A TWO-SPACECRAFT TEST OF A SINGLE SPACECRAFT METHOD OF ESTIMATING SHOCK NORMALS

R. P. Lepping

ABSTRACT By assuming the validity of a subset of the Rankine-Hugoniot conservation relations for interplanetary (IP) shocks in an isotropic medium it has been demonstrated, in principle, that improved shock normals can be calculated by using a least-squares technique on combined magnetic field and plasma data from a single spacecraft. The scheme devised by *Lepping and Argentiero* [1971] uses those six conservation relations not involving pressure and temperature. This paper deals with a test of the scheme by examining in detail a shock across which the magnetic field changed direction by a small amount ($\approx 10^\circ$). On January 26, 1968 at about 1430 UT this shock was observed by the plasma and magnetic field instruments in Explorers 33 and 35. The spacecraft were 76.6 and 56.9 R_e sunward of the earth, respectively (and 43.5 R_e from each other), and therefore well outside the earth's bow shock region, a necessary condition for a valid test. It was assumed that an IP shock's surface is locally plane over dimensions of about 100 R_e. Using this assumption and the known geometrical configuration of the positions of the spacecraft with respect to the earth at the times of the shock onset . The orientation of an "observed" normal was ascertained, and least squares best-estimate normals were then calculated for each spacecraft using three different time intervals of data in each case: 9, 12, and 18 min, before and after onset. This was repeated using only the magnetic field data and the conventional coplanarity theorem for further comparison. For the 18 min data interval it was shown that the best-estimate normals for Explorers 33 and 35 agree with each other within less than 3°, and correspond to the observed normal within its angular uncertainty due to the time uncertainty of the earth's sudden commencement.

INTRODUCTION

In this paper we test a single spacecraft method of estimating shock normals by cross checking the results of the method applied independently to the data of two interplanetary spacecraft located about 44 R_e from each other. The method, devised by *Lepping and Argentiero* [1971], uses a six-equation subset, equations not involving temperature or pressure, of the eight-equation Rankine-Hugoniot conservation relations for interplanetary (IP) shocks in an isotropic medium. They showed in principle that improved normals can be calculated by employing a least-squares technique to best fit the combined magnetic field and plasma data from a single spacecraft to three equations of the six-equation subset, after transformation to an arbitrary frame of reference. The remaining three equations are used explicitly to obtain the direction of the normal and, provided the average preshock plasma velocity is sufficiently accurate, the speed of the shock. The reasons for ignoring the equations containing temperature or pressure are:

1. The proton data for these parameters usually show the poorest approximation to a step function of all the shock parameters.
2. Use of these parameters would require electron data that are not always available.
3. Probably most importantly, the energy flux equation, which does not take into account possible heat flow across the shock front [*Hundhausen and Montgomery,* 1971], is of questionable validity.

The author is at the Laboratory for Extraterrestrial Physics NASA Goddard Space Flight Center Greenbelt, Maryland.

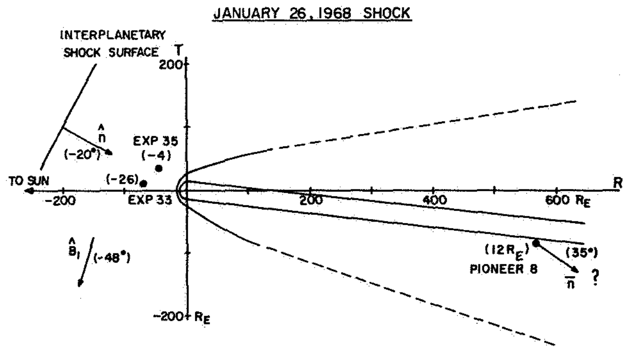

Figure 1. *The positions of Explorers 33 and 35 and Pioneer 8, at the time of the January 26, 1968 shock, shown in the ecliptic R-T plane. Also shown are the best-fit IP normal $\hat{n}$ and preshock magnetic field direction $\hat{B}_1$, as well as a roughly estimated normal (using average magnetic fields) at Pioneer 8. Quantities in parentheses refer to the direction perpendicular to the ecliptic plane in either degrees or R_e. The question mark (?) at Pioneer 8 refers to the large uncertainty (error cone 17°) of the normal's estimate at that location.*

