

MICRO-SCALE STRUCTURES IN THE INTERPLANETARY MEDIUM

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Abstract. This report describes and analyses the following micro-scale ($\lesssim .01$ AU) structures which were found in combined interplanetary magnetic field and plasma data obtained by the deep-space probe, Pioneer-6: (1) Several types of simultaneous discontinuities in the magnetic field and plasma parameters; (2) at least one clear example of a transitional region (D-sheet) associated with a plasma discontinuity; (3) other D-sheets which give evidence of magnetic-field annihilation; (4) inhomogeneous isothermal regions in which the square of the magnetic-field intensity is proportional to the density; (5) periodic variations in the magnetic-field intensity which are associated with discontinuities in the bulk speed. It is suggested that small velocity discontinuities play a fundamental role in reducing stresses in the interplanetary medium, and that large-velocity discontinuities may give rise to waves and turbulence.

1. Introduction

Recently experimental results were published which suggest that several types of structures predicted by hydromagnetic theory (see LANDAU and LIFSHITZ, 1960) are present in the interplanetary medium. Indirect evidence for the existence of tangential discontinuities in the interplanetary medium, based on magnetic-field data alone, was presented by NESS *et al.* (1966), BURLAGA and NESS (1967) and by SISCOE *et al.* (1968). Indirect evidence for the existence of tangential discontinuities, based only on plasma data was given by GOSLING *et al.* (1967). MIHALOV *et al.* (1968) have shown that temperature peaks are sometimes associated with magnetic-field discontinuities and have suggested that such heating may be produced by magnetic-field annihilation.

This report presents simultaneous, high-resolution plasma and magnetic-field data, obtained by instruments on the deep-space probe Pioneer-6, which demonstrate the existence of several distinct types of micro-scale ($\lesssim .01$ AU) structures in the interplanetary medium. These structures will be discussed from the point of view of hydromagnetic theory and will be shown to satisfy certain necessary conditions for hydromagnetic structures.

2. Orbit and Instruments

The Pioneer-6 spacecraft was launched toward the sun into heliocentric orbit on December 16, 1965. It penetrated to $\approx .81$ AU in mid-May 1966, when it was 25° ahead of the earth relative to the sun, and later it moved away from the sun and still farther ahead of the earth. The interplanetary medium was monitored essentially

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continuously from the date of launch through April 1966. Thereafter, data were transmitted only intermittently.

The magnetometer which provided the magnetic-field data that will be discussed below has been described by NESS *et al.* (1966). Briefly, it is a uniaxial fluxgate magnetometer, mounted at an angle of $54^{\circ}45'$ to the spacecraft-spin axis which is nearly perpendicular to the ecliptic plane. The instrument zero-level was calibrated in flight by physically reversing the direction of the sensor by 180° . Each orthogonal component of the magnetic-field vector is known to $\pm .24$ gamma. A complete vector measurement, consisting of three axial measurements per spacecraft rotation, is transmitted on average every 1.5 sec at the highest bit rate. The data were reduced to give $|\mathbf{B}| \equiv B$, θ and ϕ as a function of time, where these quantities were computed from 30-sec averages of the measured components. Here θ and ϕ give the direction of \mathbf{B} in solar ecliptic coordinates, i.e., θ is the latitude angle measured with respect to the ecliptic plane (+ above the plane), and ϕ is the azimuth angle relative to the spacecraft sun line ($\phi=0$ when \mathbf{B} is along the line and toward the sun, and increases as \mathbf{B} moves toward the Eastern hemisphere of the sun).

The plasma-fluid parameters which are presented below were obtained by means of a probe that has been described by LAZARUS *et al.* (1966). The detector is a Faraday cup with an energy-determining grid which gives fluxes in 14 contiguous energy intervals. An ion-flux spectrum was measured every 32 sec, and transmitted at the rate of approximately one every 71 sec at the highest bit rate. The fluid parameters for the protons were obtained by fitting the measured spectra to a convected isotropic, Maxwell-Boltzmann distribution. This reduction, which was carried out by the experimenters with the support of Dr. V. Formisano, will be described in a future publication of the M.I.T. group. Until these details are available, the data are to be regarded as preliminary. For this reason the emphasis in this paper is on significant qualitative results. Values for the densities will be presented as integers, and are considered to be accurate to this approximation. Bulk speeds and thermal speeds will be quoted with preliminary estimates of their errors.

3. Equilibrium Regions

A. THEORY

By definition, the microstructure of the interplanetary medium is seen by viewing a three-dimensional region of the medium on a scale of order .01 AU. The fluid state of such a region is specified at any instant by giving the magnetic field and the first three moments of the distribution functions for the protons, electrons and heavier particles at points throughout the region. If the curvature of the lines of force is small in a region, so that $(\mathbf{B} \times \nabla) \mathbf{B}$ can be neglected, then the motion perpendicular to the lines of force is governed by the equation

$$\rho \frac{dv_{\perp}}{dt} = -\nabla_{\perp} \left(p_{\perp} + \frac{B^2}{8\pi} \right), \quad (1)$$

where \mathbf{v} is the velocity, p is the kinetic pressure, and \mathbf{B} is the magnetic-field intensity (see PARKER, 1963, p. 157).

If the distribution functions of the particles in a region are bi-maxwellian, then the region is in equilibrium in the sense that there is no acceleration perpendicular to \mathbf{B} if and only if

$$\frac{B^2}{8\pi} + n_p k T_{\perp} + n_e k T'_{\perp} + n_{\alpha} k T_{\perp\alpha} = p = \text{constant},$$

where T_{\perp} , T'_{\perp} and $T_{\perp\alpha}$ are the perpendicular temperatures of the protons, electrons and α particles, respectively, and n_p , n_e , and n_{α} are the corresponding densities. If α particles are neglected as a zeroth approximation and if charge neutrality is assumed so that $n_e = n_p \equiv n$, then

$$\frac{B^2}{8\pi} + nk(T_{\perp} + T'_{\perp}) = p = \text{constant}.$$

For an isothermal equilibrium region, this may be written in the form

$$B^2 = a - Sn, \quad (2)$$

where $a = 8\pi p$ and $S = 8\pi k(T_{\perp} + T'_{\perp})$. The last equation gives

$$\frac{T'_{\perp}}{T_{\perp}} = \left(\frac{S}{8\pi k} \frac{1}{T_{\perp}} - 1 \right).$$

HUNDHAUSEN *et al.* (1967) have found that the interplanetary medium is anisotropic with the temperature greatest in the direction of \mathbf{B} and smallest perpendicular to \mathbf{B} ; on the average they found $T_{\text{max}}/T_{\text{av}} \approx 1.4$. The data which will be used below do not give T_{\perp} , but rather the temperature T in the direction of the earth-sun line. In view of the result of HUNDHAUSEN *et al.*, $T > T_{\perp}$. Thus, for an isothermal equilibrium region

$$\frac{T'_{\perp}}{T_{\perp}} \geq \left(\frac{S}{8\pi k} \frac{1}{T} - 1 \right), \quad (3)$$

where S is determined by (2). If α particles are not neglected, and if it is assumed that $n_{\alpha} = .04n_p$ and $T_{\perp\alpha} \approx 4T_{\perp p}$ (HUNDHAUSEN *et al.*, 1967), then (3) is replaced by

$$\frac{T'_{\perp}}{T_{\perp}} \gtrsim \left(0.93 \frac{S}{8\pi k} \frac{1}{T} - 1.07 \right). \quad (4)$$

This obviously does not differ appreciably from (3) if $T'_{\perp}/T_{\perp} \geq 1$.

B. OBSERVATIONS

Since the interplanetary medium is convected nearly radially outward from the sun at a speed of approximately 400 km/sec, which is much greater than the spacecraft speed, a 1-hour sample of the measured magnetic field describes a one-dimensional 'segment' of a region whose extent is of order .01 AU. Data for 'thermal' electrons

and heavy particles are not available, so a segment can only be incompletely described at present. In this paper a segment will be specified as in Figure 1 by plotting B (magnetic field), n (proton density), v_T (proton thermal speed), and u (bulk speed) versus universal time for an interval on the order of 1 hour.

