SIMULTANEOUS PLASMA AND MAGNETIC-FIELD MEASUREMENTS OF PROBABLE TANGENTIAL DISCONTINUITIES IN THE SOLAR WIND

GEORGE L. SISCOE, JAMES M. TURNER, ALAN J. LAZARUS
M.I.T., Center for Space Research, Cambridge, Mass., U.S.A.

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Abstract. Changes in magnetic-field and plasma data from Pioneer 6 across selected discontinuities are found to agree with those predicted for tangential discontinuities. Substantial velocity shears are found across the discontinuities, the largest observed being about 80 km/sec. From the observation of velocity shears and of the asymmetry in the orientation of tangential discontinuities, an East-West asymmetry in the solar-wind speed is inferred: Fast streams should tend to come from the West and slow streams from the East with respect to the average direction. This effect is discussed in relation to the rotation of the sun.

1. Introduction

The tangential discontinuity is one of several types of discontinuities (including shocks) that are allowed within the framework or continuum magnetohydrodynamics. The properties of the various discontinuities has been reviewed by Colburn and Sonett (1966). The tangential discontinuity is characterized by zero magnetic and mass flux through the discontinuity, but jumps in the tangential components of the magnetic field and the velocity are possible. A jump in the tangential velocity is equivalent to a slip flow or shear across the discontinuity, that is, the plasmas on each side slip by each other along the discontinuity. Zero magnetic and mass flux through the discontinuity means there is no physical connection between the plasmas on either side; they are, in a sense, independent. The only constraint is that the total pressure $(P+B^2/2\mu_0)$ be equal on the two sides. Thus, the density, temperature, and field intensity can jump across the discontinuity subject to this constraint.

The paper by Colburn and Sonett suggested the possibility of tangential discontinuities in the solar wind from geomagnetic observations. Experimental studies of solar wind discontinuities have subsequently re-enforced this conjecture. Discontinuities in solar-wind density and velocity measured by the Vela 2 satellites have been interpreted as tangential discontinuities (Gosling *et al.*, 1967). Siscoe *et al.* (1968) analyzed the thickness, structure and orientation of supposed tangential discontinuities using Mariner 4 magnetometer data. Burlaga and Ness (1968) and Burlaga (1968) have made a similar analysis using Pioneer 6 magnetometer data.

The present study of possible tangential discontinuities combines magnetic-field and plasma measurements from Pioneer 6. Pioneer 6 was launched into orbit around the sun on 16 December, 1965. The data used here were obtained during the first 40 days of the flight, while receiver coverage was relatively good and the data rate was high.

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The purpose of the paper is to show that the field and plasma data are mutually consistent with the assumption that the discontinuities studied are tangential discontinuities. Inferences are then made about solar wind structure based on the observed asymmetry in the orientations of the discontinuities.

2. Preliminary Considerations

From the requirement of zero magnetic flux and zero mass flux across a tangential discontinuity, we can derive a kinematic relationship between the discontinuities in the magnetic field and the velocity. The relevant geometry is shown in Figure 1, which is a view of the ecliptic plane from the North ecliptic pole. Distances are not to scale. The line labelled t is the intersection of a tangential discontinuity with the ecliptic plane at some time, t. The line labelled $t+\Delta t$ is the same discontinuity a time Δt later. Convection by the solar wind causes the line to move away from the sun,

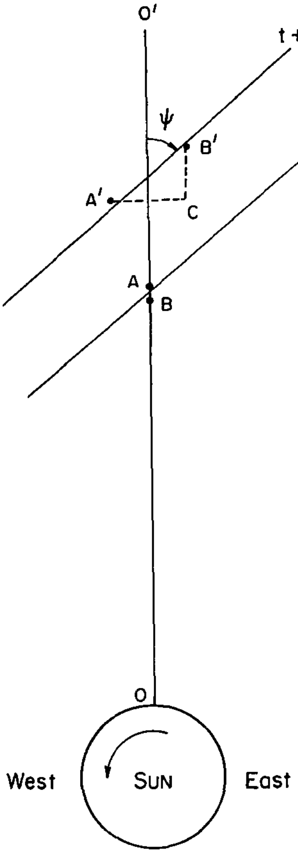

Fig. 1. Ecliptic plane from the North ecliptic pole. The conventional East-West designation is indicated and also the sense of the solar rotation. The figure shows the geometry used to relate changes in magnetic-field and plasma velocity across a tangential discontinuity (see text).

and Δt is taken sufficiently small that the two lines are essentially parallel. The discontinuity is oriented at an arbitrary angle, ψ, with respect to the radial line oo'.