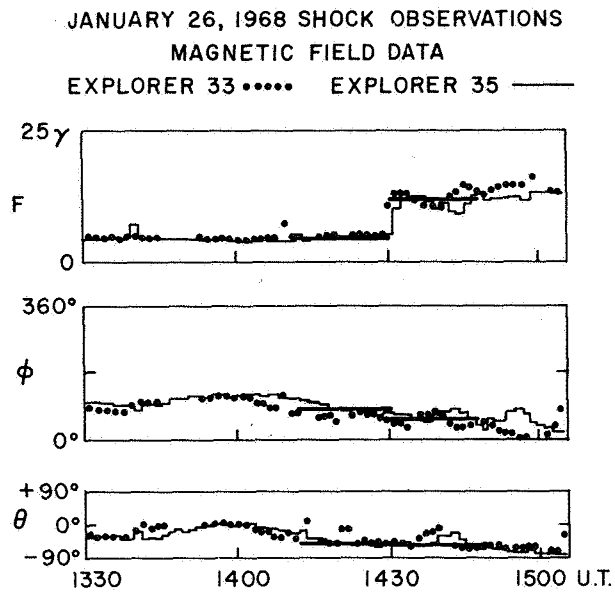

Figure 2. *Superimposed magnetic field data for Explorers 33 and 35. F is the magnitude, ϕ is the azimuthal angle measured counterclockwise in the ecliptic plane from $\phi = 0°$ in the direction of the sun, and θ is the angle of inclination measured positive northward from the ecliptic.*

OBSERVATIONS AND DISCUSSION

This paper deals in detail with a shock whose associated magnetic field changed direction by a small angle ($\approx 10°$) across the shock transition zone. On January 26, 1968, at about 1430 UT this shock was observed by Explorers 33 and 35 with an 88.8 ± 3.6-sec time delay between them (fig. 1). At about 1441 UT a sudden commencement was observed on earth. Approximately 2 hr later (1634 UT) Pioneer 8, located about 570 R_e behind the earth near the earth's tail, observed the shock after some deflection of its normal's direction. Notice that the IP shock normal was southward by 20° but at the Pioneer location it had become northward by $\approx 35°$ (95 percent certainty error cone angle is 17°). Only Explorer 33 was significantly out of the ecliptic plane and was 26 R_e below it. The IP shock normal $\hat{n}$ was almost perpendicular ($\approx 70°$) to the preshock magnetic field direction $\hat{B}_1$. Therefore, little change of direction of the magnetic field would be expected as the shock passed the two spacecraft. The quantities $\hat{n}$ and $\hat{B}_1$ are best-fit values, whose estimates will be discussed below.

Figure 2 shows superimposed magnetic field data from Explorers 33 and 35 around the time of the shock. There was essentially no change in θ across the shock surface and only about 10° change in ϕ. The horizontal lines represent the average of the two individual Explorer 33 and 35 best estimate values. The length of these lines indicate the 18-min time intervals, before and after shock onset, that were used in the best fit calculation. All six best-fit magnetic field parameters seem to have reasonable values when compared to straightforward averages allowing for deviations equal to the rms deviations for each. Notice the occurrence of a periodic structure before and especially after the shock. Behind the shock the oscillations, occurring over 30 min or so, are clearly out of phase between the Explorer 33 and 35 observations.

Figure 3 shows the plasma data also superimposed from Explorer 33 and 35 observations. The horizontal lines in the preshock case are simply averages of the dual spacecraft data. However, plasma velocity *differences* are obtained from the best-fit scheme and these along with the added preshock averages yield the postshock "best-fit" values shown. Again the lines represent an 18-min interval before and after the shock. Notice that the periodic structure after the shock, which was rather clear in the magnetic field data, also appears here, except the wavelike signature is not now quite as well defined.

