Structure of the November 12, 1978, Quasi-Parallel Interplanetary Shock

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An objective of this paper is to determine the jump in plasma parameters across the November 12, 1978, interplanetary shock, sufficiently accurately to test in a subsequent paper a major prediction of shock acceleration theory: the dependence of the energetic ion spectral index upon the density compression ratio. We use ISEE 1 and 3 measurements of the magnetic field and electron and proton densities, temperatures, and bulk velocities, as well as ISEE 3 alpha particle measurements, and confirm the ISEE 1 electron densities using plasma wave measurements. We solve for the shock normal using four independent methods and show that the upstream and downstream flow parameters are consistent to better than 10% with $\gamma = \frac{5}{3}$ Rankine-Hugoniot jump conditions. We conclude that the November 12, 1978, shock was a high-speed (612 km s$^{-1}$), supercritical, quasi-parallel ($\theta_{bn} = 41^\circ$) shock of moderate strength (fast Mach number of 2.8) propagating into an upstream plasma whose total $\beta$ was 1.14 and whose electron-to-proton temperature ratio was 2.8. This shock had three dissipative scale lengths, one of a few Larmor radii associated with its magnetic field jump, one of about 10 $R_E$ associated with electron equilibration, and one of about 30 $R_E$ associated with an energetic proton foreshock.

1. INTRODUCTION

Studies of interplanetary shocks reveal large-scale features of shock structure that are difficult to perceive in bow shock measurements. The earth's bow shock's radius of curvature is smaller than the length scale of the foreshock, and the spatial dependences of the energetic proton fluxes and MHD wave amplitudes in the foreshock are not easy to determine. Furthermore, the magnetosheath turbulence downstream of the quasi-parallel zone of the bow shock extends directly to the magnetopause, so that the decay length of the turbulence is hard to estimate. The bow shock is not perfectly separated from the magnetopause, and weak dissipation mechanisms acting over distances greater than the bow shock–magnetopause separation may have been overlooked in magnetosheath studies.

In the first of three papers concerned with the November 12, 1978, interplanetary shock, we assembled ISEE 1, 2, and 3 measurements of the upstream magnetic field, plasma, energetic ions, and MHD and plasma waves [Kennel et al., this issue] (hereinafter paper 1). We reached two major conclusions. First, the shock had entered a closed magnetic island before it encountered the ISEE spacecraft. The energetic proton flux, and the MHD and plasma wave amplitudes, were enhanced inside the magnetic bubble, whose leading edge swept over ISEE 3 two hours ahead of the shock. Second, a comoving energetic ion foreshock led the shock by 45 min. The exponential scale length of the energetic proton flux in the foreshock was about 30 $R_E$, and >10-keV protons achieved a $\beta$ of order unity at the shock. Strictly speaking, this foreshock was part of the overall shock structure. Drury and Volk [1981] have argued that for solar wind parameters, part of the decrease in shock frame flow speed mandated by the Rankine-Hugoniot conditions should occur in such a foreshock, and the remainder across a much thinner plasma subshock, in which accelerated ions play no role.

This paper, the second in the series, continues our study of the multiple dissipation lengths associated with the November 12, 1978, shock. We will find that electrons equilibrated on a 12-$R_E$ scale that would be difficult to perceive in magnetosheath measurements, and that the MHD turbulence downstream of the shock decayed on a 40-$R_E$ scale. In paper 3 (C. F. Kennel et al., unpublished manuscript, 1984) we will test shock acceleration theory using the spatial profiles of the energetic ion and MHD wave amplitudes, together with the waves' polarization and spectrum. To this end the present paper determines the jump in plasma parameters across the November 12 shock sufficiently accurately to permit a quantitative test in paper 3 of a major prediction of shock acceleration theory: the dependence of the energetic ion spectral index upon the density compression ratio. Once again, bow shock measurements are not reliable, for it is necessary to determine the full density compression occurring over one energetic proton mean free path, which was about 10 $R_E$ for the November 12 shock. Moreover, loss mechanisms due to the bow shock's finite geometry dominate the form of the spectrum, yielding an exponential in energy per charge, rather than the power law predicted for plane shocks.

In section 2 we discuss ISEE 1 and 3 magnetic and electric field measurements made near the November 12, 1978, shock. At high time resolution, the shock's magnetic field profile was similar to the bow shock's. Thus its main dissipation took place on a scale of a few ion Larmor radii. In section 3 we assemble ISEE 1 and 3 measurements of the electron and proton densities, temperatures, and bulk velocities, as well as ISEE 3 alpha particle measurements, and confirm the ISEE 1 densities using plasma wave measurements. We show that the electron temperature increased smoothly with a 12-$R_E$ scale length across the shock. In section 4 we solve for the shock normal using four independent methods. We also show that the upstream and downstream flow parameters are consistent to better than 10% with $\gamma = \frac{5}{3}$ Rankine-Hugoniot conditions applied over the 12-$R_E$ scale of the electron temperature increase. In section 5 we study the complex train of events that
followed the November 12 shock, in order to define the downstream region to which shock acceleration theory applies. We conclude with a summary in section 6.

2. ISEE 1 AND 3 MAGNETIC AND ELECTRIC FIELD MEASUREMENTS

Figure 1 diagnoses the November 12, 1978, shock with the highest-time resolution data available to us. The ISEE 1 (dashed) and ISEE 3 (solid) magnetic field magnitudes are plotted for 8.2 s surrounding the shock crossings at 0028:18 UT (ISEE 3) and 0058:26 UT (ISEE 1). The data points correspond to individual 1-s measurements (ISEE 3) and to running 1-s averages of measurements taken every 1/3 s (ISEE 1). The magnetic field jumps at ISEE 1 and 3 have been displaced by 1 s to facilitate visual intercomparison. The ISEE 1 time scale is at the top of Figure 1, and the ISEE 3 at the bottom. From the 1808-s delay between the ISEE 3 and 1 shocks and the 181.3-Re (ΔX) distance between the two spacecraft, we estimate that the effective shock speed ΔX/Δt was 646 km s\(^{-1}\), or about \(\frac{1}{2} \) Re s\(^{-1}\). Thus a time interval of 1 s corresponds roughly to a distance of 640 km, as is indicated in Figure 1. A more accurate estimate of the shock speed will be given in section 4.

The ISEE 3 and 1 magnetic field profiles were remarkably similar, even at high time resolution. The field magnitude varied between 7 and 9 \(\gamma\) during the last few seconds prior to shock encounter at both spacecraft. The magnetic field at ISEE 3 jumped from 9.2 \(\gamma\) at 0028:17 UT to 17.8 \(\gamma\) at 0028:18.40 UT, for a compression ratio of 1.93. The corresponding exponential scale length was 1360 km. The ISEE 3 plasma wave intensity and spectrum began to change at 0028:16 UT with a time scale similar to that of the magnetic field [Kennel et al., 1982]. The ISEE 1 magnetic field increased from 8.8 \(\gamma\) at 0058:26.30 to 17.3 \(\gamma\) at 0058:27.30, for a compression ratio of 1.97, and an exponential scale length of 940 km. The proton inertial length \(c/ω_p\) was 112 km, based on an upstream density of 4 cm\(^{-3}\) (Table 2). In section 4 we will find that the component of solar wind speed parallel to the shock normal was 238 km s\(^{-1}\) in the shock frame. The characteristic proton Larmor radius, based upon this flow speed and an average upstream field magnitude of 8 \(\gamma\), was 297 km. Thus the magnetic field scale length was comparable to the bow shock's [Livesey et al., 1982] in both absolute and normalized terms.

