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ABSTRACT

The Rankine-Hugoniot relations are applied to shock-like discontinuities measured by both magnetic field and plasma instruments on the satellite Explorer 34 between May 30, 1967 and January 11, 1968.

Shock normals were either determined from the magnetic field observations, or from the times of occurrence of the discontinuity at Explorers 33, 34 and 35. The Rankine-Hugoniot relations are obeyed to the accuracy of the observations, and the values of shock velocities, density ratios, and Mach numbers indicate that at 1 AU the typical interplanetary shock is not strong, although all the events studied caused geomagnetic impulses.

HYDROMAGNETIC SHOCKS IN THE SOLAR WIND

I. INTRODUCTION

Shock-like discontinuities observed simultaneously in both the interplanetary magnetic field and plasma between May 30, 1967 and January 11, 1968 are examined in this paper in order to determine whether they are consistent with the hydromagnetic theory for fast shocks. During the time when the satellite Explorer 34 was outside the earth's bow shock and at a distance of more than 24 earth radii from the earth, at least 7 shock-like discontinuities were observed. The selection criterion for such an event was the occurrence of simultaneous increases in the magnetic field intensity B, and the plasma density, bulk speed, and temperature. Since in a slow shock the tangential component of the magnetic field decreases across the discontinuity, these shock events, if they exist in the solar wind, would not be selected. All selected events were observed on terrestrial magnetometers as the sudden commencements of geomagnetic storms.

The only previous observations of a propagating shock in the interplanetary medium, in which the discontinuity in the plasma properties and in the magnetic field were both measured, were made by Sonett et al. (1964), using detectors carried on Mariner 2. They reported observations of a discontinuous increase in the interplanetary plasma parameters and the magnetic field parameters which propagated with respect to the solar wind at a speed greater than the alfvén speed. They showed that the velocity $\bar{V}_1$, density n_1 and temperature T_0, (the subscripts 0 and 1 denote preshock and post-shock values respectively) predicted from the Rankine-Hugoniot conditions for a fast, oblique, hydromagnetic shock in an one-component, isotropic plasma were consistent with the observed values, but they found that the predicted temperature T_1 was 1.4 times higher than the observed temperature. Observations of events of a similar nature where either the plasma parameters or the magnetic field were studied, have been reported by Gosling et al. (1967a,b) Taylor (1968), Ness and Taylor (1968), and Van Allen and Ness (1967). Shock velocities have been deduced using conservation relations by several of these authors. Taylor (1968) studied magnetic field observations taken by the satellite IMP-3 during 36 sudden commencements which took place in 1965, 1966 and 1967. He concluded that 26 of these events were caused by interplanetary shock waves, and after selecting eight of these with particularly well determined orientations, deduced that a typical shock front propagating from the sun to the earth has a radius of curvature somewhat less than 1 AU. This idea has also been advocated by Hirschberg (1968).

II. EXPERIMENTAL

The magnetic field observations used in this study were obtained by the triaxial fluxgate magnetometer experiment of Fairfield and Ness. This instrument has a resolution of $\pm 0.16\gamma$, and readings were taken every 2.56 seconds.

The plasma instrument has been described by Ogilvie et al. (1968), so only a very short account will be given here. It records protons and helium nuclei separately, a spectrum of each species taking approximately one minute to acquire and successive spectra are separated in time by 3.04 minutes. The proton spectra alone have been used to deduce the fluid quantities used in this paper. This procedure might introduce errors of up to 20% into the calculation of the shock densities from (8), etc. However, the helium densities are not known on both sides of all the shocks, and this order of error exists in any case as a result of other uncertainties.

The spin axis of the satellite is normal to the ecliptic plane to within 2.5°, and each of the fourteen energy per unit charge channels is sampled for 2.56 seconds during which time the satellite makes a complete revolution. The acceptance angle of the instrument is ± 9° in a plane containing the spin axis, and 2.5° in azimuth.

