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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 ~5 sec at ~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 $P = B^2/8\pi + nk(T+T_e)$ with $T_e = 1.5\times10^5\,^\circ K$ (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, $\hat{B}$, did not change appreciably across the discontinuity. From 1.5 min. averages of components of $\vec{B}$ measured before and after the discontinuity, we find $\hat{B}_1 = (-.49, .59, .64)$, and $\hat{B}_2 = (-.42, .59, .69)$ in solar ecliptic coordinates ($\hat{X}$ toward the sun, $\hat{Z}$ normal to the ecliptic). The magnitude of $\vec{B}$ 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 v_n decreases across the shock, and (3) that the changes in the fluid parameters satisfy the Rankine-Hugoniot equations which are as follows:

$$[nv_n]=0 \tag{1}$$

$$[(\rho v_n v_p - B_n B_p)/(4\pi)]=0 \tag{2}$$

$$[\rho v_n^2 + P]=0 \tag{3}$$

$$\left[\frac{(v_p^2+v_n^2)}{2} + \frac{\gamma}{\gamma-1}\,\frac{nkT}{\rho} + \frac{B_p^2}{4\pi\rho} + \frac{B_n B_p v_p}{4\pi\rho v_n}\right]=0 \tag{4}$$

where $$v_n = V_n - U. \tag{5}$$

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; ρ 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

$$U = \frac{n_1 V_{1n} - n_2 V_{2n}}{n_1 - n_2} \tag{6}$$

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

$$V_{1p} = V_{2p} \tag{7}$$

Let ω be the angle between $\vec{V}_2$ and $\hat{n}$, and let ω+ε be the angle between V_1 and $\hat{n}$. Then

$$V_{1p} = V_1 \sin(\omega+\epsilon) \tag{8}$$

$$V_{2p} = V_2 \sin\omega \tag{9}$$

and (7) gives

$$\epsilon \sim \left(\frac{V_2 - V_1}{V_1}\right) \tan\omega \tag{10}$$

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

$$U \sim \frac{n_1 V_1 (\cos\omega - \epsilon\sin\omega) - n_2 V_2 \cos\omega}{n_1 - n_2} \tag{11}$$

In the next section it is shown that to determine $\hat{n}$ we need $V_s \equiv U/\cos\omega^1$, where ω^1 is the angle between $\hat{n}$ and the radial direction. If $\vec{V}_2$ is nearly radial, as it surely is, we may set ω^1=ω; the consequent small error does not contribute significantly to the uncertainty in $\hat{n}$.

Thus,

$$V_s \approx \frac{U}{\cos \omega} = \frac{n_1V_1(1-\epsilon \tan \omega) - n_2V_2}{n_1 - n_2} \qquad (12)$$

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

Surface Orientation. The discontinuity in $\hat{B}$ 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 ($\lesssim 100R_E$), the measured time delays can be used to calculate the orientation as a function of the radial speed of the surface V_s. Let θ be the angle between the normal to the boundary surface and the ecliptic plane (θ = o implies a boundary normal to the ecliptic, θ>o, if the normal is above the ecliptic). Let φ 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. ($\varphi \sim 45^\circ$ implies a plane along the spiral direction; θ=o, φ=o implies a plane normal to the earth-sun line). Then

$$V_s = A + B \tan \theta \qquad (13)$$

$$\tan \varphi = CV_s + E \tan \theta + D, \qquad (14)$$

where $A \equiv (X_2Y_1 - X_1Y_2)/(t_1Y_2 - t_2Y_1)$,

$B \equiv (Z_1Y_2 - Z_2Y_1)/(t_1Y_2 - t_2Y_1)$, $C \equiv -t_2/Y_2$, $D \equiv -X_2/Y_2$ and $E \equiv Z_2/Y_2$.