Figure 2 shows the Y component (GSE) and the magnitude of the interplanetary magnetic field for 8 min and 40 s surrounding the ISEE 3 (top panel) and ISEE 1 (bottom panel) shock encounters. Note that the ISEE 1 and 3 vertical scales differ. The ISEE 1 and 3 shocks were similar on the time scale of Figure 2. In particular, we call attention to the enhanced magnetic field regions downstream of both shocks. At ISEE 3 the field rose sharply at the shock, then more slowly, peaked, and dropped to a more or less constant value 17 s downstream. It then remained constant until 52 s downstream, when it had a sharp local minimum. At ISEE 1 the field magnitude rose sharply, peaked, and dropped to a local minimum 30 s downstream. After the minima, the ISEE 1 and 3 magnetic field magnitudes rose smoothly and steadily to maxima that preceded field rotations 6 and 7 min downstream of the shocks.

The similarity of the downstream magnetic field enhancements at ISEE 1 and 3 suggests that they were comoving with the shock. If so, they were either 1.7 or 5.2 Re thick at ISEE 3, and 3.0 Re at ISEE 1. Thus these structures were much larger than bow shock magnetic field overshoots [Livesey et al., 1982].

Both the ISEE 1 and 3 shocks initiated large-amplitude oscillations in the Y component of the magnetic field. There is at least a visual impression that they had a higher frequency and larger amplitude in the downstream magnetic structures.
Fig. 3. ISEE 3 electric and magnetic wave fields. The top and bottom panels repeat the interplanetary magnetic field information displayed in the top panel of Figure 2. The other panels show 1-s average 31.6-kHz, 3.16-kHz, and 562-Hz electric field and 16-s average 17.8-Hz magnetic field spectral amplitudes. A few bursts of 31.6-kHz electron plasma oscillations occurred at and downstream of the shock; none were observed upstream by ISEE 3 (paper 1). The 3.16-kHz ion acoustic electric field, which had increased for the 45 min prior to the ISEE 3 encounter (paper 1), peaked at the shock, dropped suddenly about 20 s downstream, and diminished slowly thereafter. In contrast, the 562-Hz electric fields and the 17.8-Hz whistler mode magnetic field amplitudes increased at the shock and remained elevated thereafter. The behavior of the 3.16-kHz and 562-Hz electric fields and of the 17.8-Hz magnetic field was typical of quasi-parallel interplanetary shocks [Kennel et al., 1982]. Note the secondary bursts of 3.16-kHz ion acoustic noise that accompanied the magnetic field rotation at 0034 UT.

The top two panels in Figure 4 show the X and Y components of the interplanetary electric field, and the bottom three show the X, Y, and Z components of the interplanetary magnetic field (IMF). The Z component of the electric field may be inferred assuming \( E \cdot B = 0 \). The general anticorrelation of referred to above. In any case, their amplitude diminished steadily thereafter and was effectively zero just before the field rotation. The oscillations decayed in 6 min, or 36 \( R_E \) downstream of ISEE 3 and in 7 min, or 42 \( R_E \) downstream of ISEE 1. A similar decay of the hydromagnetic turbulence downstream of the bow shock would not be evident in magnetosheath measurements.

The top and bottom panels of Figure 3 repeat the ISEE 3 magnetic field data shown at the top of Figure 2. The four middle panels show ISEE 3 1-s average 31.6-kHz, 3.16-kHz, and 562-Hz electric field spectral densities, together with the 16-s average 17.8-Hz magnetic field spectral density, for the same time interval. Several bursts of 31.6-kHz electron plasma oscillations occurred at and slightly downstream of the shock. The amplitude of the 3.16-kHz ion acoustic electric field, which had increased for the 45 min prior to the ISEE 3 encounter (paper 1), peaked at the shock, dropped suddenly about 20 s downstream, and diminished slowly thereafter. In contrast, the 562-Hz electric field and the 17.8-Hz whistler mode magnetic field amplitudes increased at the shock and remained elevated thereafter. The behavior of the 3.16-kHz and 562-Hz electric fields and of the 17.8-Hz magnetic field was typical of quasi-parallel interplanetary shocks [Kennel et al., 1982]. Note the secondary bursts of 3.16-kHz ion acoustic noise that accompanied the magnetic field rotation at 0034 UT.

The top two panels in Figure 4 show the X and Y components of the interplanetary electric field, and the bottom three show the X, Y, and Z components of the interplanetary field measured at ISEE 1 between 0050 UT and 0115 UT on November 12, 1978. The two electric field components are accurate to about \( \pm 1 \) mV/m, and the third component may be estimated assuming \( E \cdot B = 0 \). The general anticorrelation of...
$E_y$ and $B_x$ is consistent with an MHD flow in the $-X$ direction. We have verified that the measured electric field is consistent with the measured solar wind speed upstream of the shock.

The average magnetic field upstream of the shock was contained in the $(X, Z)$ plane, since the $Y$ component oscillated about zero. The shock at 0058:26 UT is most apparent in $E_y$ and $B_x$; note the gentle ramp in $E_y$ that led the shock by about 1 min. The average magnetic field downstream of the shock was also in the $(X, Z)$ plane, since $B_y$ again oscillated about zero. The turbulence downstream of the shock was restricted largely to the $Y$ component, suggesting that it was linearly polarized. The sharp field rotation essentially rotated the magnetic field from the $(X, Z)$ plane to the $(X, Y)$ plane, with no change in field magnitude. $B_y$ varied only slightly.

A highly disturbed period followed the field rotation. We will see that dramatic variations of solar wind density and temperature accompanied those in the electric and magnetic fields. After 0110 UT the interplanetary field became more quiescent, and ISEE 1 entered a new and different solar wind state. We will discuss the field rotation and the disturbed period following it in section 5. Until then, we will concentrate on the shock, though we will also introduce data pertinent to the analysis in section 5.

3. SOLAR WIND ELECTRON AND ION MEASUREMENTS

Figure 5 compares ISEE 1 measurements of the $Y$ component and magnitude of the interplanetary magnetic field (top two panels) with number density measurements made by the Goddard Space Flight Center (GSFC) electron spectrometer for the period 0050-0110 UT on November 12, 1978. An electron density was computed approximately every 17 s, during which interval the shock traveled about 1.7 $R_E$. There is a slight mismatch between the magnetic field and density time scales in Figure 5, so where it is central to our argument, we will cite individual density measurements. The electron density reached a local maximum of 12.4 $cm^{-3}$ at 0059:28, approximately 6 $R_E$ downstream of the magnetic field jump.

The density at 0058:15 was 5.2 $cm^{-3}$; the magnetic jump occurred between 0058:26.30 and 0058:27.30 (Figure 1); the density at 0053:32.00, the next measurement, was 10.6 $cm^{-3}$. We do not know whether the magnetic field and density jumps coincided. The density diminished slightly, to 10.5 $cm^{-3}$, at 0058:51, about the time the magnetic field reached the local minimum downstream of the shock noted in the discussion accompanying Figure 2. Seventeen seconds later, at 0059:10 UT, the density increased to 11.9 $cm^{-3}$, and it reached a local maximum of 12.4 $cm^{-3}$ at 0059:28, approximately 6 $R_E$ downstream of the magnetic field jump.

Figure 6 shows the ISEE 1 electron temperature (top panel), density (middle panel), and bulk velocity (bottom panel) measured between 0050 and 0110 UT. No distinction was made between "core" and "halo" electrons in the calculation of the electron temperature, which was defined by the trace of the velocity dispersion tensor. Ahead of the shock, the electron density varied between 3.7 and 5.5 $cm^{-3}$ during the 8 min prior to shock encounter, with 4.5 $cm^{-3}$ a reasonable average value. The density at 0058:15 was 5.2 $cm^{-3}$; the magnetic jump occurred between 0058:26.30 and 0058:27.30 (Figure 1); the density at 0053:32.00, the next measurement, was 10.6 $cm^{-3}$. We do not know whether the magnetic field and density jumps coincided. The density diminished slightly, to 10.5 $cm^{-3}$, at 0058:51, about the time the magnetic field reached the local minimum downstream of the shock noted in the discussion accompanying Figure 2. Seventeen seconds later, at 0059:10 UT, the density increased to 11.9 $cm^{-3}$, and it reached a local maximum of 12.4 $cm^{-3}$ at 0059:28, approximately 6 $R_E$ downstream of the magnetic field jump.