Figure 1 shows a segment of the interplanetary medium that passed the spacecraft

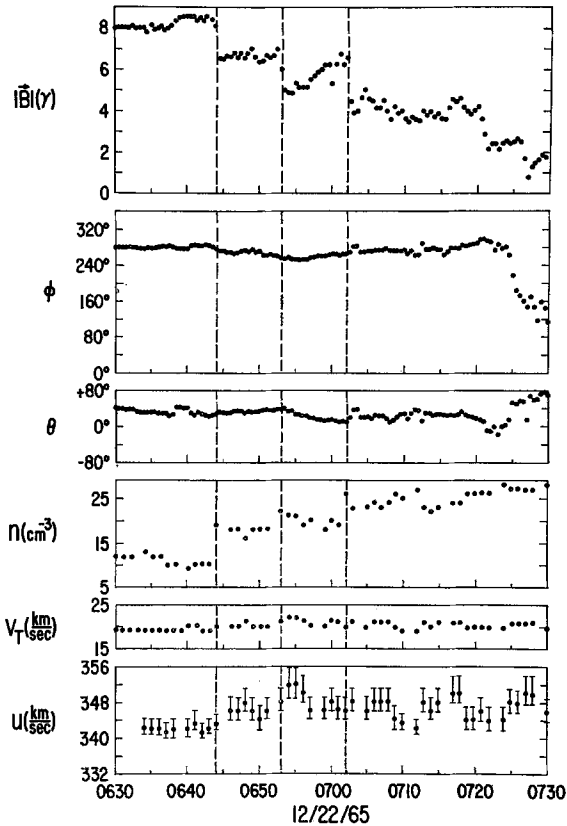


Fig. 1. A cascade of $(- + 0)$ discontinuities in an equilibrium region (see text).

between 0630 and 0730 on December 22, 1965. The segment is obviously inhomogeneous: B decreases from 8γ to 2γ while n increases from 12 cm^{-3} to 29 cm^{-3} . Figure 2 shows that B and n are anticorrelated such that (2) is satisfied. The segment is also isothermal in the sense that $v_T \approx \text{constant}$ ($v_T \approx 20 \pm 2\text{ km/sec}$). Thus, Figure 1 shows a segment which satisfies two necessary conditions for a segment of an equilibrium region. If it is assumed that the electron temperature is also constant, then T'_\perp can be calculated from (3) using S from Figure 2 and $T = mv_T^2/2k$ from Figure 1. With $S = (4.2 \pm .3) \times 10^{-10}\text{ (erg}^2/\text{cm}^3)$ and $T = 2.4 \times 10^4\text{ }^\circ\text{K}$ it is found that $T'_\perp/T_\perp \gtrsim 4$ and $T' \approx 10^5\text{ }^\circ\text{K}$. Thus it appears that in some regions the electrons may

be considerably hotter than the protons. This is consistent with the theory of STURROCK and HARTLE (1966).

Figure 3 shows a segment which is the complement of the one just described. This segment passed the spacecraft between 0350 and 0500 on December 22, 1965. It is isothermal with $v_T \approx 21 \pm 3$ km/sec; it is inhomogeneous, where now B tends to in-

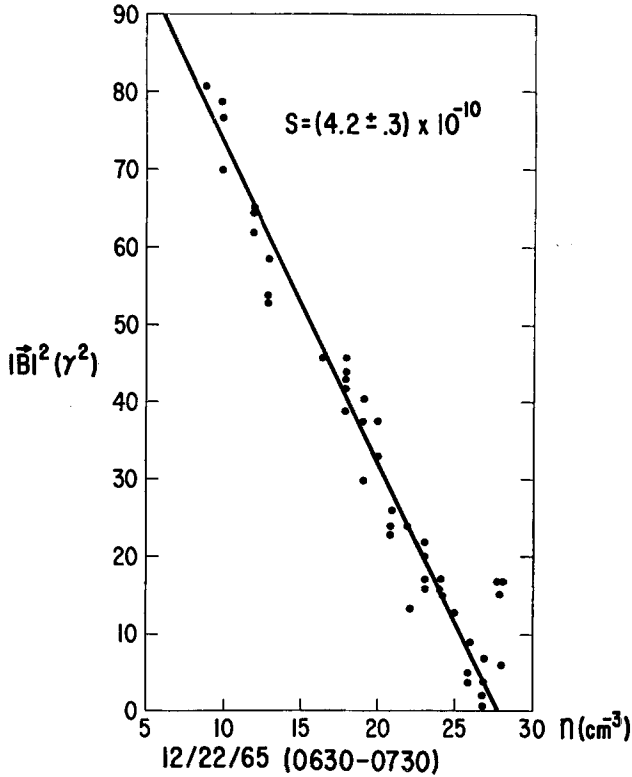


Fig. 2. This shows that $B^2 \propto n$ in the segment shown in Figure 1. Thus, the segment satisfies one necessary condition for an equilibrium region. It is possible to estimate the electron temperature from the slope of this line if the region is isothermal.

crease while n decreases; and again B^2 is proportional to n (see Figure 4). The slope of the line in Figure 4 is $S = (4.2 \pm .3) \times 10^{-10}$ (erg^2/cm^3) from which it is found that $T' \approx 10^5$ °K, $T'_\perp/T_\perp \gtrsim 4$, as before.

It was just shown that at times the electrons may be considerably hotter than the protons in the interplanetary medium. When $T'_\perp \gg T_\perp$, the kinetic pressure is primarily due to the electrons, since $p_\perp = n_p k T_\perp + n_e k T'_\perp$ and $n_e = n_p$. Moreover, if $n_p k T_\perp = 0$ ($B^2/8\pi$), as is generally observed, it is evident that at times the electrons may produce the dominant term on the RHS of (1). Thus electrons may sometimes play a dominant role in the dynamics of the interplanetary medium.

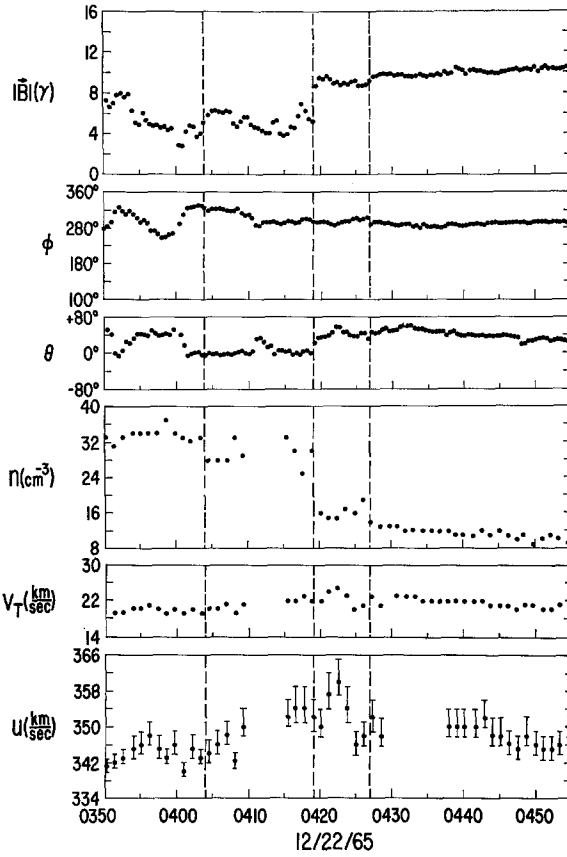


Fig. 3. A cascade of (+ - 0) discontinuities in an equilibrium region. This is the complement of the segment shown in Figure 1.

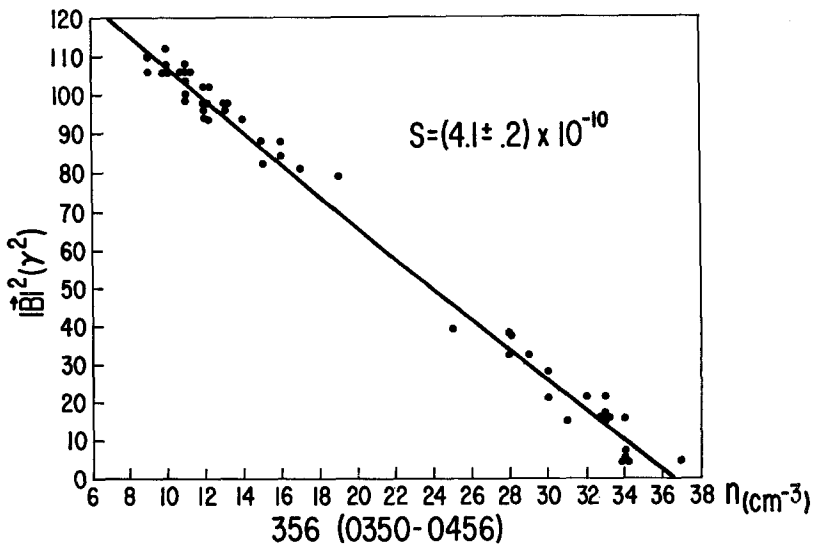


Fig. 4. A plot showing that $B^2 \propto n$ in the segment described in Figure 3.