III. DESCRIPTION OF OBSERVATIONS AND SELECTION OF DISCONTINUITIES

If it were known that the interplanetary plasma could be described as a one-component, hydromagnetic fluid with an isotropic temperature distribution, then the hydromagnetic theory implies that discontinuities across which density, bulk speed, temperature and magnetic field intensity all increase are necessarily fast shocks. In a multi-component, non-equilibrium plasma which contains about 5% of helium ions, and is neutralized, as the solar wind is, by an electron component, it is still probable, but not certain, that such a discontinuity is a shock, assumed to be fast in all subsequent discussion. In any case, such a signature is a necessary condition for a shock. Thus, events for this study were selected by scanning $\simeq$3000 hours of interplanetary plasma and magnetic field data and identifying discontinuities across which n, V, T and B all increased by more than the respective errors in measurement. By a discontinuity, we mean that the plasma parameters changed in less than 3 minutes, (the instrument resolution time) and the magnetic field parameters changed in less than 1 minute. Only events for which data were available for several minutes before and after the discontinuity were considered. Eight such clear discontinuities will be discussed in this paper. Other shock-like discontinuities were present (Burlaga and Ogilvie, 1969) but the changes in the parameters were not large enough or sufficiently well known for the type of analysis which is presented below. The dates and times of the discontinuities are shown in the 1st two columns of Table I. The position of Explorer 34 and its distance from the earth at these times is also shown, labelled X, Y, Z and R in a coordinate system centered upon the earth, in which the positive X direction points to the sun, and the positive Z axis is northward normal to the plane of the ecliptic.

Plasma Parameters at the Discontinuities

The plasma instrument determines the differential proton flux in the streaming plasma at 14 energy values. From the non-zero members of these observations, we obtain 3 or 4 values of the distribution function $\frac{dn}{dv_j}$, where v_j, is the speed corresponding to the energy of step j. An approximation to the distribution function is obtained by piecewise fitting a maxwellian distribution to the measured dn/dv_j (see Ogilvie et al., 1967). The fluid parameters are derived from the moments of this distribution function using the following equations,

$$n = \langle v_0 \rangle$$

$$u = \langle v_1 \rangle / \langle v_0 \rangle$$

$$T = \frac{m}{k} \frac{\langle v_2 \rangle - \langle v_1 \rangle^2}{\langle v_0 \rangle}$$

where

$$\langle v_x \rangle = \int_0^\infty v^x \frac{dn}{dv} dv .$$

These quantities were determined by averaging at 3 minute intervals for 20-30 minutes on each side of each of the shocks in Table I. The pre-shock and post-shock values are presented in columns 2, 3 and 4 of Table I.

In order to evaluate errors in density and temperature arising as a result of the fitting procedure, a computer program is used to simulate the process of measurement. Values of speed, density and temperature are deduced from the measured 'counts', as discussed above. The 'counts' which would have been observed by the detector in a plasma with a convected maxwellian velocity distribution having the same properties are calculated, and the fluid parameters redetermined from them. For the observations in Table I, it is found that the input and output velocities agree to ±5%, the densities to ±20% and temperatures to ±50%, in the worst case.

Magnetic Field Parameters at the Discontinuities

Let $\vec{B}_0$ be the magnetic field measured just before the shock arrived at the satellite and $\vec{B}_1$ the field measured just after arrival. Since the magnetic field usually fluctuates appreciably near a shock, as discussed and illustrated for the case of the earth's bow shock by Fredericks and Coleman (1969) it is necessary to use some smoothing procedure to obtain $\vec{B}_0$ and $\vec{B}_1$. The procedure used here is to average over six measurements (15 sec. in time) to compute $\vec{B}_0$ and $\vec{B}_1$ from the components.

The magnitude, solar ecliptic latitude θ and solar ecliptic longitude ϕ of the field vector obtained in this way for each of the events in Table I is shown in columns 6 and 7 of that Table. The last column of Table I shows a figure of merit which is defined by the equation

$$A = \left[\frac{|\Delta B|}{\left(\Sigma(SD)^2\right)^{1/2}}\right] n_0 b_0 \ .$$

The first of these two factors characterizes the magnetic measurements. ΔB is the field change caused by the shock and $\left(\Sigma(SD)^2\right)^{1/2}$ is the square root of the sum of the squares of the six standard deviations of the three field components on either side of the shock. These standard deviations are calculated for the 15 second period over which the field values are averaged. Thus a small change in a varying field would give a low figure of merit. The second factor is obtained by forming the product of the density and the number of velocity intervals with non-zero flux. Thus a low density determined from a histogram with few bars would give a low figure of merit.

IV. SHOCK NORMALS

The normal to a shock surface, $\hat{n}$, describes the orientation of that surface and also indicates the direction of propagation of the shock. As discussed in Section V, a knowledge of $\hat{n}$ is essential for a theoretical understanding of the changes which occur across a shock. This section discusses 2 methods for determining $\hat{n}$, one using magnetic field measurements from one satellite and another using the shock arrival times at 3 satellites.