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Now let us discuss the individual electron bulk velocity and temperature measurements made near the magnetic jump in Figure 1. At 0058:15, just before the jump, they were 368 km s$^{-1}$ and $4.3 \times 10^5$ °K, respectively, and, just after, at 0058:32, they were 487 km s$^{-1}$ and $5.0 \times 10^5$ °K. At the next three measurements they were 541 km s$^{-1}$, $4.8 \times 10^5$ °K; 497 km s$^{-1}$, $5.0 \times 10^5$ °K; and 489 km s$^{-1}$, $5.0 \times 10^5$ °K. Thus the electron temperature began to increase 1 min and 6 $R_E$ ahead of the magnetic ramp, rose more or less monotonically through the shock, and leveled off 1 min and 6 $R_E$ downstream of the magnetic field jump.

To one unaware of the high speed of the shock, the electron temperature profile in the top panel of Figure 6 might appear to be the classical one expected for a shock transition. The temperature went from a more or less constant value upstream to a steady value downstream, with a number of data points resolving the increase in temperature between the two states. The temperature leveled off near the point where the density stopped increasing. Yet these increases took place over a 12-$R_E$ scale length, much larger than that of the magnetic structure in Figure 1, and not readily perceivable in bow shock and magnetosheath measurements. This long scale length might be associated with the thermalization of super-
Fig. 6. ISEE 1 electron temperature, density, and bulk speed. The electron temperature increased smoothly over a 12-\(R_E\) distance from the leading edge of the shock to the trailing density maximum at 0059:28. It then remained constant until 0102 UT, when it began to decline. It dropped suddenly at the 0105:25 field rotation and minimized at the 0107:58 density maximum. The temperature and bulk speed increased downstream of the density maximum.

thermal halo electrons, which are included in the calculation of the temperature presented in Figure 6.

The bottom panel of Figure 7 shows 1-min averages of the magnitude of the ISEE 1 electron heat flux vector, \(|\mathbf{\phi}|\), measured from 0042 to 0110 UT. The direction of the heat flux vector varied considerably during this period, presumably reflecting the variability in magnetic field direction. The heat flux upstream was more or less field aligned and directed away from the oncoming shock, toward the earth; it remained pointed toward earth downstream, with the exception of the minute after the 0059:28 UT density maximum (Figures 5 and 6), when it reversed direction.

The heat flux magnitude, which was about 7 \(\times 10^{-3}\) ergs cm\(^{-2}\) s\(^{-1}\) upstream, increased to 4 \(\times 10^{-2}\) ergs cm\(^{-2}\) s\(^{-1}\) in the region of magnetic disturbance near 0108 UT. This apparently simple behavior masks an important change in the properties of the electron heat flux. The middle panel of Figure 7 shows the effective heat flux velocity \(U_e = 2|\mathbf{\phi}|/3N_eT_e\). The speed \(U_e\) was about 150 km s\(^{-1}\) upstream of the shock, consistent with ISEE 3 measurements both near the shock and far upstream (paper 1). Between the shock and the field rotation, \(U_e\) was about 75 km s\(^{-1}\), and it was roughly 220 km s\(^{-1}\) downstream of the rotation. The top panel of Figure 7 shows \(U_e\) normalized to the Alfvén speed \(C_A\) calculated using the local magnetic field strength and electron density, assuming an average \(\alpha/P\) density ratio of 0.075, roughly that measured at ISEE 3 (Figure 10). The heat flux velocity was 2–3 times the Alfvén speed upstream of the shock and downstream of the rotation. It was roughly equal to the Alfvén speed between the shock and rotation where the amplitude of the MHD turbulence was large. This suggests that the electron heat flux may have been limited by wave-particle scattering and that the relevant waves had phase velocities near the Alfvén, or perhaps the ion acoustic, speed.

Figure 8 shows the proton temperature (bottom panel), bulk speed (second panel from bottom), and velocity direction (top two panels) measured by the Los Alamos National Laboratory/Max-Planck-Institut (LANL/MPI) solar wind plasma instrument on ISEE 1 between 0000 UT and 0200 UT. The proton bulk speed stayed constant at 370 km s\(^{-1}\) during the 58 min prior to shock encounter, in agreement with the average electron bulk speed. The velocity vector was directed approximately 5° north of the ecliptic upstream, and its ecliptic plane projection became almost exactly radially outward from the sun 15 min prior to encounter. The proton bulk speed jumped to 525 km s\(^{-1}\) near the shock magnetic jump, held constant for a minute, and jumped again to 560 km s\(^{-1}\) at the 0059:28 density maximum; if then remained constant until the field rotation at 0105:25 UT. The proton bulk speed increased to 620 km s\(^{-1}\) near 0110 UT, again in agreement with electron measurements. It increased irregularly thereafter, reaching a maximum of 800 km s\(^{-1}\) at 0130 UT.

The bottom panel of Figure 8 shows the ISEE 1 proton temperature inferred from a numerical integration of the measured velocity distribution. Each computation yields the mini-
shock encounter, though it became indistinct just before the plasma line near 22 kHz was present from 0000 UT until electric field measurements for the same time interval as in Figure 8, 0000-0200 UT on November 12, 1978. An electron density maximum at 0107:58 UT. It increased to above 7.5 x 10^5 cm^-3 just before the shock. It jumped to 5.8 x 10^5 cm^-3 at the 0059:28 UT density maximum, at which it started, the shock was about 65 R_e downstream of earth.

Figure 8, ISEE 1 proton parameters. Both the proton bulk speed and temperature increased sharply at the shock and increased again at the 0059:28 UT density maximum (Figures 5 and 6). An impulsive increase in proton temperature may have occurred at the 0105:25 UT density maximum. The proton bulk speed increased to 620 km s^-1, in agreement with the electron bulk speed downstream of this density maximum. Both the electron and proton temperatures increased in the region of high-speed flow.

The middle panel of Figure 10 shows the proton density. Shown, in descending order from the top, are the alpha particle temperature, the alpha/proton density ratio, the proton density, the proton temperature, and the proton bulk speed. As in Figure 8, the maximum and minimum alpha and proton temperatures derived from a complete angular scan are plotted, this time as the extrema of error bars. These generally correspond to the parallel (maximum) and perpendicular (minimum) temperatures. Although significant data gaps surround the shock, field rotation, and high-density region, the data do indicate the solar wind conditions upstream and downstream of these features.

Let us discuss the ISEE 3 proton data first. Note the gradual changes in proton properties upstream of the shock. The proton bulk speed, though variable, increased ahead of the shock; at ISEE 1 no such variability or increase was detected (Figure 8). At ISEE 3 the bulk speed increased by about 30 km s^-1 during the 28 min preceding shock encounter, corresponding to a 30 km s^-1 decrease of the upstream flow speed in the shock frame. The bulk speed was 400 km s^-1 at the last data point before the shock, about 1 min upstream. The proton temperature, though variable, remained within a constant range between 0000 and 0020 UT; during this interval the parallel temperature was about 5 x 10^6 °K, and the perpendicular temperature was 3 x 10^6 °K. Then, much as at ISEE 1, the ISEE 3 proton temperature increased and became more isotropic during the last 7 min prior to shock encounter. The temperature was ~7.5 x 10^6 °K just before the shock.
measured by the ISEE 3 Radio Mapping Experiment indicates that the routinely calculated proton density should be increased by 25% (J.-L. Steinberg, personal communication, 1982). This correction has been applied to the proton density data in Figure 10. The upstream proton density gradually decreased from about 6 cm$^{-3}$ at 0000 UT to 4 cm$^{-3}$ at 0027 UT, the last density measurement before the shock. It increased to a maximum of 11 cm$^{-3}$ between the shock and the field rotation. The bulk speed at the first measurement downstream of the ISEE 3 shock was 571 km s$^{-1}$, and the proton temperature was $\approx 6 \times 10^{5}$ øK and isotropic. The density spike associated with the disturbed region (0107:58 UT at ISEE 1, Figures 5, 6, 7, and 9) may have been lost in a data gap at ISEE 3. The proton bulk speed increased from 600 km s$^{-1}$ to 650 km s$^{-1}$, and the temperature increased to above $10^{6}$ øK, downstream of the disturbed region. At ISEE 1 the proton bulk speed also increased by 50 km s$^{-1}$, but it jumped between two values, 570 km s$^{-1}$ and 620 km s$^{-1}$, which were 30 km s$^{-1}$ lower than at ISEE 3, reflecting the general 30 km s$^{-1}$ difference in the speeds measured at the two spacecraft (Figure 8).