4. Discontinuities

A. THEORY

The theory of discontinuities in an ideal magnetic fluid has been summarized by LANDAU and LIFSHITZ (1960), COLBURN and SONETT (1966), and others. Among the predicted types of discontinuities are tangential discontinuities which have three characteristics: (1) there is no flux of matter through the surface of the discontinuity, (2) there is no component of \mathbf{B} normal to the surface of the discontinuity, and (3) the total pressure is continuous across the discontinuity.

It is convenient to picture a tangential discontinuity in terms of two adjacent elemental, rectangular, flux tubes which lie parallel to the surface of the discontinuity. This is illustrated in Figure 5 for a special case when the flux tubes are mutually perpendicular. The density temperature and magnetic-field intensity may differ in each of the elemental flux tubes subject to the constraint

$$\frac{B_1^2}{8\pi} + n_1 k (T_1 + T_1') = \frac{B_2^2}{8\pi} + n_1 k (T_2 + T_2'), \tag{5}$$

where the subscripts 1 and 2 refer respectively to the flux tubes that arrive before and after the surface of the discontinuity, as shown in Figure 5. The ribbon of vectors

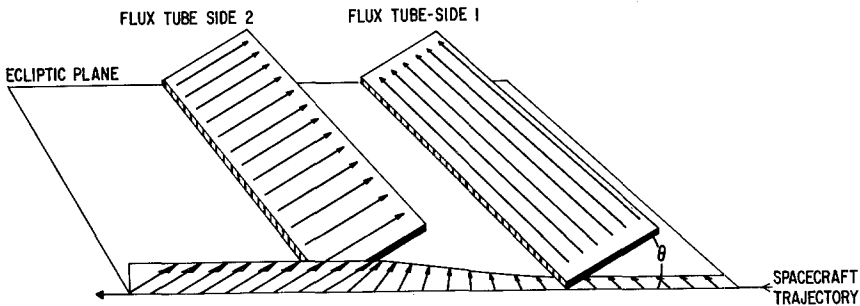


Fig. 5. A schematic illustration which describes a tangential discontinuity in terms of two hypothetical, infinitesimal, rectangular, magnetic flux tubes. The figure shows the special case when the flux tubes are mutually perpendicular and are inclined at an angle θ with respect to the ecliptic plane.

in Figure 5 illustrates the fact that sometimes the field changes directions between the adjacent flux tubes by means of a rotation fan. Such rotation fans have been discussed by SISCOE *et al.* (1968) in the analysis of Mariner-4 magnetometer data. Rotation fans were found in a few of the discontinuities which will be considered below, but they will not be discussed further because they occur on a scale on the order of 1 min, which is below the resolution of the plasma data.

Several classes of tangential discontinuities can be distinguished on the basis of (5). Let the symbol $(\text{sign } \Delta B, \text{sign } \Delta n, \text{sign } \Delta T)$ describe the qualitative changes in the magnetic-field intensity, density, and proton temperature, respectively, across a discontinuity. Thus, the symbol $(+ - -)$ denotes a discontinuity across which B in-

creases ($B_2 > B_1$) while n and T decrease ($n_2 < n_1$, $T_2 < T_1$); the symbol (0 0 0) denotes a tangential discontinuity separating two identical, non-parallel flux tubes ($B_1 = B_2$, $n_1 = n_2$, $T_1 = T_2$, but $\mathbf{B}_1/B_1 \neq \mathbf{B}_2/B_2$); and so on. From consideration of the changes in B , n and T which are consistent with (5), one finds that three classes of tangential discontinuities can be distinguished: (1) Class $T0$, containing only (0 0 0); (2) class $T2$, containing (+ - 0) and all the permutations and reflections of this set (see Table I); (3) class $T3$, containing (+ - +) and all of the permutations and reflections of this set, shown in Table I. Additional classes are possible if one includes parameters for bulk velocity, electrons and other particles.

TABLE I
Tangential Discontinuities

$T0$	(0 0 0) ^a		
$T2$	(+ - 0) ^a (- + 0) ^a	(0 + -) ^a (0 - +)	(- 0 +) ^a (+ 0 -) ^a
$T3$	(+ - +) ^a (- + -) ^a	(+ + -) ^a (- - +)	(- + +) (+ - -)

^a Observed in Pioneer-6 data.

To identify a tangential discontinuity unequivocally, it must be shown that (5) is satisfied for the adjacent flux tubes. This is not possible at the present time because unambiguous measurements of the electron temperature are not available. However, the existence of discontinuities with signatures which are given in Table I will be demonstrated below. Such a signature is a necessary but not a sufficient condition for the existence of a tangential discontinuity. On the other hand, if we assume that the hydromagnetic theory of discontinuities is applicable, then all of the signatures in Table I except (0 0 0), (- + +) and (+ - -) uniquely describe tangential discontinuities, i.e., a discontinuity with such a signature can only be a tangential discontinuity. The signature (0 0 0) may describe a tangential discontinuity or a rotational discontinuity. The signatures (- + +) and (+ - -) could describe tangential discontinuities, or a slow forward shock and a slow reverse shock, respectively.

According to the definition of a tangential discontinuity, the flux tubes in Figure 5 may move relative to one another along the surface of the discontinuity. Thus let us use the term 'glide plane' to refer to an element of a surface of a tangential discontinuity. Relative motion of elemental flux tubes along a glide plane should be observed as a discontinuity in the bulk speed. To see this, refer to Figure 6 which shows a glide plane moving away from the sun with speed u^1 , say. Let the velocities of the flux tubes relative to the glide plane be \mathbf{v}_1 and \mathbf{v}_2 . The radial component of the plasma velocity on side 1 is $u^1 + v_1 \cos \alpha_1 \cos \bar{\phi} + v_1 \sin \alpha_1 \cos \bar{\theta} \sin \bar{\phi}$ and that on side 2 is $u^1 - v_2 \cos \alpha_2$

$\cos \bar{\phi} + v_2 \sin \alpha_2 \cos \bar{\theta} \sin \bar{\phi}$. The radial component of the plasma velocity is nearly equal to the bulk speed if $|\mathbf{v}_2 - \mathbf{v}_1|/u^1 \ll 1$. In this case, neglecting aberration, the difference in the bulk speed Δu across a glide plane is approximately

$$\Delta u = v_1 (\cos \alpha_1 \cos \bar{\phi} - \sin \alpha_1 \sin \bar{\phi} \cos \bar{\theta}) + v_2 (\cos \alpha_2 \cos \bar{\phi} - \sin \alpha_2 \sin \bar{\phi} \cos \bar{\theta}) \quad (6)$$

This reduces to $\Delta u = 0$ if the plane of the discontinuity is perpendicular to the radial direction, i.e., $\theta = \phi = \pi/2$. If $v_1 = 0$, $\alpha_2 = \pi/2$, $\bar{\phi} = \pi/2$, then $|\Delta u| = v_2 \cos \bar{\theta}$. In this case

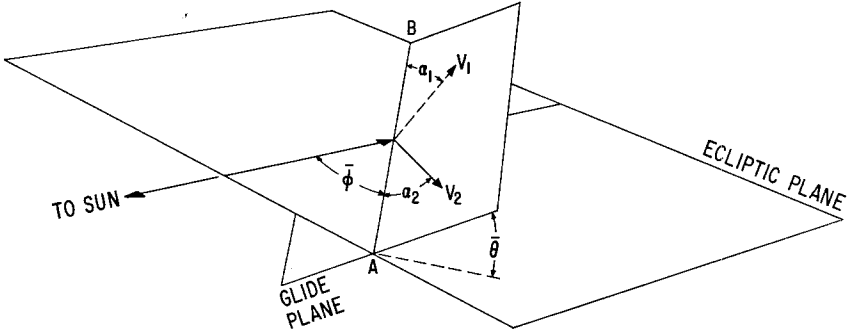


Fig. 6. Another illustration of a tangential discontinuity. This is complementary to Figure 5 in that an element of the surface of the discontinuity (the glide plane) is shown (assuming a real discontinuity – no rotation fan) but the flux tubes are not shown. The arrows indicate that the flux tubes are moving relative to the glide plane with velocities v_1 and v_2 . The glide plane moves away from the sun with the plasma bulk velocity u .

the component $v_2 \sin \bar{\theta}$ carries a plasma element above the ecliptic plane and thus away from the glide plane while the component $v_2 \cos \bar{\theta}$ carries it toward the discontinuity at such a rate that its distance from the discontinuity remains unchanged. It is evident from Figure 6 that the largest $|\Delta u|$ occurs when $\alpha_1 = \alpha_2 = \bar{\phi} = \bar{\theta} = 0$, in which case $|\Delta u| = v_1 + v_2$. Since Δu is just the radial component of the projection of the vector $\mathbf{v}_2 - \mathbf{v}_1$ on the ecliptic plane, it follows that

$$|\mathbf{v}_2 - \mathbf{v}_1| \geq |\Delta u| \quad (7)$$

B. OBSERVATIONS OF $T2$ DISCONTINUITIES

Table I shows that there are six possible types of $T2$ discontinuities – three complementary pairs. Hydromagnetic theory predicts that tangential discontinuities and only tangential discontinuities can have such signatures. The following results demonstrate the existence of five types of $T2$ discontinuities in the interplanetary medium.