Colburn and Sonett (1966) show that the shock normal vector may be determined from the equation

$$\hat{n} = (\bar{B}_0 \times \bar{B}_1) \times (\bar{B}_0 - \bar{B}_1) / |(\bar{B}_0 \times \bar{B}_1) \times (\bar{B}_0 - \bar{B}_1)| \ . \qquad (1)$$

$\bar{B}_0$ and $\bar{B}_1$ are generally well enough known for $(\bar{B}_0 - \bar{B}_1)$ to be well determined, but it is found that the magnetic field direction generally changes by only a small angle due to the passage of the shock. The angle δ in the equation

$$|\bar{B}_1 \times \bar{B}_0| = B_1 B_0 \sin \delta$$

varies between 0 and 25 degrees in the cases considered here, while the uncertainty in the magnetic field direction is 3 to 10 degrees, due to fluctuations near the shock. The accuracy of normal determination by this method was sufficient for three of the shocks, those on June 26, Sept. 13 and Sept. 19, and the results are shown in Table II and Figure 1.

For the other events, where the angle δ was insufficiently large compared to the field fluctuations, a second method, not previously used, will be described. It assumes only that the shock surface is planar over dimensions of order 50 R_e. To illustrate this method, consider the discontinuity in the magnetic field on Jan. 11 observed by experiments on three spacecraft, Explorers 33, 34 and 35, which we shall refer to as 1, 2 and 3 respectively.

We now refer to Table II, where we see that the spacecraft positions in the coordinate system used above were $\bar{R}_1$ = (58.8, 22.3, -28.4), $\bar{R}_2$ = (17.9, -22.7, 1.8) and $\bar{R}_3$ = (-42, 46.4, 3.4). These three points define a plane P, and we transfer the origin in that plane to the position of satellite 1. Putting R_{12} = $\bar{R}_1 - \bar{R}_2$, etc. we can define an angle ω by

$$\cos \omega = \bar{R}_{12} \cdot \bar{R}_{13} / |R_{12}| \cdot |R_{13}| ,$$

and from Table II we see that R_{12} = 93.9Re, R_{13} = 108.4Re giving ω = 42.2°. The relative positions of the spacecraft in the plane P are illustrated in Figure 2.

If $t_{12} = (t_1 - t_2)$, etc. we see from Table III that for the Jan. 11 event $t_{12} = (8 \pm 1)$ min., $t_{13} = (17.8 \pm 1.8)$ min., and $t_{23} = (9.8 \pm .8)$ min. The shock plane intersects the plane P in a line; let $\overline{AB}$ be a vector along that line, making an angle α with $\bar{R}_{12}$. From Figure 2 we can see that t_{12} and t_{13} depend on α, and that we define γ to be the angle between the shock normal and the normal to the plane P. Thus U Sin γ is the component of the shock velocity in P, and we can write,

$$U \sin \gamma = \frac{R_{12} \sin(\alpha)}{t_{12}} = \frac{R_{13} \sin(\omega + \alpha)}{t_{13}} .$$

Thus,

$$\sin \alpha = \frac{t_{12} R_{13}}{t_{13} R_{12}} \sin(\omega + \alpha),$$

and we find $\alpha = 30° \pm 4°$ for Jan. 11.

The vector $\overline{AB}$ is coplanar with $\bar{R}_{12}$ and $\bar{R}_{13}$ and can be expressed in terms of them.

$$\overline{AB} = -.74\, \bar{R}_{13}/R_{13} + 1.42\, \bar{R}_{12}/R_{12}$$

so that $\overline{AB} = (.47, .84, -.22)$. We can now obtain the shock normal by forming the cross product of $\overline{AB}$, a vector in the shock plane, with $(\bar{B}_1 - \bar{B}_0)$

$$\hat{n} = \overline{AB} \times (\bar{B}_1 - \bar{B}_0).$$

For the Jan. 11 shock this procedure gives a normal with a latitude angle of 2° and longitude of 153°.

Two other discontinuities, those on Aug. 29 and Nov. 29, were observed at the three satellites. The corresponding positions, time delays and the resulting shock normals and their latitudes and longitudes are given in Table II, and illustrated in Figure 1.