For simplicity, we assume the velocity lies in the ecliptic plane on both sides of the discontinuity. The final relation holds also if there is a component of velocity perpendicular to the ecliptic plane *provided* that component *does not* change across the discontinuity. We will return to this point later.

We take the velocity on the sunward side of the discontinuity to be greater than that on the other. It is easily seen that the final relation is also valid if the reverse is true. The points A and B in Figure 1 give the positions of fluid particles which at time t lie on the radial line oo' on opposite sides of the discontinuity. Since there is no mass flux across the discontinuity, the two particles will remain adjacent to the discontinuity, however, they may slide freely and independently along it. By assumption, the fluid particle at B has a greater velocity than the one at A; hence it will travel a greater distance in the time Δt. Thus, the relative positions of the two particles at time $t+\Delta t$ will be as indicated by A' and B' in the figure. Denoting by V_R and V_T the components of velocity respectively parallel and perpendicular to oo', we find

$$\tan\psi = \frac{A'C}{B'C} = \frac{\Delta V_T}{\Delta V_R}, \tag{1}$$

where Δ denotes the change across the discontinuity. The quantities on the right-hand side are obtained from the plasma measurements.

The angle ψ is obtained from the magnetic-field measurements in the following way. Since magnetic flux across the discontinuity is zero, the fields on both sides of the discontinuity are parallel to it. Hence, the cross product of the two fields is parallel to its normal. The angle ψ is the complement of the angle between oo' and the projection of the normal onto the ecliptic plane.

ψ (field) computed from the field and ψ (plasma) computed from Equation (1) will be compared in the following section for suspected tangential discontinuities.

3. Analysis and Results

A. THE EXPERIMENT

The magnetic-field data from Pioneer 6 was kindly provided by Goddard Space Flight Center (N. F. Ness, principal experimenter). The Pioneer 6 plasma data was obtained with a M.I.T. Faraday Cup. Every 71 sec the experiment measured a complete set of plasma parameters which includes the solar-wind speed (V), the angle (β) in the equatorial plane of the spacecraft (essentially the ecliptic plane) between the solar-wind velocity vector and the sun-spacecraft line, and also the angle (α) out of the spacecraft equatorial plane. These are the plasma parameters relevant to the present analysis.

The magnetic-field experiment measured the vector magnetic field at a rate considerably faster than once every 71 sec. Therefore, the field components were averaged over 71 sec to make the two sets of data commensurable.

B. ERRORS

Since the differences which appear in Equation (1) are usually small, the question of errors is important. Determining good limits of error for the plasma data is difficult because of the elaborate procedure necessary to find the plasma parameters from the basic measurement of currents in various energy ranges. The best estimate of errors for the difference between two measurements (the errors in differences are probably less than in absolute values since systematic errors are removed) is ± 10 km/sec for ΔV, $\pm 1°$ for $\Delta\beta$ and $\pm 5°$ for $\Delta\alpha$. The large error in α precludes using the out-of-ecliptic velocity component in the present study.

The angle β used here has been corrected for the aberration due to the spacecraft motion. Since β is always small ($|\beta| \lesssim 5°$), we set $\Delta V_R = \Delta V$, that is, simply the change in the measured speed; and $\Delta V_T = \Delta(V\beta)$. The various errors contribute in a complex manner to the resulting error in ψ obtained by Equation (1); however, an idea of its size will appear when the actual values of ΔV and $\Delta\beta$ are given.