Each of the segments in Figures 1 and 3 contains a remarkable ‘cascade’ of $T2$ discontinuities. Moreover, these are complementary cascades in the sense that one consists of three ($- + 0$) discontinuities while the other consists of three ($+ - 0$) discontinuities. The interpretation that these are tangential discontinuities is supported by the results in the previous section which suggest that these discontinuities are embedded in isothermal, equilibrium regions. Note that the magnetic-field di-

rection does not change appreciably across the discontinuities, indicating that the adjacent flux tubes are nearly aligned even though their contents differ greatly. The bulk speed u does not change appreciably across the $(+ - 0)$ discontinuities, but it does increase together with the increase in density in two of the three $(- + 0)$ discontinuities. The latter effect may be due to relative motions of the adjacent elemental flux tubes; it does not imply a flux of matter normal to the plane of the discontinuity.

Figure 7 shows a second set of $T2$ discontinuities, embedded in a segment of the

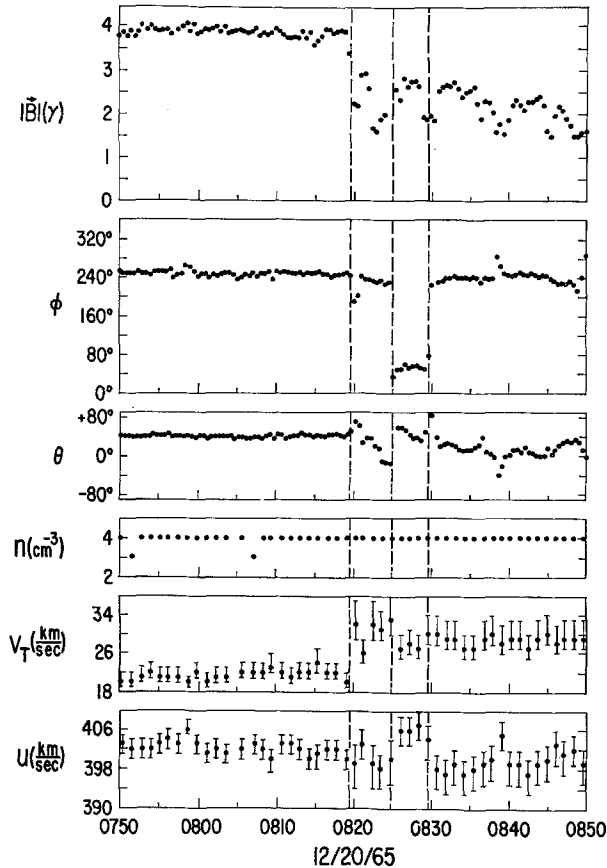


Fig. 7. A segment of a region containing a $(- 0 +)$ discontinuity and its complement, a $(+ 0 -)$. Two filaments are also shown.

interplanetary medium which passed the spacecraft between 0750 and 0850 on December 20, 1965. This set consists of a $(- 0 +)$ discontinuity and its complement, a $(+ 0 -)$ discontinuity. Note that the discontinuities combine in several ways with a third discontinuity at 0829 which cannot be classified because of the limited resolution of the plasma data. For example, the $(- 0 +)$ discontinuity separates a region of high B and low T from a region with low B and high T . The $(- 0 +)$ and $(+ 0 -)$

discontinuities define a ‘filament’ consisting of a rather complicated ‘flux tube’ which is somewhat hotter and has a predominantly lower B than the surrounding flux tube. The $(+ 0 -)$ discontinuity and the unidentified discontinuity at 0829 form the boundaries of a filament that is marked by its bulk speed, which is higher than in the surrounding regions, and by its magnetic-field direction ϕ , which is 180° out of phase with the direction of the field in the surrounding regions.

A third type of $T2$ discontinuity, a $(0 + -)$ discontinuity, is shown on the right half of Figure 8. This passed the spacecraft at ≈ 0321 on January 28, 1966. It separates

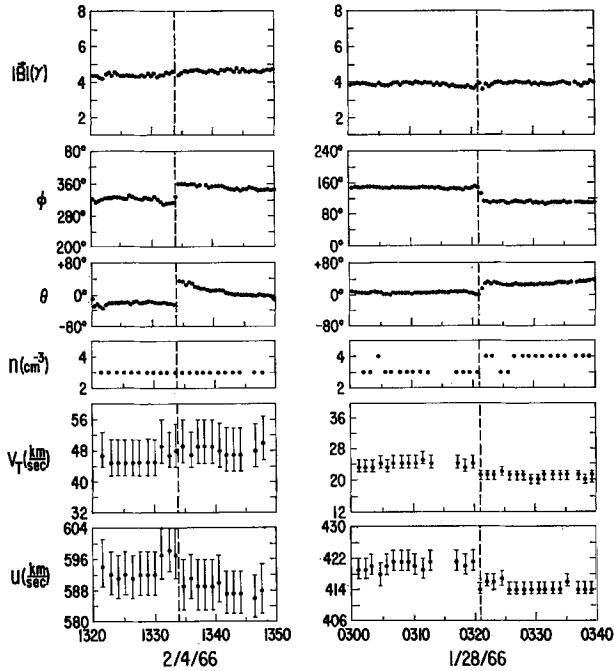


Fig. 8. Two directional discontinuities. The one on the left has the signature $(0 0 0)$. The other has the signature $(0 + -)$.

two rather uniform regions with different n , u , v_T , θ and ϕ , but with the same B . It can be visualized as two non-aligned flux tubes with the same B , but different n and T , which move relative to one another along the plane of discontinuity. No clear example of the complementary discontinuity $(0 - +)$ was found, but of course this does not mean that it does not exist.

C. $T3$ DISCONTINUITIES

Table I shows that six types of $T3$ discontinuities are possible – again, three complementary pairs. The $(- - +)$, $(- + +)$ and the $(+ - -)$ were not observed in the sample of ≈ 2000 hours of data which was examined. The existence of the remaining three types of $T3$ discontinuities is demonstrated below.

Figure 9 shows an outstanding $T3$ discontinuity which was detected at ≈ 0139 on March 28, 1966. The discontinuity has the signature $(+ + -)$ which identifies it as a tangential discontinuity if we again assume that hydromagnetic theory applies. The contents in each of the adjacent flux tubes are markedly different in this case, but the tubes are nearly aligned.

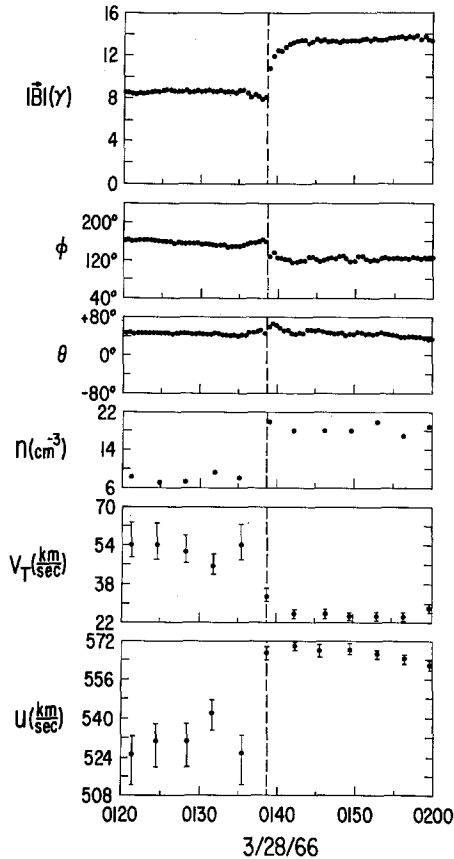


Fig. 9. A $(+ + -)$ discontinuity.

