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Scale Lengths in Quasi-Parallel Shocks

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SCALE LENGTHS IN QUASI-PARALLEL SHOCKS

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ABSTRACT

Examples of an interplanetary and the bow shock illustrate the small relative size of the electrostatic layer relative to the scale of the magnetic fluctuations in quasi-parallel shocks. While both examples are supercritical, the interplanetary example is marginally so, showing a thickness in absolute and convected ion larmor radii units that is thicker ($\sim$ 13 U/Ω_{ci}) than at the bow shock ($\sim$ 2 U/Ω_{ci}). The fluid speed changes abruptly in the quasi-parallel shock on this shorter scale. The increase in electron and ion random energies also is clearly seen on this shorter scale. In the interplanetary example the scale of the electric layer is certainly less than 1/60th that of the up or downstreams magnetic fluctuations. The thickness of the earth's bow shock deceleration layer is dramatically narrower than any domain of upstream waves as controlled by reflected, intermediate, or diffuse ions.

INTRODUCTION

In the framework of MHD theory a parallel shock seen by an observer moving with the shock is characterized by discontinuous increases in temperature and density and a discontinuous decrease in speed; neither the magnitude nor the direction of the magnetic field changes across such a theoretically idealized shock. In a collisionless plasma the shock will have a finite thickness, L_p, which may be taken to be the width of the transition in density or speed. The random energy increases across the shock at the expense of the kinetic streaming energy. This exchange is initiated by an electrostatic field E directed along the shock normal. The distance over which E is non-negligible, L_e, is approximately the same as L_p. Upstream (the low entropy side (denoted by superscript +) and downstream (-) of the shock there are fluctuations in the magnetic field with scale lengths L_m^+, L_m^-. The relationship of the scale of these fluctuation to those of $L_p \sim L_e$ is the subject of this paper. L_m^+, L_m^- have often been implicitly used to assess operationally the thickness of collisionless shocks, especially for those of the (quasi) parallel geometry, but there is neither experimental nor theoretical justification that $L_p \sim (L_m^+, L_m^-)$ is valid for all shocks.

In the natural solar wind it has proven virtually impossible to certify that a shock wave is truly describable by $\theta_{Bn}=0$, where $\theta_{Bn}=\arccos(\underline{B}.\hat{n}/|B|)$, and $\underline{B}$ is the low entropy interplanetary magnetic field and $\hat{n}$ is the local shock normal. Uncertainties of field and particle measurements, determination of the local shock normal, and the temporal variability of the upstream plasma medium all contribute to an ambiguity of as much as 10-20 degrees in any estimate of θ_{Bn}. Observations demonstrate, however, that the magnetic structure exhibits a common morphology with scale lengths L_m^+ at the earth's supercritical bow shock of several R_e for a wide range of $\theta_{Bn}<45$ degrees [Greenstadt and Fredericks, 1979]. Accordingly, we accept as the best parallel shocks in nature "quasi-parallel" shocks with θ_{Bn} estimates well below 45 degrees, and we approach the study of the theoretically ideal parallel shock by comparing L_p with $L_m^{+,-}$ for small but non-zero θ_{Bn}.

QUASI-PARALLEL SHOCKS

Q-Parallel shocks have been most intensively studied at the earth's standing bow shock where the solar wind plasma in the spacecraft frame decelerates from supersonic to subsonic speeds. In the past, and even in the ISEE instrument complement, the measurement of ions has been undertaken by detectors optimized either for supersonic flows typical of the solar wind, or "hot" plasma detectors most suitable for subsonic flows such as are found well within the magnetosheath. Ion instrumentation has therefore been deployed which are optimized for asymptotic up or downstream sonic Mach number conditions; the systematic characterization of the shock transition layer has been left, until now, by default, to the continuous magnetic field records, which do not have a change in systematic error at the shock. For shocks which are not Q-parallel, the location of a clear step-like change in the magnetic intensity is often used to locate "the" shock; in the quasi-perpendicular limiting extreme there is very little observational distinction between the location of this ramp and the interval of the upstream magnetic fluctuations. For the Q-parallel regime the theoretical Hugoniot jump in the magnetic intensity approaches zero, but observationally the magnetic fluctuations remain.