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

$$\tan\theta = (2.3\pm.8)\times10^{-3} V_s(\mathrm{km/sec}) - (.7\pm.3) \quad (15)$$

$$\tan\varphi = (2.65\pm.15)\times10^{-3} V_s(\mathrm{km/sec}) - (.04\pm.02) \quad (16)$$

The components of the shock normal are

$$\begin{aligned} n_x &= -\cos\omega = -\cos\theta\cos\varphi \\ n_y &= -\cos\theta\sin\varphi \\ n_z &= \sin\theta \end{aligned} \quad (17)$$

Results. Using the numbers in Table II and the iteration procedure discussed above, one finds $\epsilon = 4.8^\circ$ and $\omega = 45.3^\circ$. Equation (11) then gives U = 270 km/sec. From (12), (15) and (16) one gets $\theta = 10.4^\circ$, $\varphi = 44.4^\circ$ which with (17) gives the shock normal $\hat{n} = (-.70, -.69, .18)$. Thus, the surface is nearly perpendicular to the ecliptic plane and aligned along the spiral direction. The speed of the surface along $\hat{n}$ relative to a fixed frame ($U = 270$ km/sec) is less than the normal component of the solar wind on the sunward side, $V_{2n} = V_2 \cos\omega =$ 411 km/sec. This gives an important result: The surface is propagating in the sunward direction (along $-\hat{n}$) relative to the solar wind, at a speed $v_{2n} = 141$ km/sec. The normal flow speed behind the shock is $v_{1n} = V_1 \cos(\omega+\epsilon) - U = 76$ 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 $\hat{n}$ and the field $\hat{B}$ on either side of the shock is $\cos^{-1}(\hat{n}\cdot\hat{B}) = 87^\circ$. Thus, the field is parallel to the shock surface, as required by the fact that $\hat{B}_1 = \hat{B}_2$. Hence, the assumption $B_n = 0$, used to derive (7), is valid. As a check on the validity of (7), note that $V_{1p} = V_1 \sin(\omega+\epsilon) = 414$ km/sec and $V_{2p} = V_2 \sin\omega = 416$ km/sec.

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

$$\rho v_n^2 \Big|_1^2 = P \Big|_2^1, \tag{3'}$$

where $P \equiv nk(T+T_e) + B^2/8\pi$, 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, $P\Big|_2^1$ = $\underline{(8.0\pm1.5)\times10^{-10}\text{ergs/cm}^3}$. Using the values of v_{1n} and v_{2n} above, we find $\rho v_n^2 \Big|_1^2$ = $\underline{8.6\times10^{-10}\text{ergs/cm}^3}$. Thus <u>(3') is satisfied within the errors</u>.

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

$$\frac{v_n^2}{2}\Big|_1^2 = \left(\frac{\gamma}{\gamma-1}\frac{nk(T+T_e)}{\rho} + \frac{B_p^2}{4\pi\rho}\right)\Big|_2^1 \tag{4'}$$

The change in $v_n^2/2$ is $\underline{7.1\times10^{15}(\text{cm/sec})^2}$. If $T_e = 1.5\times10^5$ °K as discussed above, and if $\gamma = 5/3$, we find that the change in the RHS of (4') is $\underline{5.5\times10^{3}(\text{cm/sec})^2}$. Since the uncertainty in the RHS of (4') is certainly >50%, we conclude that <u>(4) is satisfied within the errors</u>.

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 ~585 km/sec, which is considerably higher than the most probable speed for the solar wind, ~385 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 ~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 $T_2=2.6\times10^5$°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 km/sec to 540 km/sec, the density and magnetic field intensity are unusually high and show several abrupt changes, the temperature is anamalously 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.

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TABLE I

PLASMA AND MAGNETIC FIELD PARAMETERS AT THE BOUNDARY

	V(km/sec)	n(cm^{-3})	T(kilo^{o}K)	B(γ)	Px10^{+10}ergs/cm^3
1	540±5	10.0±1.0	450±100	12.0±1.0	14.0±1.0
2	585±10	5.5±.5	260±100	8.0±.5	6.0±0.5

TABLE II

RELATIVE SPACECRAFT COORDINATES AND TIMES

	i=1	i=2
X_i (R_E)	8.09	.24
Y_i (R_E)	-46.57	-92.13
Z_i (R_E)	-14.91	-6.04
t_i (min)	9.2±.7	24.0±1.5

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 $P \equiv B^2/8\pi + nk(T+T_e)$ with $T_e = 1.5 \times 10^5\,^{\circ}K$. The width of the lines shows the extent of the scatter of the observations.