V. RANKINE-HUGONIOT CONDITIONS

Our aim here is to determine the extent to which the discontinuities in Table I can be described by the Rankine-Hugoniot conditions for a fast shock in a single component, magnetic plasma with an isotropic temperature. As has been pointed out by Krall and Tidman (1968), the distribution functions before and after a collisionless shock transition can be non-maxwellian, and there are many conservation relations which could be tested in principle, beside the Rankine-Hugoniot relations. The nature, particularly the time scale, of the measurements prevents this at present, as they also prevent the study of shock structure. Observations on the earth's bow shock indicate that a small flux of high energy particles, presumably produced by some acceleration process, move upstream from that discontinuity (Frank, 1968). These particles should be taken into account in the detailed application of conservation laws to the bow shock, and similar effects might occur here. They have been neglected since they are unlikely to be the largest source of error.

The plasma contains He^{++} ions as well as protons; our observations of the helium are not precise enough to make comparisons with the theory for both components. We thus compare observations of the proton component alone with the single component equations given below. The average proportion of helium to hydrogen in the solar wind is 5% by number, while the ion temperature anisotropy is of order two.

The shock equations are as follows;

$$\left[\rho v_{\perp}\right] = 0 \tag{2}$$

$$\left[\rho v_{\parallel} v_{\perp} - \frac{B_{\parallel} B_{\perp}}{4\pi}\right] = 0 \tag{3}$$

$$\left[\rho v_{\perp}^2 + nkT + B_{\parallel}^2/8\pi\right] = 0 \tag{4}$$

$$\left[\tfrac{1}{2}(v_{\parallel}^2 + v_{\perp}^2) + \frac{\gamma}{\gamma - 1}\frac{nkT}{\rho} + \frac{B_{\parallel}^2}{4\pi\rho} + \frac{B_{\parallel} B_{\perp} v_{\parallel}}{4\pi\rho v_{\perp}}\right] = 0 \tag{5}$$

The velocity components $v_{\perp}$ and $v_{\parallel}$ are defined with respect to a coordinate system centered at the shock and moving with the shock surface. The subscript $\perp$ refers to the direction normal to the shock surface, and the subscript $\parallel$ refers to the direction parallel to the shock surface and along the direction of the tangential component of $\bar{B}$. Clearly these relations can be applied only to events for which $\hat{n}$ is known, since the equations involve the perpendicular and parallel components of $\bar{v}$ and $\bar{B}$.

Consider Equation (2). We measure the magnitude of the streaming velocities $|\bar{V}_0|$ and $|\bar{V}_1|$ before and after the shock in a frame which is stationary to the accuracy of the measurements with respect to the sun. Furthermore, these velocities are known to be radial, within a few degrees. Thus, the magnitude of the component of $\bar{V}$ along $\hat{n}$, $\bar{V}\cdot\hat{n} \equiv |\bar{V}| \cos \chi_0$, can be computed. Since the shock velocity is by definition $U\hat{n}$, where $U = |\vec{U}|$ is the speed of the moving frame, $v_{0\perp} = |\bar{V}_0| \cos \chi_0 - U$. A similar expression may be written for $v_{1\perp}$, namely

$v_{1\perp} = |\bar{V}_1| \cos \chi_1 - U$. If it is assumed that the angle between $\bar{V}_0$ and $\bar{V}_1$ is small so that $\chi_1 = \chi_0 + \epsilon$, where $\epsilon << 90°$, then

$$v_{1\perp} = |V_1| (\cos \chi_0 + \epsilon \sin \chi_0) - U$$

$$v_{1\perp} = |V_1| \cos \chi_0 - U \tag{6}$$

Because of the small (±9°) aperture of the plasma instrument, departures from radial flow of this order in a direction perpendicular to the ecliptic plane would be detected as gross decreases in particle density. Since such drops are not observed we can be confident that ϵ is indeed small for the events in Table I. The expressions for $V_{0\perp}$ and $V_{1\perp}$ substituted into 2 give

$$U = \frac{(\rho_1/\rho_0 \; V_1 - V_0)}{(\rho_1/\rho_0 - 1)} \cos \chi_0 \; . \tag{8}$$

This is one necessary condition which must be satisfied if the discontinuities in Table I are shocks. Theoretical values of U, computed from this equation, are shown in Table III. No value of U is shown for the June 25 event, since an accurate normal direction cannot be obtained by either of the methods used for the other shocks.