A complementary pair of $T3$ discontinuities with the signatures $(- + -)$ and $(+ - +)$ is shown in Figure 10. These were observed at 1522 and 1536, respectively, on January 20, 1966. The absolute numerical values of the plasma data in Figure 10 are subject to rather large uncertainties, not indicated by the error bars, because the peak of the distribution function happened to fall nearly between two channels in the plasma probe. But the qualitative changes are real. Note that these discontinuities form the boundaries of a filament which contains a cool, dense plasma and which is embedded in a hot, low-density plasma. The density on either side of the filament is roughly the same; the magnetic-field intensity behind the filament is higher than ahead, and the temperature shows the opposite behavior.

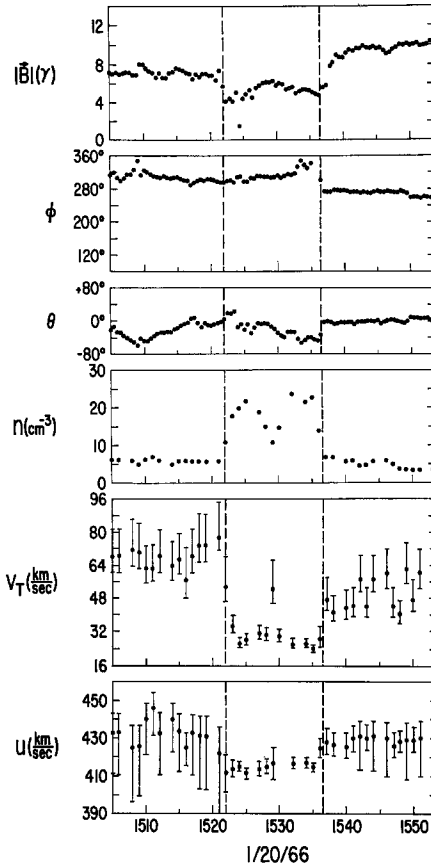


Fig. 10. A $(- + -)$ discontinuity and its complement, a $(+ - +)$ discontinuity. They combine to form a filament that separates two distinct regions.

D. $T0$ DISCONTINUITIES

Only one type of $T0$ discontinuity is possible, viz. $(0\ 0\ 0)$. From the point of view of hydromagnetics, such a signature could describe either a rotational discontinuity or a tangential discontinuity. If it is a tangential discontinuity, it consists of two elemental flux tubes which are identical but not parallel. A $T0$ discontinuity is shown on the left in Figure 8.

In an earlier paper BURLAGA and NESS (1967), who were working with magnetic-field data alone, identified a class of discontinuities which they called directional discontinuities. Loosely speaking, this means a discontinuity in the magnetic-field direction without regard to the magnitude of the magnetic field. Two directional discontinuities are shown in Figure 8. Figure 11, which is based on the data used by Burlaga and Ness, shows the distribution of the number of directional discontinuities as a function of the fractional change in B across a discontinuity. Clearly, B is nearly continuous across most directional discontinuities. An examination of the plasma

data which were available for nearly half of these directional discontinuities showed no appreciable change in n , u , or v_T in most cases. Thus, most of these directional discontinuities have the signature (0 0 0). This leads to the important hypothesis that discontinuities in the magnetic-field direction are usually not associated with discontinuities in the other fluid parameters, i.e., most interplanetary discontinuities are $T0$ discontinuities.

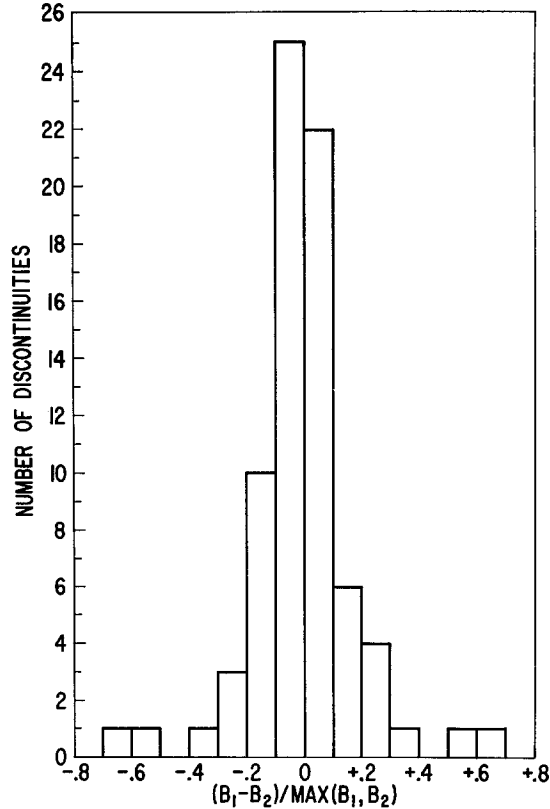


Fig. 11. This histogram shows that the fractional change of the magnitude of the interplanetary magnetic field across a directional discontinuity is usually near zero.

E. REMARKS

(1) The results which were just presented were selected to give the clearest possible examples which demonstrate the existence of several types of discontinuities. No attempt was made in this study to determine the distribution of these discontinuities. However, it seems worth noting that unlike D-sheets and waves which will be discussed below, discontinuities are frequently observed and are clearly fundamental to the structure of the interplanetary medium. Such discontinuities probably play an important role in the scattering of cosmic rays.

(2) Figures in Section 4 suggest the following hypotheses which are relevant to the study of the structure of the interplanetary medium:

(a) Fluctuations of the magnetic field are greatest in regions where the magnetic-field intensity is smallest; conversely, the unperturbed medium tends to be most uniform in regions where the magnetic tension is large. This hypothesis is suggested by Figures 1, 3, 7 and 10.

(b) Glide planes play an important role in reducing stresses in the interplanetary medium by allowing disturbances to propagate as gliding flux tubes at speeds up to the Alfvén speed. This is suggested by all of the segments in Section 4 which show that the field is usually rather uniform near a discontinuity. The largest discontinuity in bulk speed observed in these discontinuities is $\Delta u = 40$ km/sec, shown in Figure 9. In every case the observed Δu is less than the Alfvén speed.

5. D-Sheets

A. THEORY

LANDAU and LIFSHITZ (1960) show that in a medium with finite conductivity and finite viscosity, a sharp, tangential or rotational discontinuity should be replaced by a gradually widening transitional region in which the velocity and magnetic field change smoothly from one value to another. To illustrate the processes which may be involved in the formation of a transitional region, consider a tangential discontinuity formed by two antiparallel elemental flux tubes. Suppose that some physical process operates at the discontinuity which annihilates the antiparallel field lines. Then the field intensity will be zero or very small at the discontinuity, and the temperature will presumably tend to increase as the result of annihilation (i.e. conversion) of magnetic-field energy. Additional magnetic-field lines may drift toward the discontinuity carrying some matter with them. This matter will be deposited at the discontinuity and will contribute to the pressure in the transitional region. If the thermal conductivity is very high, the temperature increase in the transitional region may be small or negligible, but the density may be high. As the process continues the mass which is deposited would tend to be accumulated, unless it is ejected. Thus a jet of matter may be squeezed out by the incoming flux tubes.

If the flux tubes are not antiparallel, but are separated by an angle ω , an annihilation process would reduce the field intensity at the discontinuity to some value $B_{\min} \neq 0$, where B_{\min} depends on B_1 , B_2 and ω . A simple vector diagram (see Figure 12) shows that if $B_1 = B_2$, then

$$\frac{B_{\min}}{B_1} = \cos \frac{\omega}{2}. \quad (8)$$

Figure 12 shows that when $B_1 \neq B_2$

$$4B_{\min}^2 = B_1^2 + B_2^2 + 2B_1B_2 \cos \omega. \quad (9)$$

BURLAGA and NESS (1967) found a number of structures, which they called D-sheets, that are characterized by a dip in B at a discontinuity in θ and ϕ , which satisfy (8). We shall now re-examine these D-sheets, using the plasma data which are now available.

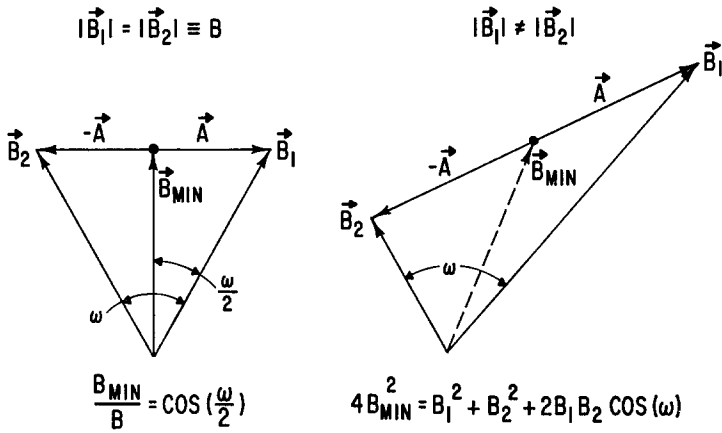


Fig. 12. Illustrations of the magnetic-field annihilation hypothesis. The vectors \mathbf{B}_1 and \mathbf{B}_2 specify the magnetic field on the two sides of a directional discontinuity. Each vector is resolved into the component $A + B_{min}$. At the discontinuity, \mathbf{B}_1 and \mathbf{B}_2 are superimposed so the A components cancel leaving B_{min} continuous across the discontinuity.