Unlike the magnetic field strength, the plasma speed must change across all (including Q-parallel) shocks. Accordingly, accurate continuous measurements of the plasma speed through the Q-parallel shock should give a clearer picture of the scale L_e of the electric layer and allow a clear delineation of the up and downstream regions of the magnetic fluctuations for this shock geometry.

The velocity space solid angle coverage $\Delta\Omega$ required for a thorough sampling of a Maxwellian plasma distribution, of thermal width w, moving with a bulk speed U as perceived in the spacecraft frame, is on the order of

$$\Delta\Omega \underset{\sim}{>} 2\pi \ (1+M^2)^{-1/2},$$

where M is the sonic Mach number of the plasma defined by M=U/w. Across the forward bow shock the ion Mach number M^+ decreases from 10 to approximately unity and $\Delta\Omega$ opens up from 0.2π to $\sim 2\pi$. In addition the ion distributions become highly non-Maxwellian with gyrating reflected and retransmitted ions which clearly necessitate 4π strd coverage to determine in a model independent way either the ion density or momentum in the shock layer or in the downstream state. In addition telemetry limitations usually influence the density of solid angle coverage permitted while retaining suitable time resolution. While 4π may be sampled the sampled distribution must be assumed to be smooth, or equivalently the Mach number sufficiently small, so that coarse solid angle sampling within the 4π coverage will be sufficient for subsequent moment quadratures. However, when such a low Mach number optimized detector is immersed in supersonic flow a significant fraction of the angular variation of the number flux is unmeasured by such an instrument and the bulk velocity is not determined accurately.

For electrons M^- ranges from 0.3 to 0.03 and the solid angle requirements range from $\Delta\Omega=(1.9-1.99)\pi$ strd when going from the solar wind to the magnetosheath. These latter conditions imply that 4π strd sampling for electrons is imperative even in the solar wind; obviously this sampling remains adequate through the shock layer into the magnetosheath even for non-Maxwellian deformations. Conversely, an ion detector optimized for either the solar wind or magnetosheath cannot by itself determine the spatial scale of the shock deceleration. The Goddard Space Flight Center (GSFC) Vector Electron Spectrometer described by Ogilvie et al. [1978] routinely samples 4π strd with sufficient speed to deterimine the electron fluid parameters through the bow shock, including the vector electron bulk velocity with sufficient precision to determine the embedded shock currents [Scudder et al. 1983]; this plasma data will be used across the bow shock examples below.

EXAMPLES

Bow Shock: Figure 1a illustrates six hours of magnetic (UCLA) and electron fluid parameters (GSFC) for an inbound set of bow shock crossings by ISEE-1 on November 19, 1977. The sub-panels from top to bottom are the electron density, N, the electron bulk speed, U, the magnitude of B, followed by the electron temperature, T. The electron foreshock traversal, S_e, has been identified by the observed (but not shown) reversal of the heat flux direction [Ogilvie et al. 1971] at 18:22 UT as well as by a sudden step like enhancement of the electron thermal anisotropy. Also indicated are the ion foreshock, S_p, the regions of reflected ions, R, diffuse ions, D, and intermediate ions, IM, reported for this event [Gosling et al., 1978].

The plasma density and speed also showed changes in power fluctuation at S_e and S_p and at the boundaries of the different upstream ion populations; these are undoubtedly the hydromagnetic signatures of the magnetic fluctuations that accompany the different regimes of electron/ion access within the foreshock. The electron fluid speed had five clear step-like changes corresponding, in our opinion, to 5 crossings of a localized electrostatic field layer, which were much smaller than any contiguous region (such as R,D,IM) within the "upstream" fluctuations. These crossings occurred at 20:45, 21:00; 21:45, 22:05; with a final inbound crossing at $\backsim$ 22:20 UT. Notice that only between these paired crossing did the flow speed drop to the low sheath level which was steadily observed after 22:20. The electron temperature increased sharply at each of the step-like decreases in the electron bulk speed and is itself a clear indicator of the location of the shock transition. Angles θ_{Bn} estimated for the solar wind outside each crossing were, in the same order, 28,33, 32,52, and 58 degrees.