When U is known, a Mach number can be computed. We define the Mach number by the equation

$$M_{A\perp}^2 = 4\pi \rho_0 v_{0\perp}^2 / B_\perp^2 \; .$$

This Mach number appears in the equations below.

The theoretical shock speeds obtained from (8) can be compared with the observed shock speeds for the events of Jan. 11, Aug. 29 and Nov. 29. The component of the shock speed in the plane P, illustrated in Figure 2 is given by the eo'iation

$$U \sin \gamma = \frac{R_{13}}{t_{13}} \sin (\omega + \gamma) .$$

Now γ is the angle between the shock normal $\hat{n}$ and $\hat{n}_P$, the normal to the plane P. This latter is $(\bar{R}_{13} \times \bar{R}_{12})/|\bar{R}_{13} \times \bar{R}_{12}|$. Writing $\hat{n} \cdot \hat{n}_P = \cos \gamma$, we get for Aug. 29, Nov. 29 and Jan. 11 respectively, $\gamma = 1°$, $\gamma = 41°$ and $\gamma = 29°$. The corresponding shock speeds are then (436±110) km sec^{-1}, (670±140) km sec^{-1}, and (705±70) km sec^{-1}; and these values are entirely reasonable by comparison with those obtained for these and other events by the application of mass conservation, and illustrated in Table III.

2.) Now consider Equation 3, which is a statement of conservation of momentum flux across a shock. Using (2), and the condition for continuity of tangential electric field in an infinitely conducting plasma, Wilkerson (1968) has obtained the following condition which must be satisfied if (3) is valid and if the discontinuities are shocks:

$$\frac{n_0}{n_1} = \frac{B_{0\parallel}}{B_{1\parallel}} \left[1 + \left(\frac{B_{1\parallel}}{B_{0\parallel}} - 1 \right) M_A^{-2} \right] \tag{9}$$

the ratio n_1/n_0 was computed for all events for which a satisfactorily accurate shock normal could be obtained by either of the methods described above. When M_A is greater than 2, the error in the calculated value of n_1/n_0 is approximately 20%; values of M_A less than 2 lead to larger uncertainties of up to 40%. The observed and calculated densities agree within the stated errors, except for the

Nov. 29 event, for which the post-shock density was determined indirectly, using the relation between the change in the geomagnetic field and solar wind pressure discussed by Ogilvie, Burlaga and Wilkerson (1968).

3.) Up to this point no assumptions have been made concerning the relationship between temperature and pressure in the plasma. Since the properties of the discontinuities examined above are consistent with magneto-hydrodynamic theory as far as we have gone, it is interesting to investigate Equation 4, which does not involve $v_{\parallel}$, and can therefore be solved immediately for the temperature ratio in terms of measured quantities.

$$T_1/T_0 = \frac{n_0}{n_1}\left\{1 + r_0\left(1 - \frac{n_0}{n_1}\right) + \frac{1}{\beta_0}\left(1 - \left(\frac{B_{1\parallel}}{B_{0\parallel}}\right)^2\right)\right\}$$

where

$$r_0 = \rho_0 v_{0\perp}^2/nkT_0 \text{ and } \beta_0 = nkT_0/B_{0\parallel}/8\pi .$$

This equation, due to Wilkerson (private communication) provides a test of Equation 4, assuming now a maxwellian velocity distribution on each side of the shock. The predicted temperature ratios are compared to the observed ratios in Table III.

4.) Equation 5 cannot be verified because γ is not known for the interplanetary plasma. However, it can be used to determine an effective γ which will guarantee that (5) is satisfied.

Consider the relatively simple case when $B_{\perp} \approx 0$. Equation 5 together with the other Rankine-Hugoniot conditions gives the well known relation (eg. Wilkerson, 1968),

$$T_1/T_0 = \frac{X\, n_1/n_0 - 1 + R\,(n_1/n_0 - 1)^3}{n_1/n_0\,(X - n_1/n_0)}$$

where

$$X = \frac{\gamma + 1}{\gamma - 1}$$

Thus

$$X = \frac{1}{n_1/n_0\,(T_1/T_0 - 1)}\left[(n_1/n_0)^2\, T_1/T_0 - 1 + \frac{1}{\beta}(n_1/n_0 - 1)^3\right]$$

The result for the discontinuity of Aug. 29 is $\gamma = 2.3 \pm 1.0$. The experimental errors are thus too large to distinguish between $\gamma = 5/3$ and $\gamma = 2$.