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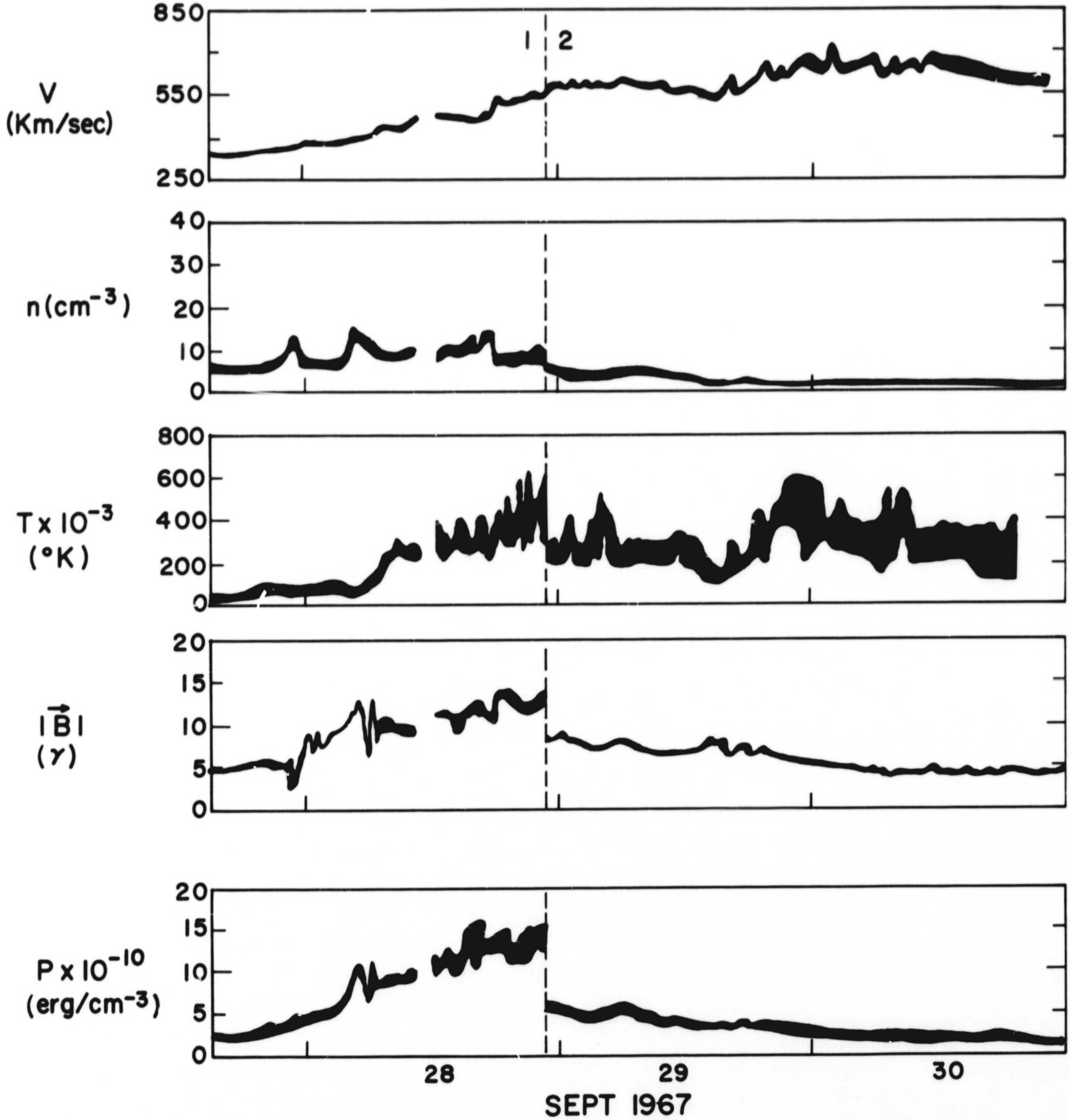
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550
250
V
(Km/sec)
1
2
40
30
20
10
0
n(cm⁻³)
800
600
400
200
0
T x 10⁻³
(°K)
20
15
10
5
0
|B|
(γ)
20
15
10
5
0
P x 10⁻¹⁰
(erg/cm⁻³)
28
29
30
SEPT 1967

Figure 1