The first of the transitions at 20:45 was the most nearly Q-parallel one with the weakest jump in the time average magnetic intensity. Subsequent crossings were less oblique, as evidenced by the stronger $\Delta|B|$ steps and as also indicated by the θ_{Bn} determinations. This compact example affords, therefore, a visual comparison to be made of the thickness L_p as a function of θ_{Bn}. In zeroth order these thicknesses are essentially the same and not grossly dissimilar. We suggest that the large "shock widths" that would be inferred from magnetic fluctuations alone do not represent the scale of the localization of the electric field which precipitates the conversion from directed to internal energy which is the essence of "the" shock layer. We suggest that a more appropriate interpretation of L_m^+, L_m^- (regardless of shock obliquity) is that it reflects the spatial extent of particle and wave access upstream or down from the localized electrostatic layer. In the Q-perpendicular extreme $L_m^+ \backsimeq L_p$ because the magnetic topology makes upstream particle and wave access very difficult; accordingly that near agreement is not an intrinsic association for all obliquities. The 20:45-21:00 shock encounter is displayed in detail in Figure 1b where the large variation in direction and strength of the magnetic field in the shock are illustrated. The wide ranges and continuous fluctuation of absolute level of all field components contrasts with the clear demarcation of plasma regions having different average parameter values. There is no difficulty differentiating shocked from unshocked electron states by the bulk speed or temperature signatures.

Interplanetary Shock: Interplanetary Q-parallel shocks have only recently been reported by Acuna et al. [1979, 1981] and recently studied in terms of their associated turbulence by Vinas et al. [1983], Tsurutani et al. [1983]. Because these shocks are propagating on the background supersonic flow, rather than standing in the flow as at the earth's bow shock, the ion flow velocity in the spacecraft frame is supersonic on both the high and low entropy sides of the shock, while the flow for the observer riding with the shock does appear to undergo the super-sub sonic transition. Accordingly solar wind optimized ion detectors (high sonic Mach number) can determine L_p at interplanetary shocks without the systematic uncertainties discussed above for the standing earth's bow shock.

The most quasi-parallel ($\theta_{Bn} \sim 23 \pm 15^\circ$), interplanetary shock reported to date is that found by Acuna et al. [1979, 1981] and illustrated here as Figure 2 with the shock transiting Voyager 1 at 09:18 UT on January 29, 1978; the plotted data are the magnetic intensity averaged over 1.92s, followed by the plasma number density, N, proton flow speed, U, and ion temperature as resampled at 12s resolution for a two-hour period in the solar wind at 2.17 AU.

The deceleration layer scale, L_p, has been indicated and is certainly bounded to be less than 24s, which is the time interval spanned by three plasma spectra. Magnetic fluctuations were observer, L_m^+, for at least 30 min ahead of this layer. Thus the L_p layer is at least 60 times shorter than L_m^+. Downstream fluctuations were also seen indicated by L_m^-. Acuna et al. estimated $L_m^+ \simeq 5\times10^5$km and $L_m^- \simeq 2.5\times10^5$km. Although the Alfvén Mach number for this example is approximately 2.2, and therefore much smaller than M_A at the supercritical bow shock, this shock appears to be operationally supercritical by virtue of its ability to produce reflected ions thought necessary to understand the upstream turbulence in Figure 2 [Vinas et al., 1983]; the density overshoot is an observational property of the supercritical, Q-perpendicular shocks and it is also seen in this circumstantially super-critical, quasi-parallel interplanetary shock. As at the bow shock example, L_p at the interplanetary shock, while $\sim 10^{1}$ km, is much smaller than $L_m^{+,-}$ by factors in excess of 50:1. It is probably true, however, that the absolute size of $L_p \lesssim L_e$ is Alfvén Mach number dependent since $L_p(M_A \sim 2) \lesssim 13\ U_{in}/\Omega_{ci}$, whereas $L_p(M_A \lesssim 10) \lesssim 1\text{-}2\ U_{in}/\Omega_{ci}$. This fact notwithstanding the scale of L_e is clearly much smaller than L_m^+, L_m^- in either Alfvén Mach number regime.