SUMMARY

We find as a result of examining the discontinuities detailed in Table I that, insofar as the difficulties associated with the small angular change in the magnetic field could be overcome, their properties are consistent with being fast magneto-hydrodynamic shocks.

The discrepancies shown in Table III, namely the predicted density ratio on Nov. 29 and the predicted temperature ratio on Jan. 11 are not too large to be the result of uncertainties in the determination of the shock normal. This work shows the determination of the shock normal to be by far the most difficult and critical part of the analysis of shocks, and emphasizes the advantages of multiple satellite observations.

The only inconsistent event is that of Aug. 11, in which the only available method for determination of the shock normal is the application of the coplanarity theorem. This should have given a well-determined result, but the value of θ obtained was 77°, inconsistent with other observed properties of the event. Experimental difficulties associated with a flow direction at an appreciable angle to the ecliptic plane could have been responsible; it is not necessary to assume the event to be a shock whose properties would not satisfy the Rankine-Hugoniot equations.

The values of shock velocities, density ratios and Mach numbers indicate that at 1 AU the typical interplanetary shock is not strong, but the observations show that all these events caused geomagnetic storms. The Rankine-Hugoniot equations are obeyed to the accuracy of the data.

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Table I

Observed Properties of Shocks

Date	Time	V_0	V_1	n_0	n_1	T_0	T_1	X	Y	Z	R	B_0	θ_0	ϕ_0	B_1	θ_1	ϕ_1	Figure of Merit
1967	U.T.	Km Sec^{-1}		cm^{-3}		$\times 10^4$ °K		R_e				γ Degrees			γ Degrees			
June 25	0215	295	326	8.4	19.7	6.1	8.5	7.3	28.6	-6.4	30	5.1	35	130	8.4	25	132	29
June 26	1455	416	448	14.5	27.7	7.1	8.5	8.8	30.9	0.2	32	3.8	-32	13	5.9	50	25	81
Aug 11	0554	430	525	6.5	26 *	16	37	19.6	11.8	-7.6	31	7.7	21	293	15.9	-64	299	40
Aug 29	1732	418	452	2.6	3.7	6.5	12	32.7	7.2	-3.3	34	5.5	51	295	7.2	51	296	40
Sept 13	0340	330	360	11.3	17.4	15.4	21.5	26	-1.4	4	26	11.1	-15	353	12.2	-24	342	61
Sept 19	1954	471	552	3.9	8.3	11	20	30.4	-4.1	-5.4	31	6.3	-31	286	10	-34	268	59
Nov 29	0515	386	453	2.8	9 *	6	22	6.4	-32.4	1.0	33	7.7	13	149	10.2	18	148	10
1968																		
Jan 11	1256	364	508	3.0	8	26	35	-18	-27	1.8	33	7.2	20	252	10.7	-5	249	150

*Post-shock density determined from geomagnetic field change.

Table II

Event	$\bar{R}_1$	$\bar{R}_2$	$\bar{R}_3$	t_{12}	t_{13}	t_{23}	$\hat{n}$	θ_n	ϕ_n
	Re				Minutes			Degrees	
Aug 29	32.7, 7.2, -3.3	18.8, -58.7, 4.6	-26.6, 53.9, 1.7	8.9 ± 6	10 ± .7		-.68, -.24, .11	9	200
Nov 29	62.6, 31.7, 5.6	45.1, -32.1, -.2	.6, -32.4, 1.0	9.2 ± 3.6	18.7 ± 3.8		-.72, -.22, -.66	33	163
Jan 11	58.8, 22.3, -28.4	-17.9, -22.7, 1.8	-42 , 46.4, 3.4	8 ± 1	17.8 ± 1.8	9.8 ± .8	.71, .39, .03	2	153

Table III

Calculated Properties of Shocks

Date	θ (n)	ϕ (n)	X_0	U	$M_A(B_\perp)$	n_1/n_0 (obs)	n_1/n_0 (calc)	T_1/T_0 (obs)	T_1/T_0 (calc)
1967		Degrees		km/sec					
June 25	—	—	—	—	—	2.3 ± .2	—	1.4 ± .4	—
June 26	7	357	7.8	482	3.1	1.9 ± .3	1.9	1.2 ± .4	1.7
Aug 29	8.5	200	21	496	15	1.4 ± .2	1.3	1.9 ± .5	1.8
Sept 13	-3.3	4	5.2	416	1.0	1.5 ± .2	1.0	1.4 ± .2	1.6
Sept 19	-9.1	335	26.5	497	1.3	2.1 ± .2	1.3	1.8 ± .3	1.1
Nov 29	33.4	163	37	394	1.7	3.2 ± 1.0	1.2	3.7 ± 1	3.3
1968									
Jan 11	2.1	151.4	28.6	524	11.3	2.6 ± .5	1.5	1.4 ± .5	4.1