Table 1 gives the best estimate values of the IP shock parameters for the two spacecraft and average values of these best estimates. The subscripts 1 and 2 refer to pre- and postshock, respectively, and the RTN coordinate system, centered at the spacecraft of interest, refers to the unit vectors: $\hat{R}$ radially away from the sun in the

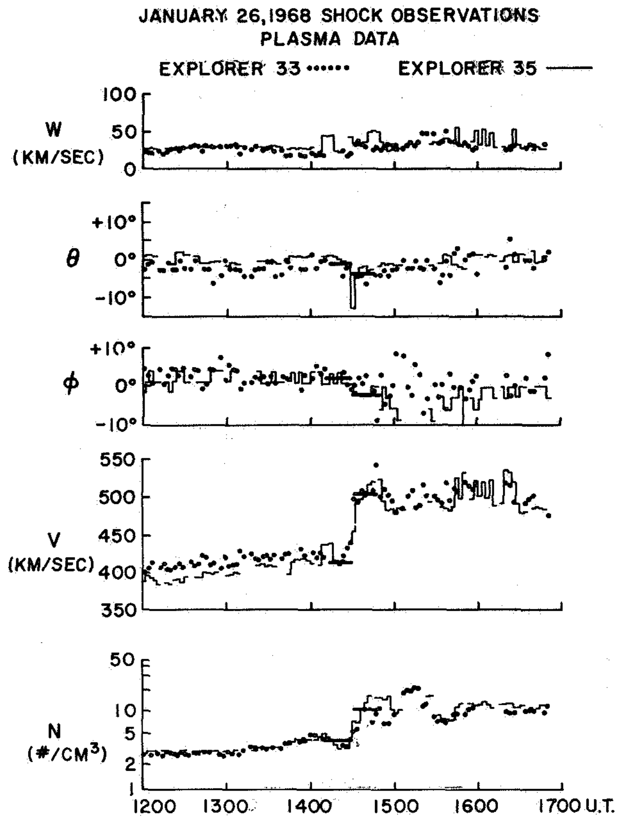

Figure 3. *Superimposed plasma data for Explorers 33 and 35. W is the thermal speed and V is the magnitude of the bulk plasma velocity, whose direction is designated by θ (same as fig. 1) and φ (φ = 0° in antisolar direction). N is the plasma number density.*

Table 1. *January 26, 1968, shock parameters best estimate values for the 18-minute interval*

Parameter	Best Estimate Explorer 33	Value Explorer 35	Average of best estimate for Explorers 33 and 35
B_{1R} (γ)	-1.59	-0.24	-0.92
B_{1T}	-3.16	-3.07	-3.12
B_{1N}	-3.49	-3.83	-3.66
B_{2R}	-5.15	-3.41	-4.28
B_{2T}	-6.60	-6.09	-6.35
B_{2N}	-7.54	-8.26	-7.90
W_R (km/sec)	78.6	85.6	82.1
W_T	-37.0	-35.0	-36.0
W_N	-28.3	-24.2	-26.3
N_1 (#/cm^3)	4.19	4.45	4.32
N_2	9.67	10.52	10.1
n_R	0.826	0.850	0.838
n_T	-0.440	-0.416	-0.428
n_N	-0.352	-0.324	-0.338

ecliptic plane, and $\hat{T}$ perpendicular to $\hat{R}$ and lying in the ecliptic such that $\hat{R} \times \hat{T} = \hat{N}$ is normal to the ecliptic and "northward." $\mathbf{W} = (W_R, W_T, W_N)$ is the plasma bulk velocity difference $\mathbf{V}_2 - \mathbf{V}_1$. The Ns are the number densities and n_R, n_T, and n_N are the components of the shock unit normal. The Alfvén Mach numbers for pre- and postshock were 8.5 and 5.5, respectively; these compare well with those of previously studied IP shocks [*Hundhausen,* 1970]. The best estimate Explorer 33 and 35 normals (calculated from the 18-min interval) differed by less than 3°. The associated calculated shock speeds were 507 and 520 km/sec, respectively, giving an average value of 513 km/sec. An average preshock plasma bulk velocity $\mathbf{V}_1 = (426, 17.4, -7.0)$ km/sec from the data of both spacecraft was used.

TWO-SPACECRAFT TEST

The best-fit IP normal was checked for accuracy by comparing its angular displacement from two fixed and intersecting lines in space. These lines were: first, the segment between Explorers 33 and 35 and, second, that between Explorer 33 and the earth; they intersected at 47°. Each of these angles can be calculated in two ways: first, by a straightforward calculation using the best estimate normal, which gives the *calculated* check angles; and second, by assuming, for dimensions of about 100 R_e, (1) a plane shock front, and (2) a constant shock speed (513 km/sec) and constant normal. The latter are the *observed* check angles. The calculated and observed check angles can then be compared.