Magnetic Fluctuations in the L_p Layer of the Q-parallel Shock

A further point of considerable theoretical interest is the nature of the magnetic fluctuations in the electrostatic layers of both the bow and interplanetary shocks. The amplitude of the fluctuations of $|\underline{B}|$ (Figures 1, 2) and the frequency of angular changes (Figure 1b) were larger inside the layer than outside. These large angular fluctuation imply that the instantaneous angle between $\underline{B}$ and the electrostatic field within the layer departed strongly from the average θ_{Bn} determined from the Hugoniot jump conditions based on the asymptotic states on either side of the layer. Accordingly, the actual shock layer was more tortuous for electrons $\underline{E} \times \underline{B}$ drifting through the layer; the precise reversible energy gain imparted to electrons traversing the shock layer is significantly reduced in the case of the Q-parallel geometry by the presence of these deflections of $\underline{B}$ from the normal within the layer. In an ideal parallel shock electrons should gain the full cross shock potential if the magnetic fields directions were not modified within the layer [Scudder and Goodrich, 1983]; if this were so electrons should gain 100-200 eV or change their temperature by $>10^{6}$ °K at the shock which is contrary to the observations (cf. Figure 1). The precise magnetic topology within L_e clearly controls the energy partition between electrons and ions, which is not specified by the Hugoniot conditions. This scenario does not directly explain why the frequency of magnetic fluctuations goes up at the layer except that $\hat{\underline{B}}$ must be distorted on a smaller scale than the overall length of L_p which must be sufficiently small that the ions cannot $\underline{E} \times \underline{B}$ drift within the layer. Since this constraint does not occur in the up or downstream regimes, it may explain the decreased apparent wavelength during the transition.

DISCUSSION

A quasi-parallel shock in a collisionless magnetized plasma has several scales, corresponding to different regions such as the "fore-shock", or "the electrostatic layer of the shock" and the "thermalization layer" behind the shock. We have shown that the deceleration layer scale L_p over which the speed and density change (which is assumed to be the same as L_e of the electrostatic layer) is considerably smaller than the scale L_m^+ or L_m^- of the magnetic fluctuations upstream (foreshock) and downstream (thermalization) of it. These up and down stream zones result from particles or waves reflected or transmitted from, or initiated at this deceleration layer; the distinguishable scale of the layer L_e is not significantly degraded by small θ_{Bn} at fixed Mach number, whereas the magnetic fluctuation zone is. The absolute scale L_e is observed to be Alfvén Mach number dependent.

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REFERENCES

Acuna, M. H., L. F. Burlaga, R. P. Lepping, and N. F. Ness, "Initial Results from Voyagers 1, 2 Magnetic Field Experiments", NASA TM 79711, 1979, and Solar Wind Four, p. 143, (H. Rosenbauer, ed.) MPAE Report W-100-81-31, 1981.

Gosling, J. T., J. R. Asbridge, S. J. Bame, G. Paschmann, and N. Sckopke, "Observations of Two Distinct Populations of Bow Shock Ions in the Upstream Solar Wind", Geophys. Res. Lett., 957, 1978.

Greenstadt, E. W., and R. W. Fredericks, "Shock Systems in Collisionless Space Plasmas", in Solar Plasma Physics III, p. 3, (E. N. Parker, C. F. Kennel, and L. J. Lanzerotti, eds.) North Holland Publishers, New York, 1979.

Ogilvie, K. W., J. D. Scudder, and M. Sugiura, "Electron Energy Flux in the Solar Wind", J. Geophys. Res., 76, 8165, 1971.

Ogilvie, K. W., J. D. Scudder, H. Doong, "The Electron Spectrometer Experiment on ISEE-1", IEEE, Trans. Geoscience Electronics, GE-16, 3, 1978.

Scudder, J. D., et al., "Detailed Studies at a Supercritical Quasi-Perpendicular Bow Shock including Particle Detection of Cross Field Current System, to be submitted to J. Geophys. Res., 1983.

Scudder, J. D. and C. C. Goodrich, "The Energy Gain of Plasma Electrons at Collisionless Shocks", submitted to J. Geophys. Res., 1983.

Tsurutani, B. T., E. J. Smith, and D. E. Jones, "Waves Observed Upstream of Interplanetary Shocks", J. Geophys. Res., 88, 5645, 1983.