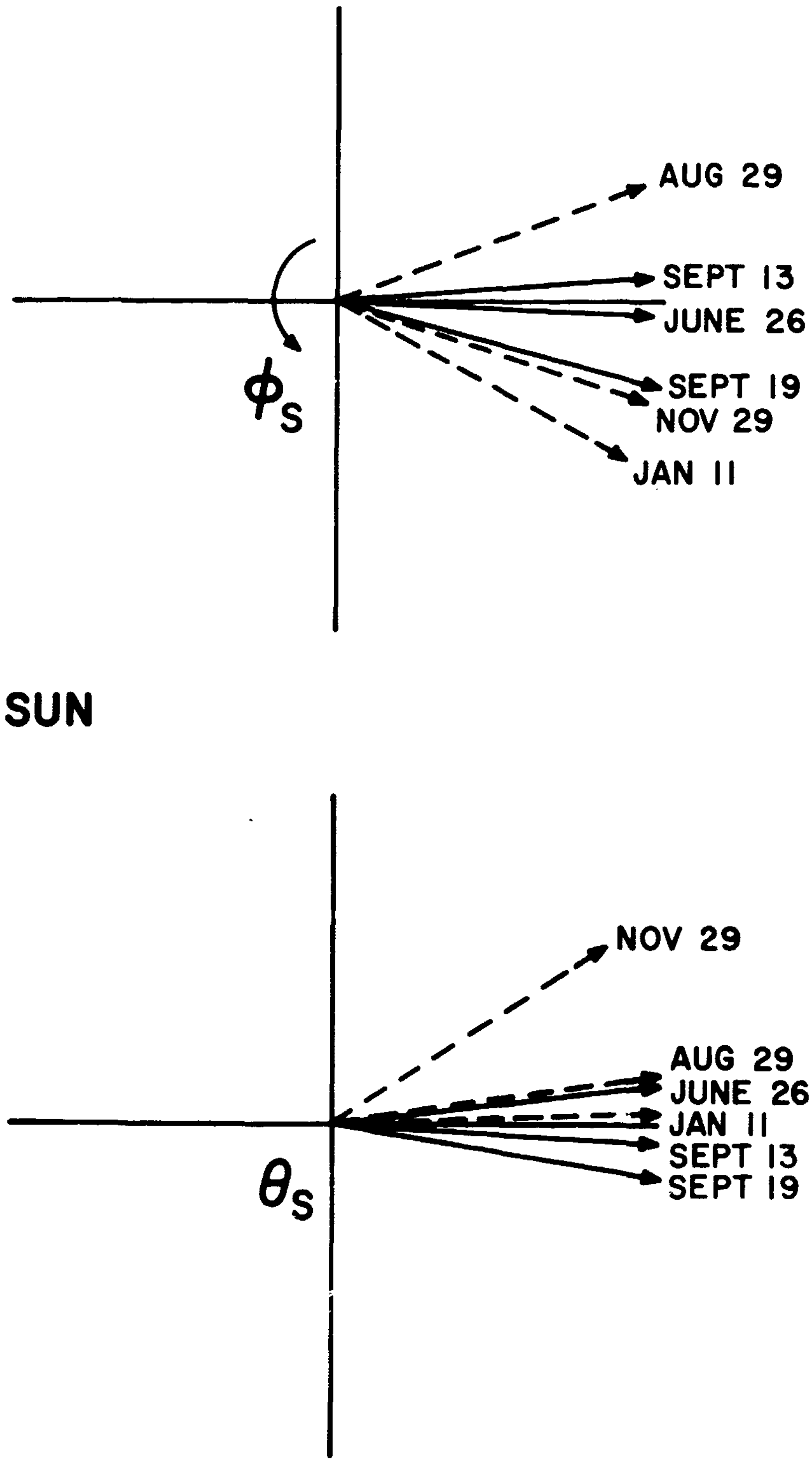

Figure 1. The distribution of the individual values of the elevations and azimuths of the six calculated shock normals. The dotted lines represent the multiple satellite observations and the solid lines the directions obtained by application of the coplanarity theorem. Since all of the latter point away from the sun, the ambiguity in the former has been resolved in favor of the direction away from the sun.