In the case of the Explorer 33-35 line the observed and calulated angles were 80.5° and 84.1°, respectively, giving less than a 4° difference. In the case of the Explorer 33-earth line the observed and calculated angles were 47° and 44°, respectively, giving approximately a 3° difference. The sudden commencement (SSC) time at earth was taken to be 1441 UT, giving an 11-min delay. If 1440 UT is taken as the SSC time, giving a 10-min delay, the angles become 52° and 44°, respectively, an

≈8° difference. Assumptions (1) and (2) for the region from Explorer 33 to the earth, even over the path from the bow shock encounter to the earth, are justified within an angle error of 8° or so, because the shock effectively spends only about one-tenth of its total Explorer 33-earth travel time in this latter region.

The (95 percent certainty) error cone angle associated with the normal was 7.6°, which is consistent with the check angles, or is perhaps somewhat conservative.

COMPARISON OF ANALYSIS-INTERVALS

To obtain some understanding of the importance of using the proper time interval around the shock for the shock analysis, other time intervals, as well as the 18-min interval, were used. Henceforth, the term *best estimate* refers only to a given analysis-interval for a given spacecraft, and not necessarily to the *final* best estimate of the IP normal. Figure 4 shows, for the three separate input data intervals, estimates of the January IP shock normal, as projected on the R-T plane, for Explorers 33 and 35. The results of both the *average magnetic field method* (coplanarity theorem) and the *best estimate method* (auxiliary use of plasma data) of estimating the IP normal are shown. The latter are represented by either dashed (Explorer 33) or solid (Explorer 35) *arrows*, and the former by dashed or solid *lines*. The following features should be pointed out:

1. There is a large (70°) spread of the average normals but a reasonably narrow (14°) spread of the best estimate normals over the three time intervals.
2. Lengthening the time interval of data around the shock for use in calculating the normal does not necessarily improve the estimate, even within the short range considered here (up to 18 min).
3. For each given time interval the best estimate normals between Explorers 33 and 35 are closer together than the average normals.
4. The 18-min interval was clearly the "proper" choice of interval giving a few degrees difference between the Explorer 33 and 35 best estimate normals.

Figure 5 corresponds to figure 4 except now the estimates of the IP normal are projected into the R-N

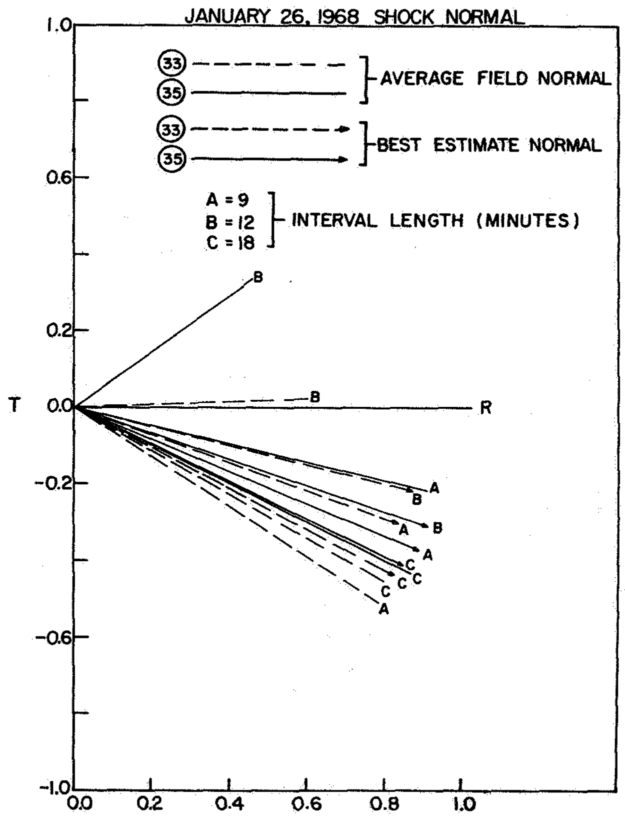

Figure 4. *Estimates of the January 26, 1968, shock normal from Explorers 33 and 35 data and projected into the R-T plane. Both average-field and best-fit methods are shown, each for three separate data intervals.*

