= -\cos \omega - \cos \theta \cos \varphi \\
    n_y &= -\cos \theta \sin \varphi \\
    n_z &= \sin \theta
\end{align*}
\]

(17)

Results. Using the numbers in Table II and the iteration procedure
discussed above, one finds \( \varepsilon = 4.8^\circ \) and \( \omega = 45.3^\circ \). Equation (11)
then gives \( U = 270 \text{ km/sec} \). From (12), (15) and (16) one gets \( \theta = 10.4^\circ \),
\( \varphi = 44.4^\circ \) which with (17) gives the shock normal \( \textbf{n} = (-.70, -.69, .18) \).

Thus, the surface is nearly perpendicular to the ecliptic plane and
aligned along the spiral direction. The speed of the surface along
\( \textbf{n} \) relative to a fixed frame \( U = 270 \text{ km/sec} \) is less than the normal
component of the solar wind on the sunward side, \( V_{2n} = V_2 \cos \omega = 411 \text{ km/sec} \). This gives an important result: The surface is propagating in
the sunward direction (along - \( \textbf{n} \)) relative to the solar wind, at a
speed \( \frac{V_{2n}}{2} = 141 \text{ km/sec} \). The normal flow speed behind the shock is
\( V_{1n} = V_1 \cos (\omega + \varepsilon) - U = 76 \text{ km/sec} \). Thus, the relative normal speed
diminishes across the discontinuity, as it must if the discontinuity
is a shock.

The angle between the normal \( \textbf{n} \) and the field \( \textbf{B} \) on either side
of the shock is \( \cos^{-1} (\textbf{n} \cdot \textbf{B}) = 87^\circ \). Thus, the field is parallel to
the shock surface, as required by the fact that \( \frac{B_1}{B_2} = \frac{B_1}{B_2} \). Hence, the
assumption $B_n = 0$, used to derive (7), is valid. As a check on the validity of (7), note that $V_{1p} = V_1 \sin(\omega + \epsilon) = 414 \text{ km/sec}$ and $V_{2p} = V_2 \sin \omega = 416 \text{ km/sec}$.

Now let us show that the data satisfy (3). This equation can be written

$$P_{V_2}^2 - P_{V_1}^2 = P_{V_1}^1,$$  \hspace{1cm} (3')

where $P = nk(T + T_e) + B^2/8\pi$, which says that the pressure change across the surface must be balanced by a change in the momentum flux normal to the surface. From Table I, $P_{V_1}^1 = (8.0 \pm 1.5) \times 10^{-10} \text{ ergs/cm}^3$. Using the values of $v_{1n}$ and $v_{2n}$ above, we find $P_{V_1}^2 = 8.6 \times 10^{-10} \text{ ergs/cm}^3$. Thus (3') is satisfied within the errors.

Finally, consider (4). Since $v_{1p} = v_{2p}$ and $B_n = 0$, this can be written

$$\frac{v_{n1}^2}{2} = \left( \frac{v}{\gamma - 1} \left( \frac{nk(T + T_e)}{\rho} + \frac{B_p}{4\pi p} \right) \right)^{1/2}.$$ \hspace{1cm} (4')

The change in $v_{n1}^2/2$ is $7.1 \times 10^3 (\text{cm/sec})^2$. If $T_e = 1.5 \times 10^5 \text{K}$ as discussed above, and if $\gamma = 5/3$, we find that the change in the RHS of (4') is $5.5 \times 10^3 (\text{cm/sec})^2$. Since the uncertainty in the RHS of (4') is certainly >50%, we conclude that (4) is satisfied within the errors.

We conclude that the discontinuity shown by the dashed line in Figure 1 is a reverse shock.
V. The Shock as a Boundary between a "Driver-Gas" and a "Driven-Gas"

Figure 1 shows that the shock precedes a high-speed stream in which the flow has a nearly constant value \( \sim 585 \text{ km/sec} \), which is considerably higher than the most probable speed for the solar wind, \( \sim 385 \text{ km/sec} \). (see Burlaga and Ogilvie, 1970). Figure (1) shows that a second high speed stream passed the spacecraft nearly a day later, preceded by a bulk speed gradient and hot spot beginning \( \sim 18 \) hours after the boundary. Between the second (much weaker) interaction region and the shock, the flow is more or less uniform with no marked density or bulk speed changes and with the temperature and magnetic field intensity varying slowly in a complementary fashion. Moreover, the temperature \( T_2 = 2.6 \times 10^5 \text{ K} \) is essentially the same as that predicted from \( V_2 \) by the \((V,T)\) relation. (Burlaga and Ogilvie, 1970)

Thus, this flow has the characteristics of an advancing high speed stream of fresh, equilibrium, solar wind plasma.

Ahead of the boundary one sees a rather different kind of flow. The bulk speed is steadily increasing from \( 350 \text{ km/sec} \) to \( 540 \text{ km/sec} \), the density and magnetic field intensity are unusually high and show several abrupt changes, the temperature is anomalously high (this is one of the regions designated as a "hot spot" by Burlaga and Ogilvie, 1970), and the energy density is increasing rapidly and nonuniformly. Thus, this is characteristic of the interaction regions which commonly precede high speed streams (Burlaga et al. 1970, Burlaga and Ogilvie, 1970) with material presumably undergoing dynamical changes.

It appears, then, that the boundary represents a transition between a uniform "driver" gas (possibly a corotating stream) and the dynamical material piled up ahead of this gas.
Acknowledgements

This analysis is based on the magnetic field data of Drs. N. F. Ness and D. H. Fairfield and the plasma data of Drs. K. W. Ogilvie and T. D. Wilkerson.
<table>
<thead>
<tr>
<th>( \text{V(km/sec)} )</th>
<th>( \text{n(cm}^{-3})</th>
<th>( \text{T(kilo K)} )</th>
<th>( \text{B(\gamma)} )</th>
<th>( \text{P \times 10^{10}} ) ( \text{ergs/cm}^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>540\pm5</td>
<td>10.0\pm1.0</td>
<td>450\pm100</td>
<td>12.0\pm1.0</td>
</tr>
<tr>
<td>2</td>
<td>585\pm10</td>
<td>5.5\pm.5</td>
<td>260\pm100</td>
<td>8.0\pm.5</td>
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</table>
### TABLE II

**RELATIVE SPACECRAFT COORDINATES AND TIMES**

<table>
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<tr>
<th></th>
<th>$i=1$</th>
<th>$i=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_i$ (R_E)</td>
<td>8.09</td>
<td>24.0±1.5</td>
</tr>
<tr>
<td>$Y_i$ (R_E)</td>
<td>-46.57</td>
<td>-92.13</td>
</tr>
<tr>
<td>$Z_i$ (R_E)</td>
<td>-14.91</td>
<td>-6.04</td>
</tr>
<tr>
<td>$t_i$ (min)</td>
<td>9.2±.7</td>
<td>24.0±1.5</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Fig. 1 The dashed line indicates the reverse shock discussed in the text. The plots show connected traces of plasma parameters for spectra measured at 3 minute intervals, samples of the magnetic field intensity taken at 3 minute intervals, and the corresponding pressure $P=\frac{B^2}{8\pi} + nk(T+T_e)$ with $T_e=1.5\times10^5$ K. The width of the lines shows the extent of the scatter of the observations.
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**Figure 1**

- **$V$ (Km/sec)**
- **$n$ ($cm^{-3}$)**
- **$T \times 10^{-3}$ ($°K$)**
- **$|\vec{B}|$ ($\gamma$)**
- **$P \times 10^{-10}$ (erg/cm$^3$)**

Dates: 28, 29, 30 Sep 1967