The top two panels of Figure 10 show the alpha particle temperature and the alpha/proton number density ratio. The alpha temperature was roughly 4 times the proton temperature upstream and at the one alpha particle data point recorded between the shock and the field rotation. The alpha/proton density ratio was highly variable. In our calculations of the Rankine-Hugoniot relations in section 4, we will assume that 7.5% was a reasonable average upstream value.

4. Shock Normal and Rankine-Hugoniot Solutions

4.1. Introductory Remarks

In section 4.2 we derive the ISEE 1 and 3 shock normals in four different ways, three of which yield mutually consistent results. The fourth may not be consistent with the fact that the November 12 shock was produced by a central meridian solar flare. We also estimate the shock speed more accurately than we did in section 2. In section 4.3 we show that the densities, speeds, temperatures, and magnetic fields upstream and downstream of the ISEE 3 shock are consistent with the Rankine-Hugoniot jump conditions.

4.2. Shock Normal Solutions

We calculated the normal to the November 12, 1978, shock by using the coplanarity of the upstream and downstream magnetic field vectors at ISEE 1 (method 1); by using coplanarity at ISEE 3 (method 2); by using three-dimensional LANL/MPI ISEE 3 solar wind data in the mixed mode method of Abraham-Schrauner [1972] and Abraham-Schrauner and Yun [1976] (method 3); and by taking the cross products of the magnetic field jumps calculated from the possible combinations of ISEE 1 and 3 upstream and downstream magnetic field vectors (method 4). The method 3 results reported by Kennel et al. [1982], which used two-dimensional plasma data, will be amended here. Russell et al. [1983] have found that method 3 generally leads to the most accurate results in studies of other interplan-
The shock speed \(U_{SH}\). The three values of \(\theta_{sh}\) accompanying the method 4 solution correspond to the use of the upstream magnetic field vectors determined from methods 1, 2, and 3; the upstream magnetic fields used in methods 2 and 3 differed slightly, in particular because the method 3 magnetic field corresponded to an average surrounding the last plasma measurement upstream of the shock.

Given the vector displacement \(d\) between ISEE 1 and 3, the shock normal \(n\), and the time delay \(\Delta t\) between the two shock encounters, we may calculate the shock speed \(U_{SH}\) from

\[
U_{SH} = \frac{d \cdot n}{\Delta t} = \frac{d \cos \theta_{sh}}{\Delta t}
\]

\(U_{SH}\) is not the speed with which the line of intersection between the ecliptic plane and the shock plane moves, but rather the component of shock speed parallel to the shock normal, the quantity needed to test the Rankine-Hugoniot relations. Using the locations of ISEE 3 and 1 at the time of the ISEE 3 shock encounter, we have

\[
d = (-181.3, +25.1, +20.1)
\]

\[
= 184.1(-0.985, +0.136, +0.110)
\]

where distances are expressed in earth radii. From the times of the two encounters, we find \(\Delta t = 1808\) s, so that

\[
U_{SH} = 655.7 \cos \theta_{sh} \text{ km s}^{-1}
\]

where \(\theta_{sh}\) may be computed given a shock normal solution.

Methods 1, 3, and 4 lead to shock normals in excellent agreement with one another, and therefore to almost identical values of \(U_{SH}\) and of \(\theta_{sh}\). The fact that the shock normal was directed approximately 15° south of the ecliptic plane is consistent with the north solar hemisphere location of the flare that launched the shock (paper 1). Although it is only slightly different from the other normals, we tend to mistrust the method 2 shock normal, because its \(Y\) component, which was at least 3 times larger than those from the other methods, is difficult to reconcile with the central meridian location of the parent flare.

In closing, we note that the values of \(U_{SH}\) in Table 1 correspond to the average speed of the shock between ISEE 3 and 1. The interplanetary shock may have changed its speed and strength slightly as it entered the disturbed region upstream of the bow shock. Since this region is typically only about 50 \(R_E\) thick, the calculated \(U_{SH}\) may represent the instantaneous shock speed at ISEE 3 fairly well, but may be somewhat inaccurate for ISEE 1.

### 4.3. Rankine-Hugoniot Solution

Here we determine the extent to which the measured solar wind density, flow speed, temperature, and magnetic field upstream and downstream of the shock are consistent with the

<table>
<thead>
<tr>
<th>(\theta_{sh}) deg</th>
<th>(U_{SH}) \text{ km s}^{-1}</th>
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<tbody>
<tr>
<td>41.6</td>
<td>609</td>
</tr>
<tr>
<td>34.9</td>
<td>624</td>
</tr>
<tr>
<td>41.0</td>
<td>612</td>
</tr>
<tr>
<td>43.5, 41.3, 42.8</td>
<td>605</td>
</tr>
</tbody>
</table>

**Table 1. Shock Normal Solutions**

<table>
<thead>
<tr>
<th>Method</th>
<th>Normal (n_x)</th>
<th>Normal (n_y)</th>
<th>Normal (n_z)</th>
<th>(\theta_{sh})</th>
<th>(U_{SH}) \text{ km s}^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) ISEE 1 coplanarity</td>
<td>-0.966</td>
<td>+0.043</td>
<td>-0.256</td>
<td>41.6</td>
<td>609</td>
</tr>
<tr>
<td>(2) ISEE 3 coplanarity</td>
<td>-0.942</td>
<td>+0.029</td>
<td>-0.152</td>
<td>34.9</td>
<td>694</td>
</tr>
<tr>
<td>(3) ISEE 3 mixed mode</td>
<td>-0.966</td>
<td>+0.073</td>
<td>-0.247</td>
<td>41.0</td>
<td>612</td>
</tr>
<tr>
<td>(4) Double delta B</td>
<td>-0.954</td>
<td>+0.104</td>
<td>-0.279</td>
<td>43.5, 41.3, 42.8</td>
<td>605</td>
</tr>
</tbody>
</table>
and halo electrons were probably scattered on the longer scale. In so doing, we will estimate the fast Mach number of the shock and test the shock normal solution found in section 4.2.

A theoretician usually specifies the shock frame upstream flow speed parallel to the shock normal, \( U_{\text{sh}} \), the upstream ratio of thermal to magnetic pressure, \( \beta_1 \), the shock normal angle \( \theta_{\text{sn}} \), and the ratio of specific heats, \( \gamma \), and then obtains the downstream plasma parameters using the RH relations. In the present case, we found \( \theta_{\text{sn}} \) in section 4.2, we can calculate \( \beta_1 \) from observation, we must continue to assume a value of \( \gamma \), and given \( U_{\text{sh}} \) and the upstream spacecraft frame solar wind velocity \( V_1 \), we can estimate \( U_{\text{ow}} \). We therefore could proceed directly to the downstream parameters. We will actually go about our task slightly differently. We will specify the magnetic field compression ratio \( B_2/B_1 \), rather than \( U_{\text{ow}} \), which requires the shock normal solution as an intermediate step. This strategy enables us to test the mutual consistency of the shock normal and Rankine-Hugoniot solutions. Furthermore, we will present the dependence of the RH solution upon \( B_2/B_1 \) and \( \beta_1 \), to illuminate the sensitivity of the RH solution to measurement errors.