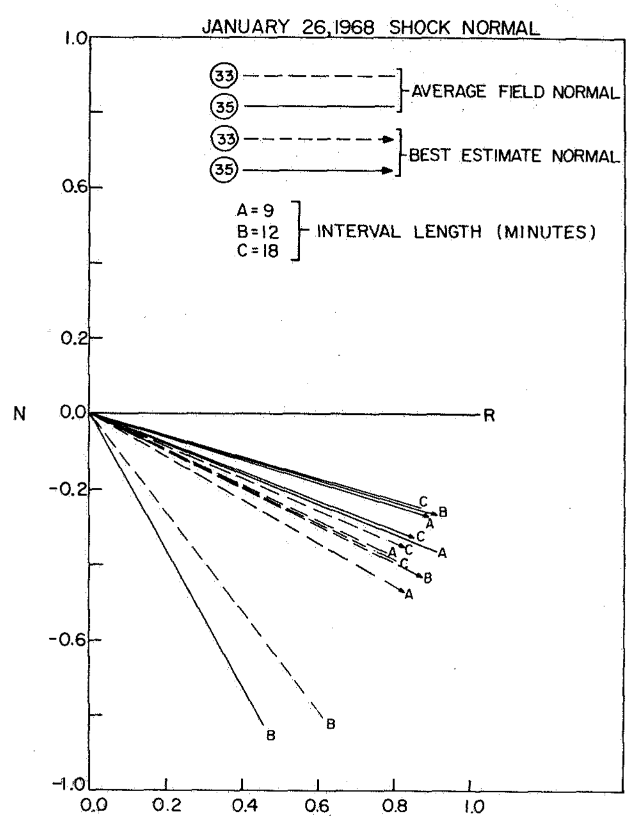

Figure 5. *Estimates of the January 26, 1968, shock normal from Explorers 33 and 35 data and projected into the R-N plane.*

plane. All the above comments again hold except for (3). In (1) the spread angle for the average normals becomes 46° but that for the best estimate spread remains 14°.

If one had been satisfied with only 12 min (*B* interval) of data around the shock and had not taken advantage of the available plasma data (or did not have such data) one might have been led into a false sense of certainty about the results because of the relatively good agreement between the results of the two spacecraft for this time interval.

CONCLUSIONS

We have accurately estimated an interplanetary shock normal and have shown its direction to be significantly different from the $\hat{R}$ direction both in inclination angle θ and azimuthal angle ϕ ($\theta = -20°$, $\phi = 153°$); the ecliptic plane projection was approximately along the average magnetic field spiral direction. There was no obvious solar flare associated with this shock. The shock may or may not have originated at the sun but *it probably did not start as a spherical front near the sun unless the front was severely distorted over 1 AU.* The periodic structure occurring behind the shock as seen especially in the magnetic field data is no doubt, in part, responsible for the fact, stated above, that lengthening the analysis interval does not necessarily improve the estimate of the normal. A proper analysis-interval is probably one that encompasses, as exactly as possible, two oscillations if such quasiperiodic structure exists after the shock, or at most should be limited to the interval just up to the first obvious discontinuity appearing after the shock.

ACKNOWLEDGMENTS

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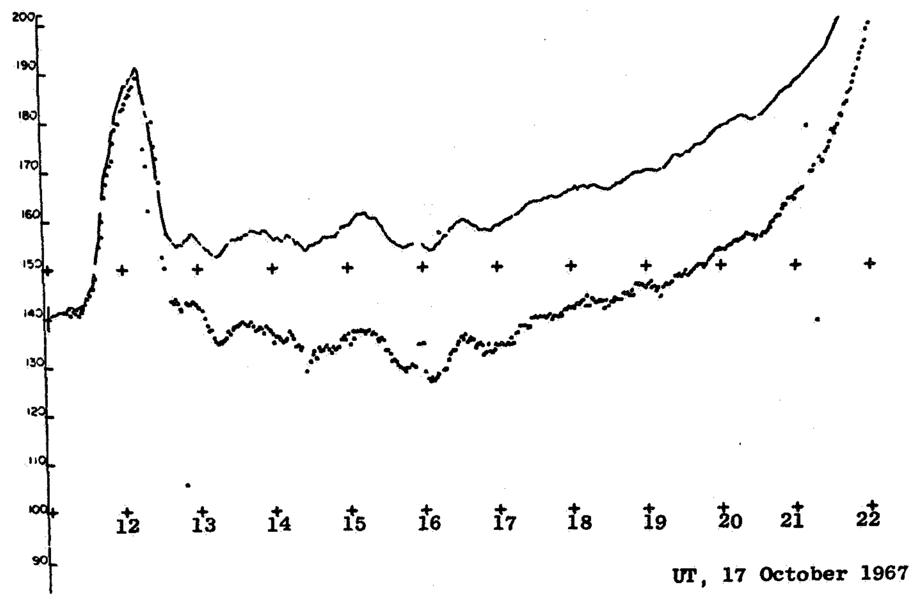
COMMENTS