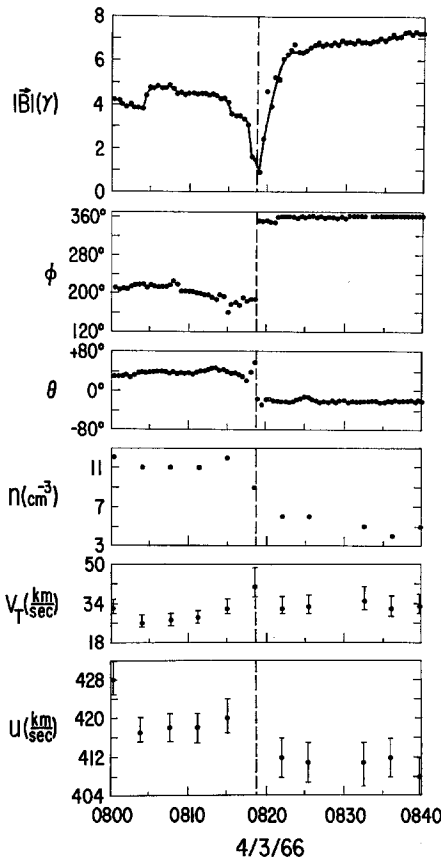


Fig. 13. A D-sheet at a plasma discontinuity. It is suggested that the dip in $|\mathbf{B}|$ marks a transitional region associated with a tangential discontinuity as described by LANDAU and LIFSHITZ (1960).

B. OBSERVATIONS

Figure 13 shows a D-sheet which is associated with a well-defined plasma discontinuity that was detected at ≈ 0819 on April 3, 1966. The signature of the discontinuity may be $(+ - 0)$ or $(+ - +)$, but in either case it is a tangential discontinuity according to MHD theory. There is a significant change in bulk speed across the discontinuity. There is also some evidence for heating and for a low bulk speed ($u \approx 388$ km/sec) at the discontinuity but this rests on only one point. The observed minimum field intensity in the D-sheet, $B_{\min} = (1.3 \pm .3) \gamma$, agrees well with that calculated from the annihilation hypothesis, Equation (9), which gives $B_{\min} = (1.5 \pm .5) \gamma$. Thus, Figure 13 apparently shows a transitional region associated with a tangential discontinuity, as described by LANDAU and LIFSHITZ (1960).

Figure 14 shows a remarkable D-sheet which passed the spacecraft near 0915 on January 21, 1966. This is distinguished by the large amount of magnetic-field energy which vanishes at the directional discontinuity ($\approx 7 \times 10^{-10}$ ergs/cm³). Unfortunately, the plasma data are rather sparse, and they are somewhat difficult to interpret because

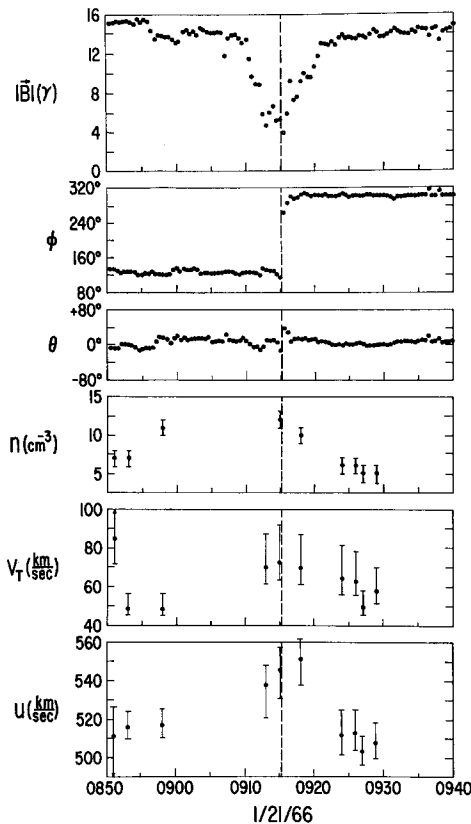


Fig. 14. A D-sheet for which the decrease in magnetic pressure is accompanied by an increased plasma density and temperature.

the bulk speed ($u \approx 515$ km/sec) happened to be very near the edges of adjacent energy channels of the plasma probe; this last fact may account for the peculiar point at 0851. The plasma data show that the temperature, density and bulk speed are highest where the magnetic-field intensity is lowest. The minimum magnetic-field intensity which was calculated from the annihilation hypothesis (Equation (8)) using $B_1 = B_2 = (14.0 \pm .2) \gamma$ and $\omega = 166^\circ$ is $B_{\min} = (1.7 \pm 2.0) \gamma$, which compares favorably with the measured

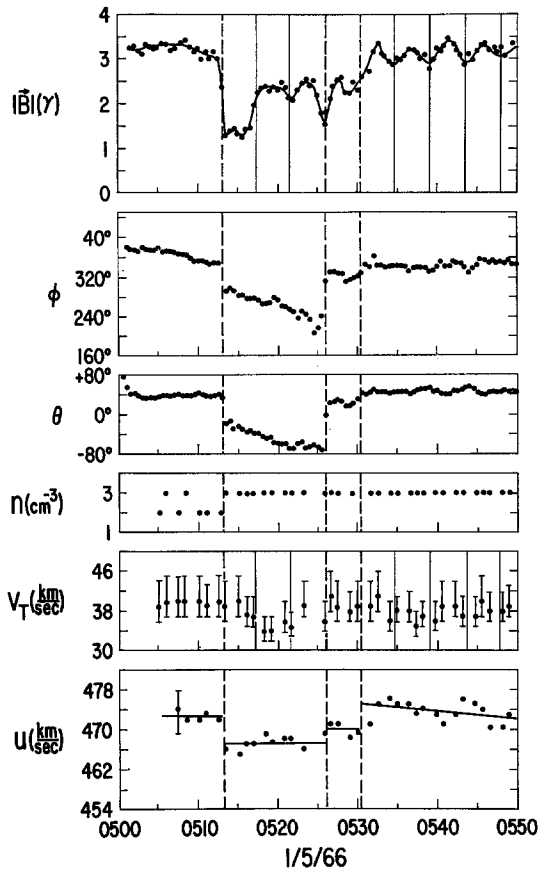


Fig. 15. Periodic variations in the interplanetary magnetic-field intensity. Note that the wave is nested among a series of discontinuities in the bulk speed and magnetic-field direction.

$B_{\min} = (3.5 \pm 1.0) \gamma$. These results are consistent with the model which was described above. It is interesting to note that again the field direction is rather uniform in this region, where the magnetic-field pressure is dominant.

BURLAGA and NESS (1967) showed six other D-sheets with various values of ω . Plasma data are available for four of these. The magnetic-field data may be found in the paper just cited, and the plasma data are summarized in Table II, which gives the averages u , n , and v_T for the points 10 min before and 10 min after the directional

TABLE II

Day/hour	ω	u (km/sec)			n (cm ⁻³)			v_T (km/sec)		
		Before	At	After	Before	At	After	Before	At	After
352/4	119°	321 ± 3	328 ± 2	326 ± 2	5.7	7.0	5.9	21 ± 2	18 ± 2	19 ± 2
354/6	150°	413 ± 3	394 ± 5	393 ± 5	4.0	5.0	4.3	28 ± 4	33 ± 5	32 ± 5
361/10	85°	561 ± 6	613 ± 9	589 ± 6	3.1	3.0	3.0	48 ± 7	53 ± 7	47 ± 6
25/10	130°	594 ± 8	596 ± 10	596 ± 7	2.4	3.0	2.4	54 ± 9	60 ± 6	48 ± 6

discontinuities, as well as the values of u , n , and v_T at the discontinuities. There is no significant change in B , n or v_T across any of these D-sheets, but a significant change in u is found in two cases. On the other hand, the density is significantly enhanced at the discontinuity in every case except one, and that case is characterized by a small ω ($\omega \approx 85^\circ$) and a correspondingly small dip in B . No statistically significant enhancement in temperature is observed, but the errors are rather large and may mask a small temperature increase. Neither these data nor those which were presented in the earlier parts of this paper show strong temperature spikes associated with discontinuities, as MIHALOV *et al.* (1968) have suggested.