Our first task is to tabulate the upstream and downstream flow parameters whose consistency with the RH relations is to be tested. In so doing, we must keep in mind the nature of the data available to us. In particular, the limited time resolution of the plasma data means that we can apply the RH relations to the jumps in plasma parameters, not over the short magnetic field scale length of Figure 1, but over the longer scale length over which the electron temperature, for example, reached a steady downstream state (Figure 6). In fact, we will identify the downstream state with the 0059:28 UT ISEE 1 density and temperature maximum, and its analog at ISEE 3. This strategy has two implications. First, although the electrons might have behaved isothermally over the short magnetic scale length, we can assume \( \gamma = \frac{5}{3} \) here, since both core and halo electrons were probably scattered on the longer scale length (Figure 7). Furthermore, Russell et al. [1983] found that the jumps in plasma and magnetic field across other interplanetary shocks are better predicted using \( \gamma = \frac{2}{3} \) rather than \( \gamma = 2 \) in the RH relations. Second, we should use averaged upstream and downstream magnetic field measurements, to correspond to the time scales over which the plasma measurements were taken, and to remove the effects of the large-amplitude MHD waves on both sides of the shock.

We will not include the MHD wave fluxes in the Rankine-Hugoniot calculation. The wave amplitude upstream of the shock, normalized to the background magnetic field, was about 25%, so that the wave energy density was about 12% of the magnetic field energy density. In other words, the "wave \( \beta' \) was about 0.12, whereas the upstream thermal \( \beta_1 \) was \( \approx 1.14 \). Thus the neglect of the MHD waves in the RH calculation is probably justified.

Tables 2 and 3 present our estimates of the upstream and downstream flow parameters, respectively. The first column in each table indicates the instrument or technique from which the estimate was obtained, and the second and third columns list the ISEE 1 and ISEE 3 parameters, respectively. All the estimates are derived from data presented in this paper, with the exception of the ISEE 3 electron parameters, which are taken from Figure 4 of paper 1. Where vector quantities are known, we present them as a magnitude times a unit vector in the GSE coordinate system. We give two types of estimate of the upstream and downstream magnetic fields, 2.5-min mathematical averages of the vector fields and magnitudes taken from Figure 2 at the specific times indicated. The two types of magnitude estimate agree within about 5%. The ISEE 3 electron data are routinely analyzed in terms of a superposed core plus halo electron distribution function model, and so we give both the core and the core plus halo average temperature for ISEE 3; only the average electron temperature is available from ISEE 1.

The number densities and bulk velocities derived from electron and ion data agree separately for ISEE 1 and 3, insofar as

---

### Table 2. Upstream Parameters

<table>
<thead>
<tr>
<th></th>
<th>ISEE 1</th>
<th>ISEE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number Densities, ( \text{cm}^{-3} )</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LANL/(MPI) protons</td>
<td>~4</td>
<td></td>
</tr>
<tr>
<td>LANL/(MPI) alphas</td>
<td></td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>LANL electrons</td>
<td>~4</td>
<td></td>
</tr>
<tr>
<td>Iowa plasma line electrons</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>GSFC electrons</td>
<td>4–5</td>
<td></td>
</tr>
<tr>
<td><strong>Bulk Velocities, ( \text{km s}^{-1} )</strong></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>LANL/(MPI) protons</td>
<td>370(−0.994, +0.017, +0.105)</td>
<td></td>
</tr>
<tr>
<td>LANL/(MPI) electrons</td>
<td>~400</td>
<td></td>
</tr>
<tr>
<td>GSFC electrons</td>
<td>375 ± 40</td>
<td></td>
</tr>
<tr>
<td><strong>Temperatures, ( ^\circ\text{K} )</strong></td>
<td></td>
<td>8–10 ( \times ) ( 10^4 )</td>
</tr>
<tr>
<td>LANL/(MPI) protons</td>
<td>7–9 ( \times ) ( 10^4 )</td>
<td></td>
</tr>
<tr>
<td>LANL/(MPI) alphas</td>
<td>3 ( \times ) ( 10^3 )</td>
<td></td>
</tr>
<tr>
<td>LANL core electrons</td>
<td>1.2 ( \times ) ( 10^3 )</td>
<td></td>
</tr>
<tr>
<td>LANL core and halo average electrons</td>
<td>2.5 ( \times ) ( 10^3 )</td>
<td></td>
</tr>
<tr>
<td>GSFC core and halo average electrons</td>
<td>3.6 ( \times ) ( 10^3 )</td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic Field, ( \gamma )</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5-min average</td>
<td>6.70(±0.899, +0.043, −0.439)</td>
<td>6.85(±0.889, −0.133, −0.436)</td>
</tr>
<tr>
<td>at 0028 UT</td>
<td>~7</td>
<td></td>
</tr>
<tr>
<td>at 0058 UT</td>
<td>~7.5 increasing</td>
<td></td>
</tr>
</tbody>
</table>
it is possible to determine. The electron and proton bulk velocities are in excellent agreement, and the electron number density exceeds the proton density by an amount that is reconcilable by imposing charge neutrality using the measured ISEE 3 alpha/proton density ratio of about 7.5%.

Although the conditions upstream of the ISEE 1 and ISEE 3 shocks were quite similar, there were noticeable differences. The magnetic field magnitude was roughly constant during the 1 min before the ISEE 3 shock, whereas it increased upstream of the ISEE 1 shock. The electron temperature increased approaching the ISEE 1 shock, while it was more nearly constant at ISEE 3. The core plus halo average electron temperature was 50% larger ahead of the ISEE 1 shock than at ISEE 3. Of greatest interest, the proton bulk velocity increased from 370 to 400 km s\(^{-1}\) in the half hour before the ISEE 3 shock, whereas it remained constant at 370 km s\(^{-1}\) at ISEE 1. Thus at ISEE 1 the solar wind was 30 km s\(^{-1}\) slower upstream of the shock than it was at ISEE 3. This 30 km s\(^{-1}\) difference in solar wind speed is consistent with the deceleration typically observed in the earth’s foreshock [Bame et al., 1980]. Thus our RH solution should be more reliable for the ISEE 3 shock, because of the complex interaction between the interplanetary shock and bow shock at ISEE 1.

The top panel of Figure 11 shows solutions of the RH relations with the magnetic field compression ratio \(B_2/B_1\) as the independent variable rather than the fast Mach number. Since the electron temperature jump across the ISEE 3 shock was consistent with a \(\gamma = \frac{3}{2}\) adiabatic law, we assumed \(\gamma = \frac{3}{2}\). In order to gauge the effect of uncertainties in the upstream magnetic field and plasma densities and temperatures, we performed the computations for a range of values of upstream plasma \(\beta_1\) which may be linked to measured quantities by

\[
\beta_1 = \frac{8\pi}{B_1^2} \left( \frac{N_p T_p + N_e T_e + N_p T_e}{N_p + 2N_e} \right)
\]

(3)

where the temperatures are expressed in energy units.

The RH relations actually yield the mass density compression ratio \(\rho_2/\rho_1\), where

\[
\rho = N_p M_p + 4N_e M_p + (N_p + 2N_e)M_e
\]

(4)

and \(M_p\) and \(M_e\) are the proton and electron mass respectively. We will assume that the alpha/proton density ratio did not change across the shock, so that the mass density and proton number density ratios are identical.