Dr. T. A. Croft Many people have said there is a need for comparison of data among spacecraft and a need for diagnostics to tell whether observed events are corotating or outward-convecting. I would like to point out that such data are available from Mariner 5 and Pioneers 6, 7, 8, and 9 on which there is a radio propagation experiment that measures the average electron density from earth to the spacecraft. Figure 1 shows a good example of the data derived from the experiment. The bottom curve shows the data obtained during occultation of Mariner 5 by Venus. On the top you see a similar record obtained two days earlier. The significance of this slide is that the fluctuating-density events in the earlier record *must* be due to outward-convecting irregularities in the electron number density; they cannot be due to a corotating event. You can eliminate that possibility by considering how long a corotating event would stay in the path, the "corotation delay," and these fluctuations are too rapid.

If some of you are trying to analyze a particular event, we might be able to offer some diagnostic help like that shown here. You can determine whether we might help you by considering the following: Did the event occur when Mariner 5 was between earth and its occultation by Venus? (We stopped tracking it a month later.) For Pioneer 6, the spacecraft had to be within 1 AU of the earth for our equipment to operate, and I should point out that Pioneer 6 has gone around the sun and is now operating again, within 1 AU. Pioneer 7 was about the same as 6; it works only out to 1 AU, but Pioneers 8 and 9 have operated since their launch and are continuously operating now. They work well at 2 AU.

The experiment can only help you if one of these spacecraft is at least 0.1 AU away from earth and it has to be above Stanford's horizon to operate, so it can only obtain measurements half of every day.

If we can help anyone in this kind of diagnostic work, we would be glad to do so.



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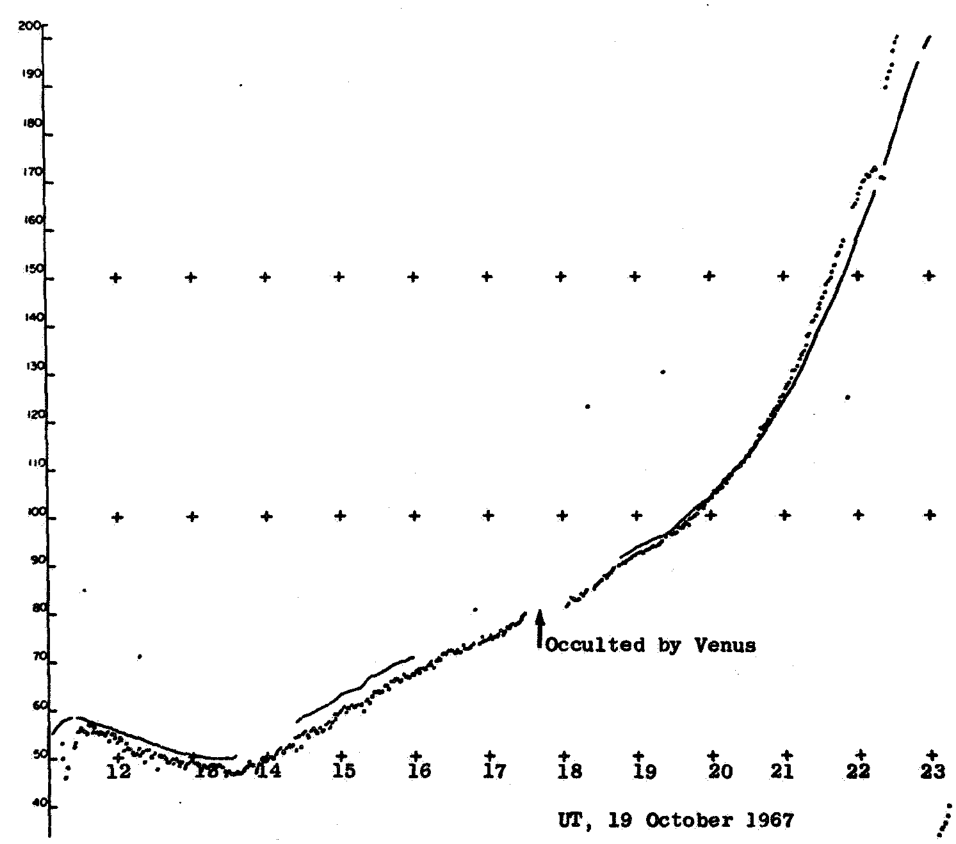