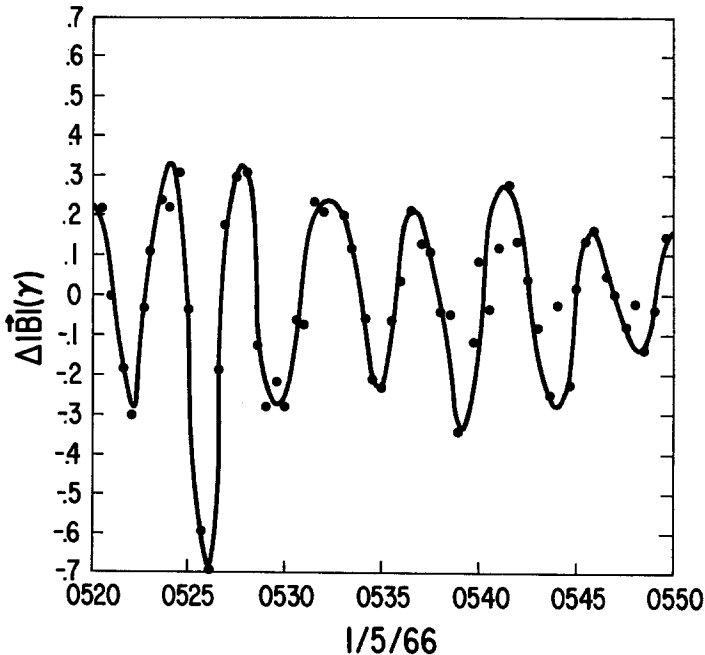


Fig. 16. Another view of the wave in the interplanetary magnetic-field intensity which was observed on May 5, 1966 (see text).

6. Waves

A. OBSERVATIONS

Figure 15 shows what appears to be a periodic wave in the interplanetary magnetic-field intensity. It is eight cycles long and has an 'apparent' period of 4.5 min. Since this wave is distorted by a gradually changing background field on which it is superimposed, the background field was calculated by taking running averages of B over the apparent wave period and was subtracted from the measured B to obtain the result shown in Figure 16.

Figure 16 clearly demonstrates the existence of a periodic wave in the interplanetary magnetic-field intensity. The amplitude of the wave is rather small ($\approx .3\gamma$), but

the individual points in Figure 16 should be accurate to $\lesssim .1\gamma$ if the field varies smoothly through the wave, because each of the points is computed from an average of 20 vector measurements of \mathbf{B} . Note that the large minimum at 0526 coincides with a discontinuity in the magnetic-field direction.

Periodic variations cannot be seen in the plasma data in Figure 15. The density appears to remain constant at $3/\text{cm}^3$, but recall that the nearest integral value for the density is used, so we can only say that the variation in density in the wave is less than

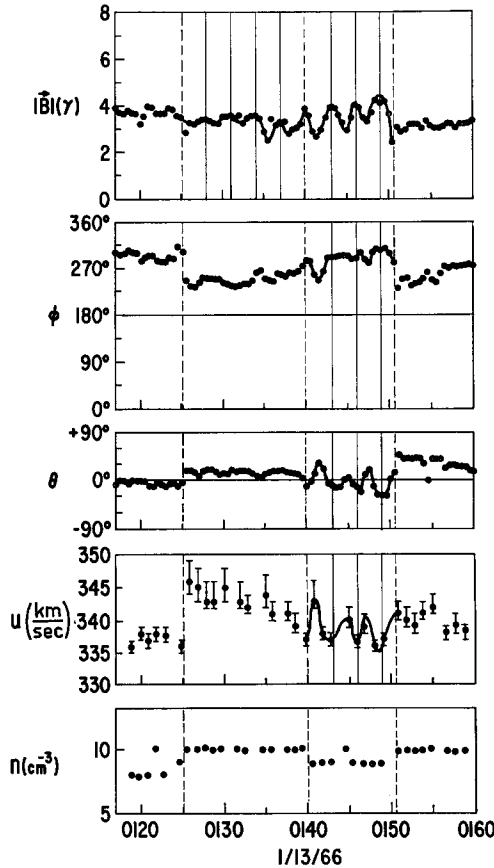


Fig. 17. Another wave in the interplanetary magnetic-field intensity. Note the oscillations of the magnetic-field direction in the filament between 0140 and 0151.

approximately 20%. There is some indication that the temperature is highest near the minima of the wave, but the errors are large so the evidence is inconclusive. Likewise, no periodic change in the bulk speed is observed, but again the errors are large. In short, the plasma data presented here are not sufficiently refined to establish that the wave in Figure 15 is a hydromagnetic wave.

Note how the wave fits among the discontinuities which are shown in the segment in Figure 15. The discontinuity at 0513 has the signature $(- + 0)$ which identifies it

as a tangential discontinuity if hydromagnetic theory applies. The other discontinuities, which are marked by changes in the magnetic-field direction, appear to have the signature (0 0 0). All three discontinuities seem to be associated with discontinuities in the bulk speed, but note the size of the error bars as indicated by the point at 0507.

Another interesting compressional wave nested among three discontinuities is shown in Figure 17. Again the apparent period is on the order of 5 min (actually 3 min in this case), but now it seems to consist of two parts. Part I shows only a small variation in B and no fluctuation in ϕ and θ ; it is nested in a filament between 0125

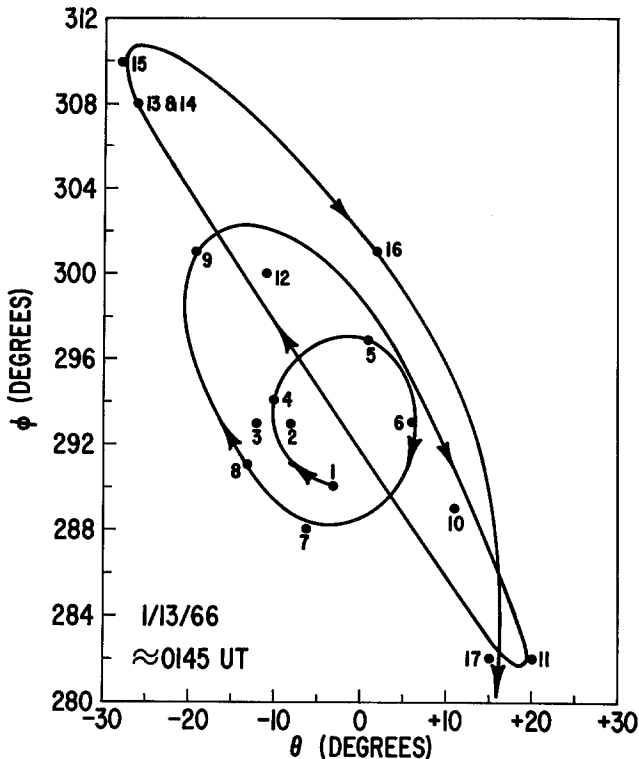


Fig. 18. This shows that the magnetic-field vector in the filament in Figure 17 was rotating systematically about the observation point between 0142 and 0151, indicating that the wave was polarized.

and 0140, and follows a large bulk-speed discontinuity. Part II is nested in an adjacent filament and is characterized by large-amplitude periodic changes in both the magnitude and direction of \mathbf{B} . Figure 18, which gives the θ , ϕ coordinates of successive 30-sec averages of magnetic-field vectors from 0142.5 (point 1) to 0151 (point 17), shows that part II of the wave is polarized, i.e., the magnetic-field vector rotates about the mean direction of \mathbf{B} with the same frequency as the compressional oscillation. Figure 17 shows that there are statistically significant peaks in the bulk speed at minima in B .