Let us now estimate the magnetic compression ratio and the upstream \(\beta_1\), and so proceed directly to a theoretical solution for the ISEE 3 shock. Using the 2.5-min averages in Tables 2 and 3, we find \(B_2/B_1 = 2.19\). With \(\beta_1 = 6.85\ \gamma\), \(T_{p1} = 7.5 \times 10^4\ K\), \(T_{e1} = 4T_{p1}\), and \(T_{e1} = 2.5 \times 10^5\ K\), we find \(\beta_1 = 1.14\). The corresponding solutions are marked by a plus in
Figure 11. Rankine-Hugoniot solution for the November 12, 1978 shock. The top panel shows the proton density compression ratio, calculated, assuming a constant alpha-proton density ratio, as a function of the magnetic compression ratio for values of the total upstream \( B \), ranging from 0.113 to 1.52. For ISEE 3, \( B_2/B_1 \) was 2.19, and \( B_3 \) was 1.14, so that the expected compression ratio was 2.85 (plus) while the measured ratio was 2.75 (asterisk). The middle panel shows \( U_{0n} \), the shock frame upstream flow speed parallel to the shock normal, divided by the upstream field magnitude \( B \), in units of \( 1 \gamma = 10^{-5} \) G. These solutions were calculated using the upstream parameters in Table 3. For ISEE 3, \( B_3 = 6.85 \gamma \); the corresponding velocity scale is to the right; the calculated and measured values are again shown by a plus and an asterisk, respectively. The bottom panel shows the downstream effective temperature defined by equations (5a) and (5b), normalized to \( B_1^2 \). The corresponding absolute scale for ISEE 3 is at the right.

Figure 11. The measured values are shown as asterisks in Figure 11, and the scales appropriate to \( B_3 = 6.85 \gamma \) are shown on the right. The calculated proton density ratio of 2.85 agrees within 3%, and measurement uncertainty, with the measured ratio of 2.75. For \( B_1 = 6.85 \gamma \), the shock frame normal flow speed \( U_{0n} \) is 247 km s\(^{-1}\). Let us compare this calculated value with an experimental estimate based upon the method 3 shock normal. The shock speed calculated in section 4.2 may be related to \( U_{0n} \) by

\[
U_{5n} = U_{0n} + V_1 \cdot \mathbf{n}
\]

where \( \mathbf{n} \) is the shock normal and \( V_1 \) is the average ISEE 3 upstream flow speed between the ISEE 3 and 1 shock encounters. If we assume, as an estimate, that \( V_1 \) has the magnitude measured at ISEE 3, 400 km s\(^{-1}\), and the direction measured at ISEE 1, we find

\[
U_{0n} = (612 - 400 \cos 20.6^\circ) = 238 \text{ km s}^{-1}
\]

which agrees within 4% with the calculated value. Inserting the measured ISEE 3 values, \( T_{s2} = 7 \times 10^5 \) K, \( T_{s2} = 4T_{01} \), and \( T_{s2} = 5 \times 10^5 \) K into (5b), we find \( T_s = 1.29 \times 10^6 \) K, which agrees within 12% with the calculated value for \( B_1 = 6.85 \gamma \) of \( 1.46 \times 10^6 \) K.

4.4. Concluding Remarks

We have provided the RH solutions in parametric form so that the reader may inspect the data and form his own opinion of the accuracy of the Rankine-Hugoniot solution. To us,
it seems clear that the method 3 shock normal, and the related Rankine-Hugoniot solution, were consistent with the measured upstream and downstream plasma parameters. Our solution seems accurate to better than 10%.

The fast Mach number of the shock was about 2.8, and the downstream flow speed in the shock frame was less than the local sound speed, so that the shock was supercritical [Kantrowitz and Petschek, 1966; Coroniti, 1970; J. P. Edmiston and C. F. Kennel, unpublished manuscript, 1984]. In conclusion, the interplanetary shock of November 12, 1978, was high speed, moderately strong, supercritical, and quasi-parallel. Its density compression ratio was 2.75.

5. DOWNSTREAM HYDROMAGNETIC STRUCTURE

5.1. Introductory Remarks

In this section we characterize the complex changes in flow state that followed the November 12, 1978, shock. In section 5.2 we discuss the strong magnetic field rotation that initiated these changes. A sheet or filament of dense cold plasma followed the field rotation (section 5.3). Immediately afterward, the solar wind speed and temperature increased, and the density decreased (section 5.4). Finally, both ISEE 3 and ISEE 1 detected a magnetic neutral region about 25 min after shock encounter (section 5.5). We summarize our observations in section 5.6.

5.2. Magnetic Field Rotation

Figure 2 shows that the magnetic field strength increased monotonically between the local minimum terminating the magnetic structure trailing the shock and a local maximum that preceded the field rotation by 30 s at ISEE 3 and 15 s at ISEE 1. During this interval the X and Y components of the interplanetary field remained relatively constant, while the Z component became more negative, so that the interplanetary magnetic field (IMF) gradually became more perpendicular to the shock normal. By combining information from Tables 1, 3, and 4, we find that the angle between the magnetic field and the method 3 shock normal, which was 69ø downstream of the shock, increased to 98ø at ISEE 1 and 105ø at ISEE 3, just ahead of the rotation.

The leading edge of the field rotation arrived at ISEE 3 at 0034:06 UT, 348 s after the shock, but the full rotation was not completed until 34 s later, at 0034:40 UT. By contrast, the ISEE 1 field rotation, which occurred at 0105:25 UT, 419 s after the shock, took less than a second to complete. The 71-s increase in the shock rotation time delay between ISEE 1 and ISEE 3 suggests that the rotation propagated more slowly than the shock, or that the planes of the shock and field rotation were inclined to one another, or both.

The full rotation at ISEE 3 was similar to the sharp rotation at ISEE 1. Table 4 shows the magnetic field vectors upstream and downstream of these rotations, B₁ and B₂ respectively, together with the difference vector B₂ - B₁. The rotation, which left the field magnitude constant, took the interplanetary field essentially from the (X, Z) plane upstream to the (Y, Z) plane downstream at both spacecraft. Since B₁ and B₂ then had the same sign, the field downstream of the rotation was in an anti-garden hose direction.

ISEE 1 had been magnetically connected to the bow shock before its encounter with the interplanetary shock, which changed the field direction and disconnected ISEE 1 from the bow shock. ISEE 1 probably continued to be disconnected from the bow shock after the rotation, since the magnetic field...
was largely in the $Y$ direction. Energetic ion measurements reveal no particle signature of further connection to the bow shock until 0130 UT, well after the interplanetary shock and field rotation [Scholer and Ipatich, 1983].

Figure 12 presents the results of a principal axis analysis of the magnetic field for a 3-min period surrounding the passage of the field rotation over ISEE 3. The top three panels show the three magnetic field components, $B_1$, $B_2$, and $B_3$, resolved along the directions of maximum, intermediate, and minimum variance, respectively, defined for the period 0033:35 UT to 0036:35 UT. The bottom two panels plot $B_3$ and $B_2$ against $B_1$. Table 4 lists the GSE coordinates of the unit vectors, $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$, corresponding to $B_1$, $B_2$, and $B_3$. Because $B_3$ was very nearly zero, the field rotated almost exactly in the $(\hat{e}_1, \hat{e}_2)$ plane. The direction of minimum variance, $\hat{e}_3$, is quantitatively consistent with the unit vector parallel to $B_2 \times B_1$, where $B_2$ and $B_1$ are the magnetic fields measured at 0034:40 UT and 0034:06 UT respectively. The method 3 shock normal made an angle of 15.4° with the minimum variance direction. Since $\cos 15.4° = 0.964$, this angle could well be consistent with zero within measurement errors, although the $Y$ component of $\hat{e}_3$ is probably larger than that of the shock normal vector by a significant amount.

The magnetic field rotation shared two features in common
with a magneto-hydrodynamic rotational discontinuity [Kantrowitz and Petschek, 1966]. The field magnitude remained constant, and the field vector rotated from the \((V, B)\) plane upstream to perpendicular to that plane downstream. However, other features of the rotation are not in accord with the rotational discontinuity interpretation. The apparent sharpening of the rotation as it propagated between ISEE 3 and 1 is inconsistent with the fact that rotational discontinuities do not steepen. Figure 8 indicated that the proton bulk velocity changed direction by about 5° at the field rotation, too small by at least a factor of 3 to give a change in velocity component perpendicular to the upstream magnetic field equal to the Alfvén speed, as would be required for a rotational discontinuity in a plasma with isotropic pressure. Most importantly, the magnetic field component in the direction of minimum variance was essentially zero, whereas a rotational discontinuity conserves a nonzero component of magnetic field parallel to its direction of propagation.