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DISCUSSION

E. C. Roelof I would like to add some support to Ogilvie's identification of a possible corotating shock on September 28, 1967, from three spacecraft analyses that I carried out with Tom Cornelius, Tom Armstrong, and Jim Van Allen. As I read Keith's slide his candidate for a corotating shock comes at the termination of a 0.3 MeV corotating proton event that we identified at all three spacecraft as its being corotating by several signatures that we developed including a velocity anisotropy, and the demand, of course, the obvious demand for similar spatial profiles at the three spacecraft. So this looks like a supporting piece of evidence.

D. W. Forslund I just wanted to mention something in connection with the observations Scarf presented earlier. There has been important research done lately on a collisionless dissipation mechanism that may occur near discontinuities or in interplanetary shocks and is particularly important in laboratory shocks. This mechanism is an instability driven by currents flowing perpendicular to the magnetic field; that is, whenever a sharp magnetic field gradient exists one has an instability due to electron cyclotron waves driven unstable by inverse Landau damping, provided the relative drift is greater than the ion thermal speed. Figure 1 illustrates the basic idea of how it works. The diagram shown here is a plot of roots of the dispersion relation, with the wave frequency ω plotted vertically and the wave number K plotted horizontally. The horizontal branches are Bernstein modes, which propagate exactly perpendicular to the magnetic field and in the absence of ion drift are undamped. And if one has ions flowing relative to the electrons as indicated by the diagonal line in the diagram where the two dashed diagonal lines indicate the ion thermal spread, the ions resonant with the phase velocities of the Bernstein modes drive the electrons unstable as indicated by the mode distortion and growth rates indicated along the curves in units of the electron gyrofrequency. The curves at the bottom are the growth rates for each harmonic. The solid curve on the right of the ion drift line is the slow ion acoustic root which is stable as indicated by the negative growth rates. We've done fully nonlinear studies of the instability and show it causes strong electron and ion heating through a nearly steady turbulent resistance and probably most important for the applications here a significant cross field diffusion, hence reducing the magnetic field gradient which is driving the instability and hence implying there would be a minimal thickness to any discontinuity or shock that would be observed.

J. R. Spreiter We've been hearing of using MHD relations to interpret interplanetary shocks and of the existence of slow shock waves. This brings up an interesting question that I don't think any mention has been made of today. That is, in addition to satisfying the conservation equations, slow shock waves must satisfy an evolutionary condition or else they can't occur according to the MHD theory. Now, this evolutionary condition is the MHD counterpart of the entropy-must-rise statement of gas dynamics, but it isn't exactly identical. It would be interesting in doing this type of MHD interpretation, particularly the slow shock waves, to inquire whether the evolutionary conditions are being satisfied.

S. Olbert I didn't show the two shocks I promised. They are slow shocks and the analysis has been published. We've checked exactly the question of evolutionary character of these shocks. The crude way of testing is the following: After you have analyzed orientation, the speed, and checked every consistency observation and theoretical prediction from MHD approximations, you can then determine the pressure of the plasma, electrons and protons put together; you can then ask the basic question, what are the Mach numbers relative to the slow mode ahead of the shock and behind the shock? And it has to come out that the Mach number ahead of the slow shock relative to the slow mode is larger than one, smaller than one. Furthermore, the main Mach number has to be smaller than one on both sides of the shock, and if these conditions are all satisfied you can then demonstrate that the evolutionary conditions are satisfied. This has been tested in the two shocks shown.