The major contribution to the error in the value of ψ obtained from the magnetic-field data comes not from the error in the measurement but from the fluctuations in the field. The normal to the discontinuity was found from the cross product of measurements 1 and 4 of a sequence in which the discontinuity occurred between 2 and 3. This was compared with the cross product of measurements 2 and 3. The angle between the two vectors thus obtained was typically 10°, which is, therefore, a reasonable estimate of the error in the field value of ψ.

C. SELECTION OF EVENTS

Four criteria were used to select events: (1) $|\Delta V| \geqslant 10$ km/sec for two adjacent measurements, (2) the five values of V before and after the jump be relatively constant, (3) the five values of β before and after the jump be relatively constant, and (4) the jump in density be sufficiently small to exclude the possibility of a shock. The primary requirement was a substantial discontinuity in the velocity. Out of 40 days searched, only 20 events satisfied all requirements. The frequency of magnetic field discontinuities is far greater, but the majority are attended by small velocity changes.

The present selection procedure does not distinguish between tangential discontinuities and intermediate shocks (also called Alfvén shocks and rotational discontinuities). The latter are characterized by no jump in density, pressure, or, field intensity, conditions which usually hold for the events used here, but there exist non-zero normal field and velocity components. Thus, the angles ψ computed from the field and the plasma data will not agree in the case of an intermediate shock.

From the 20 events, we discarded 8 for which Equation (1) would be affected appreciably by a jump in α. Thus discontinuities with normals within 30° of the ecliptic pole and those with $\psi > 60°$ were excluded. In the first instance a small jump in α would produce a large jump in V which would mistakenly be attributed to a jump in β. In the second instance any jump in V is most likely associated with one in α

since a jump in β changes V very little. The agreement between ψ(field) and ψ(plasma) for the excluded events was generally poor.

D. RESULT

The relevant parameters for the 12 accepted events are given in Table I, and a comparison of ψ(field) and ψ(plasma) is shown in Figure 2. Under ideal conditions and with perfect measurements, the points for a tangential discontinuity should fall on the dashed line in the figure (ψ(field) $= \psi$(plasma)). Of the 12 points, 7 show good agreement, but for 5 of them ψ(plasma) is approximately twice ψ(field). However, the possible error in the values of ψ(plasma) are generally large, and of the 5 stray points only event number 8 (see Table I) deviates significantly from agreement when the errors are included. That is, the two ψ's for 11 of the 12 events agree within the possible measurement errors. There will also be a contribution to the scatter from jumps in α, although this affect has been minimized. We feel the results support the basic assumption that the events analyzed are tangential discontinuities and that slip planes allowing considerable total shear in the solar wind exist.

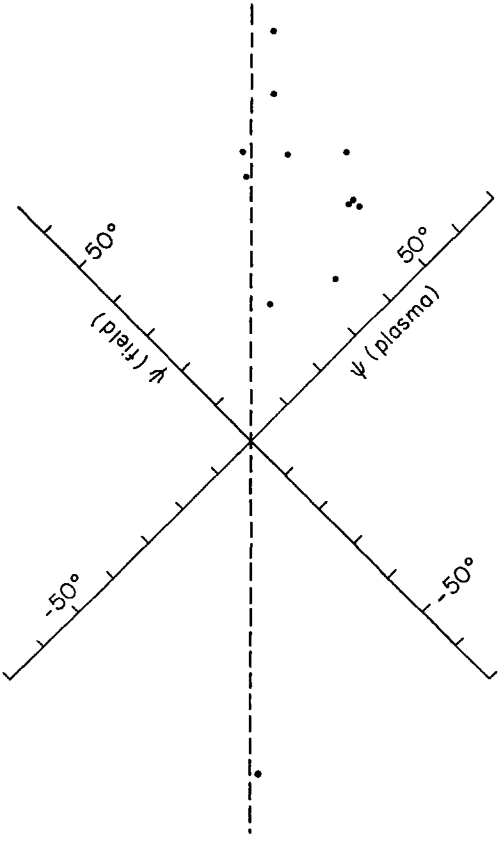

Fig. 2. A comparison of ψ(field) against ψ(plasma) for 12 suspected tangential discontinuities.