Vinas-Figueroa, A., M. L. Goldstein, M. H. Acuna, "Turbulence Analysis in Upstream Waves near Interplanetary Shocks", submitted to J. Geophys. Res., 1983.

FIGURE CAPTIONS

Figure 1 a) Multiple crossings of earth's Q-parallel bow shock observed by ISEE-1 on November 19, 1977. Combined electron moment parameters (GSFC) and magnetic intensity (UCLA) illustrate the short scale of the deceleration and increase of electron random energy at each of the crossings at (20:45, 21:00), (21:45, 22:05), $\sim$ 22:20. b) Detail of ISEE-1 (20:45, 21:00) crossing including components of $\underline{B}$. Illustrates the contrast between field and plasma signatures across the deceleration layer.

Figure 2 Voyager 1 interplanetary Q-parallel shock observed on January 29, 1978. Ion signatures clearly show the narrow scale of the deceleration layer relative to the up and downstream turbulence.

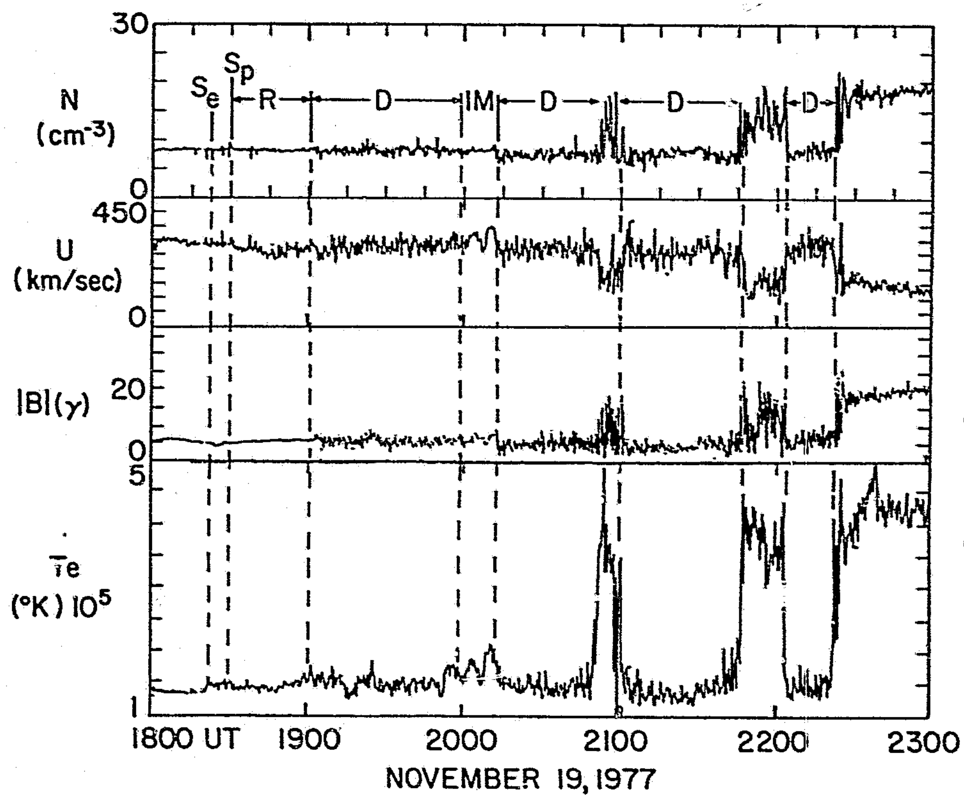

Figure 1a

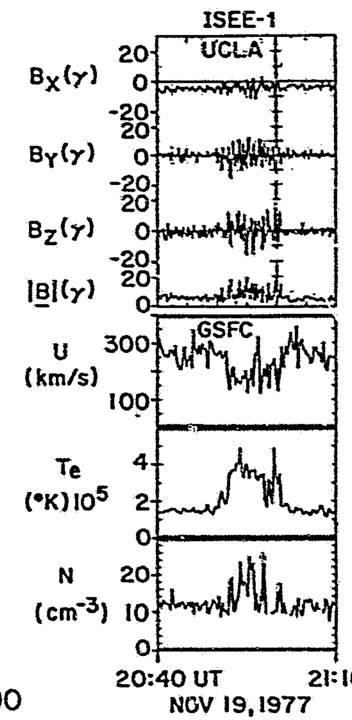

Figure 1b

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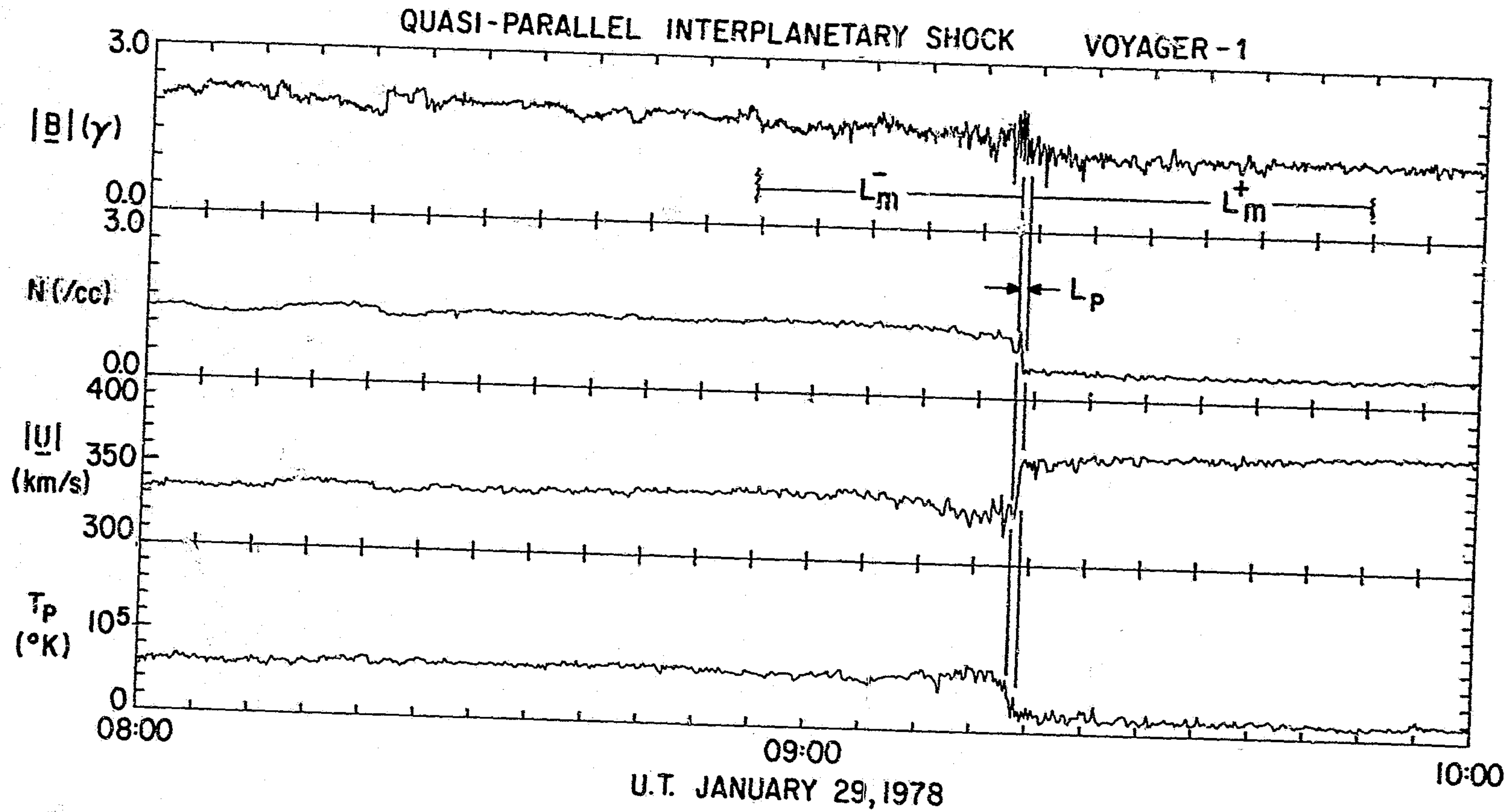

Figure 2

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