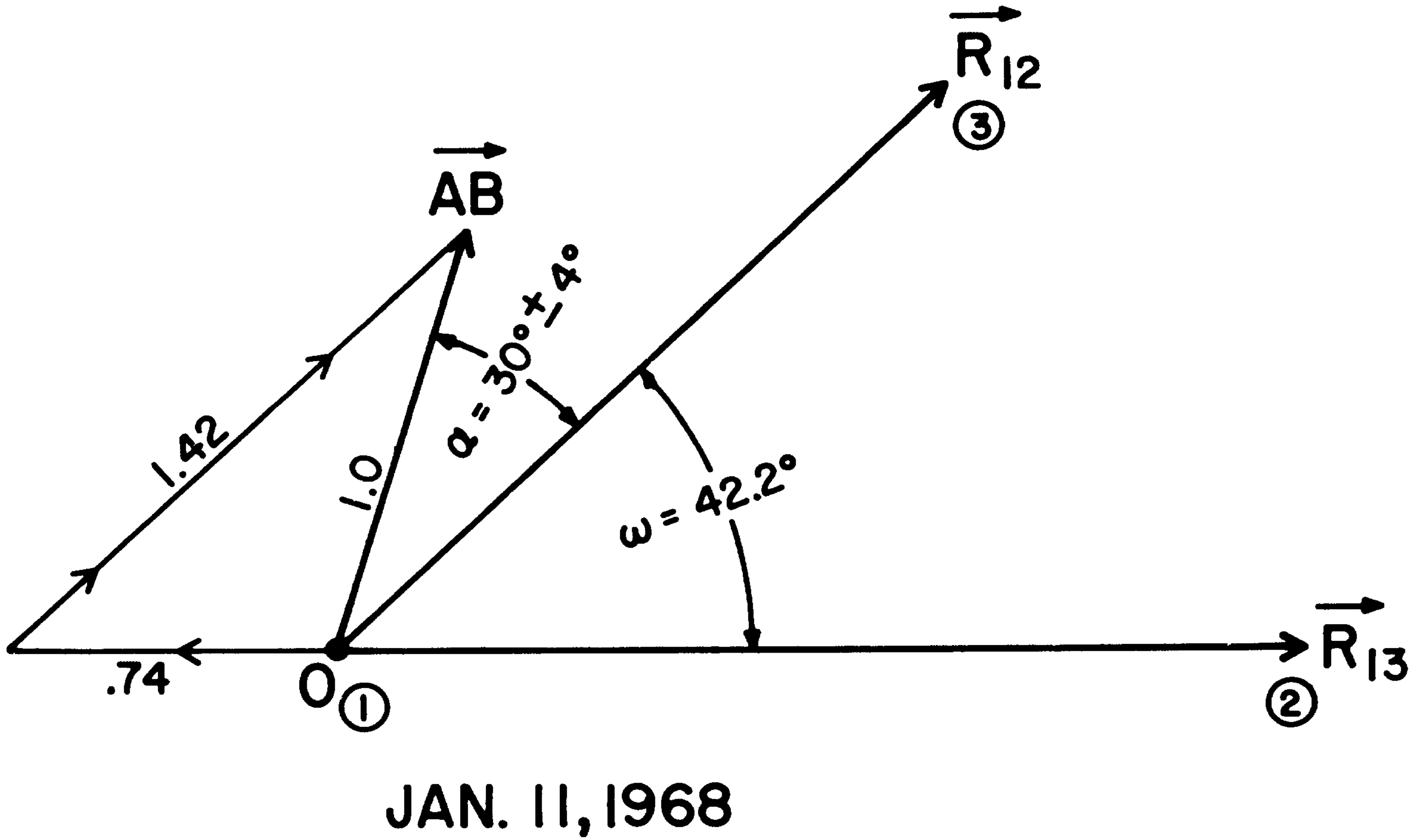

Figure 2. This figure illustrates the calculation of shock normal directions from the times of observations of the Jan. 11 shock by the satellites Explorer 33, 34 and 35. The plane of the paper is the plane P referred to in the text.