The plasma density and temperature changed across the field rotation. Table 4 lists the ISEE 1 electron measurements made nearest the rotation. The electron density was 7.2 cm\(^{-3}\) 11 s before the rotation and 16.4 cm\(^{-3}\) 7 s after it; approximately 17 s later, the density had diminished to 12.3 cm\(^{-3}\) (Figures 5 and 6). The electron temperature decreased slightly, and the electron bulk velocity changed by an insignificant amount across the rotation. Figure 8 suggests that there was also an impulsive increase in apparent proton temperature at the rotation. If we interpret this as a true increase, rather than as a change in proton thermal anisotropy, the proton pressure increased across the rotation. Table 4 shows estimates of the ion and total ion plus electron pressure, calculated by assuming that \(N_{\text{i}}/N_{\text{e}} = 0.075\) and \(T_{\text{e}} = 4T_{\text{i}}\). The total pressure might have increased by as much as a factor of 3 between 0105: 14 UT and 0105: 32 UT. If this jump occurred entirely at the field rotation, it is inconsistent with an ideal MHD rotational discontinuity, which must leave the density and temperature unchanged. In any case, the pressure increase and the change in magnetic profile between ISEE 3 and 1 suggest that the field rotation was part of a dynamically evolving structure.

5.3. Region of Dense Cold Plasma

A period of uniform flow followed the magnetic field rotation. The ISEE 1 electron temperature (Figure 6), which had begun to decrease near 0102 UT and had dropped suddenly at the field rotation, only varied between 3.4 \(\times\) 10\(^5\) °K and 3.75 \(\times\) 10\(^5\) °K from the rotation of 0105: 25 until 0107: 58. The electron density, which had dipped just before the field rotation, and peaked just after it, also remained roughly constant until 0107: 40, varying between 12.3 cm\(^{-3}\) and 13.1 cm\(^{-3}\). Between the rotation and 0107: 40, the magnetic field strength was approximately constant at 22 \(\gamma\); \(B_{\text{z}}\) was constant at 20 \(\gamma\); \(B_{\text{x}}\), varying slightly, was about 8 \(\gamma\); and \(B_{\text{y}}\), while highly variable, averaged about 1–2 \(\gamma\).

A region of dense, cold plasma then passed over ISEE 1. The electron density, which was 12.6 cm\(^{-3}\) at 0107: 21, rose to 19 cm\(^{-3}\) at 0107: 40 and reached a peak of 21.5 cm\(^{-3}\) at 0107: 58. This electron density peak also appears in the SFR measurements of Figure 9. The electron temperature remained constant at 3.4 \(\times\) 10\(^5\) °K during the rise in electron density. The peak electron density corresponded to the local minimum in a brief, 48 s depression in the magnetic field strength, which diminished from 22 to 20 \(\gamma\) and then increased to 23 \(\gamma\). The electron temperature decreased to 2.7 \(\times\) 10\(^5\) °K at the trailing edge of the electron density peak. The proton temperature (Figure 8) dropped from 5 \(\times\) 10\(^5\) °K to 3 \(\times\) 10\(^5\) °K, presumably at the same time. The increase in electron plus ion pressure associated with the density maximum can account quantitatively for the decrease in magnetic pressure in the accompanying magnetic field depression. Thus the cold dense region appears to have been in pressure equilibrium with its surroundings.

Violent magnetic field rotations occurred at the trailing edge of the cold dense region. Figure 5 shows that \(B_{\text{y}}\) decreased briefly and then recovered its original value. \(B_{\text{z}}\), which was approximately zero at 0108: 09, jumped to +24 \(\gamma\) at 0108: 18 and then turned negative equally suddenly.

A gap in the ISEE 3 proton data (Figure 10) prevents us from locating the high-density region at that spacecraft. Low-time resolution electron measurements (Figure 4 of paper 1) do indicate that the density rose to 22 cm\(^{-3}\) 5–10 min downstream of the shock, consistent with the peak electron density at ISEE 1. We may time the arrival of this density maximum at ISEE 3 more accurately using magnetic field data. The sequence of events in the interplanetary field at ISEE 3 was entirely similar to that at ISEE 1. A region of uniform field, whose sense was the same as at ISEE 1, followed the rotation. There followed a small depression in magnetic field strength and then a brief dip in \(B_{\text{y}}\) accompanied by an increase in \(B_{\text{z}}\) from \(-\) 6 \(\rightarrow\) +15 \(\gamma\). \(B_{\text{z}}\) then turned negative. The field magnitude minimum, which presumably locates the density maximum at ISEE 3, occurred at 0035: 42. Thus the dense cold structure took 1938 s to propagate between ISEE 3 and ISEE 1; it trailed the ISEE 3 and ISEE 1 shocks by 434 s and 574 s, respectively.

5.4. Transition to Low-Density Fast Flow

At the trailing edge of the region of high-electron density, both the electron and proton temperatures decreased to minima, and there was a rotational disturbance in the magnetic field that affected both \(B_{\text{y}}\) and \(B_{\text{z}}\). When \(B_{\text{y}}\), which had turned positive for the first time in many hours, again swung negative, the electron density, which was 21.5 cm\(^{-3}\) at 0107: 58, diminished to 6.23 cm\(^{-3}\) at 0109: 20 and then to 4.75 cm\(^{-3}\), comparable with the density upstream of the shock, at 0109: 49. A density minimum following the density maximum may also be discerned in the SFR plasma wave measurements of Figure 9. Between the electron density maximum and the minimum at 0109: 49, the electron temperature doubled from 2.7 \(\times\) 10\(^5\) °K to 5.4 \(\times\) 10\(^5\) °K, the proton temperature increased from 2 \(\times\) 10\(^5\) °K to above 10\(^6\) °K, and most importantly, the electron bulk speed increased to about 620 km s\(^{-1}\).

The sequence of events following the inferred density maximum at ISEE 3 was similar to that at ISEE 1. We have already discussed the similar behavior of the magnetic fields at the two spacecraft. The ISEE 3 proton bulk velocity (Figure 10) increased from 600 km s\(^{-1}\) to 650 km s\(^{-1}\), and the proton temperature increased from 6 \(\times\) 10\(^5\) °K to 10\(^6\) °K at 0038: 20 UT. Thus the delay between ISEE 3 and 1 of the sudden velocity increase was 1838 s, 90 s less than the delay of the cold high-density region. The high-velocity flow arrived 602 s and 683 s after the ISEE 3 and ISEE 1 shocks, respectively.

After the minimum at 0109: 48, the ISEE 1 electron density increased slowly, but the electron temperature and bulk speed remained elevated, and the interplanetary field retained the same sense without violent swings in direction. It is clear that the magnetic field rotation initiated a complex transition from the postshock flow to a new state of the solar wind, in which
the density was lower and the flow speed and temperature were higher than immediately downstream of the shock. The IMF, which had been in the \((X, Z)\) plane for several hours upstream of the shock, was essentially in the \((X, Y)\) plane in the high-speed flow. The solar wind speed in the new state was about equal to that of the shock.