Figure 19 shows a segment of the interplanetary medium that passed the spacecraft between 0300 and 0350 on December 22, 1965. A D-sheet with its associated directional discontinuity and a discontinuity in the bulk speed are imbedded in the centre of the segment and are followed by a damped wave in the magnetic-field intensity. The observed jump in bulk speed is rather small (≈ 10 km/sec), but the glide plane (assuming that we are dealing with a tangential discontinuity) is nearly normal to the bulk velocity, so a rather large-velocity shear is implied by (6). The density and temperature do not change significantly across the discontinuity, but they are fluctuating incoherently throughout the region ($n \approx (29 \pm 2)$ cm⁻³ and $v_T \approx$

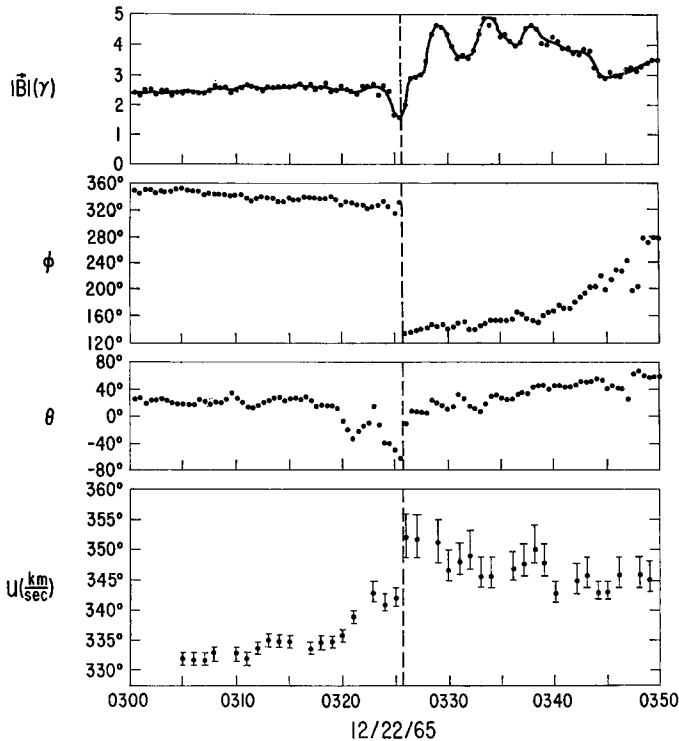


Fig. 19. A D-sheet at a discontinuity in bulk speed which is followed by a large amplitude, nearly periodic variation in the magnetic-field intensity.

(21 ± 3) km/sec, but v_T tended to be near 19 km/sec ahead of the discontinuity). No periodic variations in the magnetic-field direction can be seen.

Finally, consider the peculiar, but not uncommon, sort of wave which is presented in Figure 20. The term ‘wave’ is not really appropriate because the period is not constant, although it is again on the order of 5 min. Unlike the waves discussed above, the amplitude of the wave is rather large ($\geq 1\gamma$). These ‘giant undulations’ are nested in a filament which is marked by its high u and its low v_T . The field direction does not change appreciably across the discontinuities which define the filament and it does

not oscillate in the filament. The density and magnetic-field intensity are anti-correlated in the filament, but the data are not sufficiently precise to establish the quantitative relationship.

B. THEORY

Waves were found associated with bulk-speed discontinuities in each of the four regions described above. It is natural to attribute the waves to a kind of Kelvin-Helmholtz instability resulting from the relative motion of flux tubes along a glide plane analogous to the motion of the wind on the sea. The stability conditions for such a situation in an incompressible medium are (LANDAU and LIFSHITZ, 1960):

$$v \equiv |\mathbf{v}_2 - \mathbf{v}_1| < 2 \left[\frac{(\mathbf{H}_1^2 + \mathbf{H}_0^2)/2}{4\pi\rho} \right]^{1/2} \quad (10)$$

$$(\mathbf{H}_1 \times \mathbf{H}_2)^2 \geq 2\pi\rho \{(\mathbf{H}_1 \times \mathbf{v})^2 + (\mathbf{H}_2 \times \mathbf{v})^2\}. \quad (11)$$

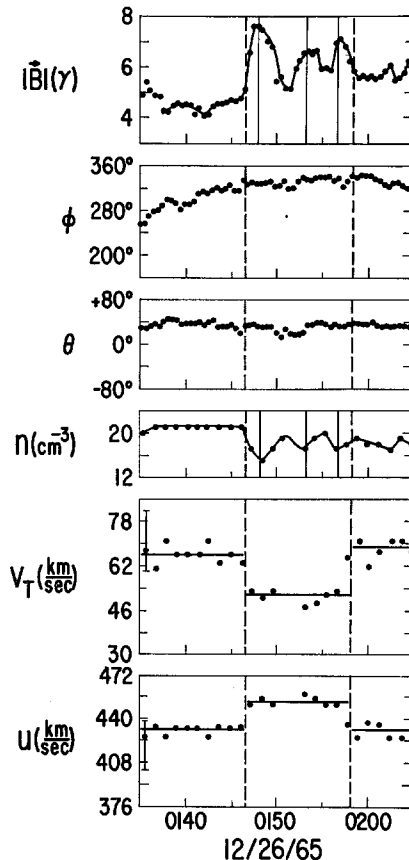


Fig. 20. Large amplitude, non-periodic variations in magnetic-field intensity and proton density, nested in a filament which is characterized by a lower thermal speed and a higher bulk speed than surrounding regions.

These conditions show that the magnetic field tends to stabilize the flow when the adjacent flux tubes are not parallel, which explains why velocity discontinuities can exist. Equation (10) shows that the medium becomes unstable when flux tubes try to transport matter at a relative speed which is greater than a quantity which is on the order of the Alfvén speed. For the wave on December 22, 1965, it is found that $H_1 \approx 2.5\gamma$, $H_2 \approx 3\gamma$ and $n \approx 30 \text{ cm}^{-3}$, so (10) predicts that an instability should develop if $v > 20 \text{ km/sec}$. Equation (7) and the measured Δu give $v > 10 \text{ km/sec}$, which is near the limit of stability, if incompressible hydromagnetic theory is applicable. This suggests that the interplanetary medium is on the verge of instability when B is low and n is high. Under these conditions the medium may become turbulent. It is clear that there is a need for a better theoretical understanding of the physics of gliding flux tubes and complete vector measurements of the bulk velocity.

7. Summary

This report analyzes micro-scale ($\lesssim .01 \text{ AU}$) structures which were found in combined interplanetary magnetic-field and plasma data obtained by the deep space probe Pioneer-6. The major new results are as follows:

(1) Regions exist in the interplanetary medium in which the proton temperature, T , is constant and $B^2 \propto n$. These are interpreted as isothermal, inhomogeneous, equilibrium regions. It is shown that the electron temperature, T_e , can be determined from the slope of the B^2 vs. n line for such a region. Two regions are discussed for which it is found that $T_e/T_p \approx 4$. This result is based on preliminary determinations of temperatures which are near the instrument threshold, so it should be confirmed by further measurements. It is significant because it suggests that electrons may play a dominant role in the dynamics of the interplanetary plasma.

(2) Simultaneous discontinuities in the plasma parameters and magnetic-field parameters do exist in the interplanetary medium. A classification scheme is presented which identifies 13 possible types of tangential discontinuities in terms of signatures which describe the changes in \mathbf{B} , n and T across a discontinuity. Nine of these signatures were found among the hydromagnetic discontinuities in the Pioneer-6 data.

(3) Small discontinuities in the bulk speed, u , often occur simultaneously with discontinuities in n , T and \mathbf{B} . It is shown that this effect would be produced at the spacecraft by the passage of two flux tubes which move relative to one another along a 'glide plane' that moves radially from the sun. It is noted that \mathbf{B} is very uniform near discontinuities in u . This shows that the interplanetary medium is not everywhere turbulent and it suggests that glide planes may play a fundamental role in reducing stresses in the interplanetary medium.

(4) The magnitude of \mathbf{B} is nearly constant across most of the directional discontinuities discussed by BURLAGA and NESS (1967). It is hypothesized that most discontinuities in the interplanetary medium are (0 0 0) discontinuities.

(5) A D-sheet is shown at a discontinuity in n , u , and T . This is interpreted as a transitional region at a tangential discontinuity as described by LANDAU and LIFSHITZ

(1960). Plasma data for the D-sheets discussed by BURLAGA and NESS (1967) show that the density is enhanced at the dip in $|\mathbf{B}|$ in a D-sheet, except when the dip is very small. A significant temperature peak was observed at the dip in $|\mathbf{B}|$ in only one case; that case was exceptional because of the large amount of magnetic-field energy which was 'annihilated'.

(6) Sometimes the interplanetary magnetic field oscillates sinusoidally with an apparent period of approximately 5 min. One case is shown for which the magnetic-field vector also rotates, indicating a polarized wave. All of the observed waves are attached to a discontinuity in the bulk speed. It is suggested that these waves are produced by a Kelvin-Helmholtz instability which results when adjacent flux tubes move along a glide plane at a relative speed which is greater than the Alfvén speed. This leads to the hypothesis that turbulence may be observed near large discontinuities in the bulk speed, particularly in regions of low $|\mathbf{B}|$ and high n .

Acknowledgements

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