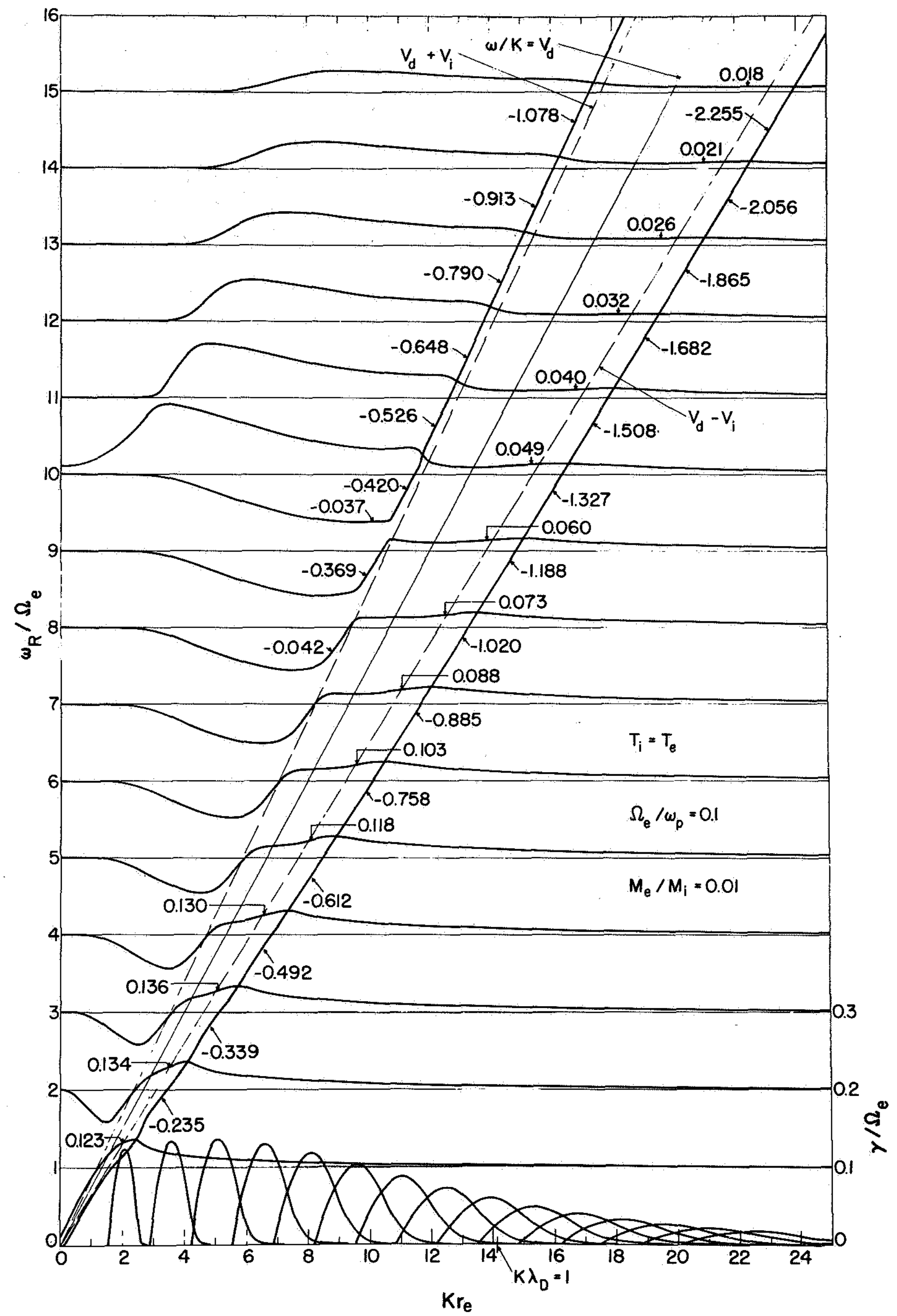

Figure 1. *Frequency versus wave number diagram for electron cyclotron waves driven unstable by ion streaming relative to electrons across a magnetic field.*

G. L. Siscoe One question relating to the heat flux problem is whether there is a flux of heat away from the shock. Isn't there a simple way to test that? Because if the density jump ever gets to be bigger than 4 for very high Mach number shock, you know there's some heat flux away. Has anyone seen density jumps bigger than 4 here at the earth's bow shock?

S. Olbert No, the strongest shock we have seen of the 4 shocks we have shown are in the increasing order of strength. The biggest you have seen was the first one. And the biggest jump density in interplanetary space I have ever seen was 13/4.4.