5.5. Magnetic Neutral Region

After the events described above, the properties of the solar wind remained stable until a magnetic neutral region passed over ISEE 3 and 1. The top four panels of Figure 13 show the ISEE 3 magnetic field magnitude and components for the period 0048–0100 UT, and the bottom panel shows the ISEE 1 field magnitude for 0116–0128 UT. The neutral region traversal was complete at ISEE 3, since the field magnitude reached a minimum of less than 17, \(B_x\) and \(B_y\) changed sign, and \(B_z\) hovered around zero. Note that the magnetic field retained its anti-garden hose sense, since \(B_x\) and \(B_y\) had the same sign on either side of the neutral region. ISEE 1 detected only a partial field reversal, since the field strength minimum was larger than that at ISEE 3 and while \(B_x\) and \(B_y\) dipped to zero, they recovered their original positive values after the neutral sheet encounter. This was the first occasion, among all those discussed here, in which the general sense of the interplanetary field differed at ISEE 1 and 3, and it suggests that the neutral sheet was inhomogeneous on the space and time scales separating the two spacecraft encounters.

The ISEE 1 electron density, which was about 8 \(\text{cm}^{-3}\) near 0116 UT, when the field strength began to diminish, increased to 11 \(\text{cm}^{-3}\) at 0122:16 at the field minimum. This increase in density, combined with a proton temperature in excess of \(10^6\) °K, probably accounts for the increased plasma pressure needed to balance the observed decrease in magnetic pressure in the neutral region. The electron density returned to 8–9 \(\text{cm}^{-3}\) after 0122 UT, when the field magnitude had substantially recovered.

Exactly 28 min, or 1680 s, separated the ISEE 3 and ISEE 1 field minima. Given the distance, \(\Delta X = -181.3 \ R_p\), separating ISEE 3 and 1, we estimate that the \(X\) component of the average speed of the neutral region was about 695 km s\(^{-1}\), about equal to the local proton bulk velocity at ISEE 1 (Figure 8) and ISEE 3 (Figure 10). Therefore the neutral region comoved with the solar wind.

5.6. Summary

The November 12, 1978, interplanetary shock evidently had overtaken a number of solar wind structures just before it encountered ISEE 3 and 1. A uniform region of postshock flow was terminated at each spacecraft by a strong magnetic field rotation at which an increase in plasma density took place. The rotation initiated a complex transition between the shocked solar wind, in which the IMF was in the \((X, Z)\) plane, and a less dense, hotter, and faster flow whose magnetic field was in the \((X, Y)\) plane. Embedded in this transition region...
was a sheet or filament of cold high-density plasma. The differences in the delays between the arrivals at ISEE 3 and 1 of the shock, field rotation, cold dense region, and high-speed flow indicate that the region downstream of the shock was not in steady state, or that the various structures were inclined to one another, or both.

Following the structures above was a magnetic neutral sheet that comoved with the local solar wind speed between ISEE 3 and 1. Although the very different senses of the IMF upstream of the shock and near the neutral region obscure the relationship between the neutral sheet and the closed magnetic island upstream of the shock, the fact that both were observed strengthens the interpretation that ISEE 3 and 1 were near the reversal region of the heliospheric field during the November 11–12 event.

Only the uniform region between the shock and field rotation corresponds to the conditions postulated by theories of particle acceleration by shocks. Because large-amplitude waves were absent, the physics of energetic particle acceleration and transport was very different downstream of the magnetic field rotation.

6. DISCUSSION

One objective of this paper was to determine as accurately as possible the jump in plasma parameters across the November 12, 1978, shock, to permit a quantitative test of one of the major predictions of shock acceleration theory, the sensitive dependence of the energetic ion spectral index upon the density compression ratio [Axford et al., 1977]. We will carry out this test in paper 3. Our strategy here was to accumulate reinforcing, redundant information about the shock jump. We used information from both the ISEE 3 and ISEE 1 shock encounters. For the ISEE 1 shock we compared densities obtained from independent measurements of protons, electrons, and electron plasma waves. For ISEE 3 we used electron, proton, and alpha particle measurements. We solved for the shock normal in four different ways. We had information to test the consistency of our measured upstream and downstream parameters with the Rankine-Hugoniot jump conditions. We concluded that the November 12, 1978, shock was a high-speed (612 km s⁻¹), supercritical, quasi-parallel (θₐₙ = 41°) shock of moderate strength (fast Mach number of 2.8) propagating into an upstream plasma whose total β was 1.14 and whose electron-to-proton temperature ratio was 2.8. These parameters are similar to those expected for old supernova shocks propagating in the hot, low-density phase of the interstellar medium [Axford, 1981].

We also found that the ISEE 3 and 1 shocks differed slightly. In particular, the solar wind speed ahead of the ISEE 1 shock was 30 km s⁻¹ slower than at ISEE 3, an effect attributable to deceleration in the earth’s foreshock. Together with other evidence that ISEE 1 was magnetically connected to the bow shock, this means that only the ISEE 3 shock can be used in a quantitative comparison with acceleration theory. Scholer and Ipavich [1983] have already shown that the spatial profiles of >30-keV protons differed ahead of the ISEE 3 and 1 shocks because of the ISEE 1 bow shock connection.

Our close scrutiny of the November 12, 1978, shock revealed that the magnetic field and electrons changed on different scale lengths. The magnetic field jumped over about 1000 km, whereas the core plus halo electron distribution equilibrated on a 12-Åₚ scale which would not be readily perceived from bow shock and magnetosheath measurements. The long electron scale length is presumably associated with the thermalization of superthermal electrons. The Rankine-Hugoniot conditions applied over a ~10-Åₚ scale did agree with observation, assuming that the ratio of specific heats was 5/3. In any case, to test shock acceleration theory, we must obtain the full density compression ratio achieved over one energetic proton mean free path, which we will show in paper 3 was also about 12 Åₚ. Thus although we were unable to resolve that part of the density jump occurring across the thin magnetic discontinuity, we believe that our measured compression ratio of 2.75 is suitable for a test of acceleration theory.

In summary, the November 12, 1978, shock had three dissipative scale lengths: one of a few Larmor radii associated with the magnetic field jump, one of about 12 Åₚ associated with electron equilibration, and one of about 30 Åₚ associated with energetic protons in the foreshock.

Diagnosis of the region downstream of shocks is necessary to test acceleration theory, because downstream MHD turbulence is needed to scatter energetic protons. For this reason, we studied the MHD properties of the flow downstream of the November 12, 1978, shock. We found that the uniform shocked flow was suddenly terminated by a field structure at 36 Åₚ (42 Åₚ downstream of the ISEE 3 (ISEE 1) shock. The thickness of this uniform flow region was much larger than that behind the bow shock in the magnetosheath. The field rotation initiated a complex, unsteady transition to a new solar wind state in which large-amplitude MHD turbulence was absent. This turbulence appears to have damped away before the rotation, so that these observations may provide sufficient information for a reliable test of theory. However, it will be useful to choose shocks with larger downstream regions of uniform flow in future studies.

Acknowledgments. We are grateful to our colleagues, K. Wenzel, T. Sanderson and P. Van Nes (ESA-Noordwijk), M. Scholer (Max-Planck-Institut, Garching) and G. Parks (University of Washington, Seattle) for their collaboration on this series of papers. One of our referees stimulated us to study carefully the differences between the ISEE 3 and 1 shocks. We are indebted to M. A. Lee (New Hampshire) for a critical reading of the typescript. We thank D. A. Gurnett (Iowa) for the use of the ISEE 1 plasma wave data. The work at TRW was supported by NASA-20682; at the University of Iowa by NASA-26819; at UCLA by NASA-25772 for magnetic field measurements, and by NASA NGL-05-007-190, for theory; at UC Berkeley by NASA-5-25770; and at Goddard by NASA. The work at Jet Propulsion Laboratory represents one phase of research carried out under NAS7-100 sponsored by the National Aeronautics and Space Administration. The work at LANL was supported by NASA under the auspices of the U.S. Department of Energy. C.F.K. thanks the Aspen Center for Physics, Aspen, Colorado, for its hospitality during the summer of 1983, when part of this paper was written.

The Editor thanks M. Lee and another referee for their assistance in evaluating this paper.

REFERENCES


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(Received January 9, 1984; revised March 15, 1984; accepted March 16, 1984.)