TABLE I

Plasma and field parameters for 12 discontinuities

Event #	V_1(km/sec)	V_2(km/sec)	β_1(°)	β_2(°)	$B_1(\gamma)$	$B_2(\gamma)$	ψ(plasma) (°)	ψ(field) (°)	V(shear) (km/sec)
1	394	383	0.3	−2.6	(0.4, 4.3, −8.5)	(6.1, 8.7, 0.7)	62^{+26}_{-31}	56	20
2	518	573	−1.9	2.9	(0.7, −3.5, −5.3)	(1.8, −1.3, 6.1)	40^{+11}_{-11}	43	76
3	534	503	−1.2	2.7	(0.0, −6.3, −2.7)	(−5.6, 5.1, 3.9)	48^{+16}_{-23}	50	49
4	544	525	5.7	3.5	(2.6, −1.2, 3.2)	(4.6, 1.2, 0.5)	49^{+24}_{-28}	18	20
5	564	587	3.5	5.7	(3.7, 4.2, −1.1)	(3.5, 2.8, 0.1)	46^{+22}_{-26}	36	29
6	587	605	4.5	6.6	(2.0, 3.2, −1.8)	(3.3, −2.5, 2.7)	53^{+23}_{-31}	47	27
7	555	585	2.5	4.6	(−4.3, 0.1, 1.9)	(1.4, 4.0, 2.4)	37^{+20}_{-21}	39	39
8	523	563	3.9	8.1	(4.6, 0.2, 1.5)	(0.4, 2.9, 3.6)	48^{+10}_{-17}	20	43
9	562	544	8.1	5.7	(−1.0, 2.8, 3.4)	(2.1, −1.2, 3.6)	55^{+21}_{-29}	28	20
10	537	552	0.0	1.1	(−1.3, 4.9, −4.4)	(0.6, −5.1, −4.4)	35^{+40}_{-33}	11	15
11	552	532	1.1	−1.3	(0.8, −4.9, −4.5)	(0.9, −4.9, 4.1)	49^{+24}_{-25}	20	21
12	504	532	2.6	4.0	(−6.5, 1.4, 0.6)	(−4.6, 0.1, 4.6)	22^{+28}_{-16}	17	29

The angle β is measured from the solar direction West in the equatorial plane of the spacecraft (essentially the ecliptic plane). The magnetic-field coordinates system is right handed with X toward the sun and Z toward the North ecliptic pole. V(shear) is the discontinuity in the tangential velocity. Errors in ψ (plasma) are maximum errors with error $(\Delta\beta) = \pm 1°$ and error $(\Delta V) = \pm 10$ km/sec.

Two points of interest are revealed by Table I. For only one event was ψ found to be negative, which implies an anti-hose angle orientation of the discontinuity. In other events, the discontinuities were aligned roughly parallel to the ideal spiral field. In five of the events the solar wind speed dropped across the discontinuity; in the other seven, it increased. However, more events would be needed to know if this ratio is typical.

The total shear listed in the last column of Table I is the discontinuity in the tangential velocity component. From Figure 1 it is seen that the total shear is given by

$$V(\text{shear}) = \frac{A'B'}{\Delta t} = \frac{B'C}{\Delta t \cos \psi} = \frac{\Delta V_R}{\cos \psi} \tag{2}$$

ψ(field) was used in computing V(shear) since it is less subject to error. It is apparent that substantial shears exist in the solar wind; the largest observed here is 76 km/sec which is of the same order as the proton thermal speed.

Work is in progress to obtain more reliable values of β by a more sophisticated data reduction program than used here. When these are available, the events will be re-analyzed and events from Pioneer 7 included. It will be interesting to see if the discrepancies are reduced.

4. Discussion

We will find it useful in the following to speak of solar-wind streams. By these we mean spiral tube-like regions of the solar wind connected at one end to the solar corona and characterized by more or less uniform velocity over a cross-section. The tubes need not have physical walls. They merely represent regions over which the solar wind plasma is reasonably uniform in character.

Solar-wind velocity – direction correlation (fast from the West, slow from the East). We showed in the previous section that the solar-wind speed and direction change across tangential discontinuities as predicted by theory. From the studies of Siscoe *et al.* (1968), Burlaga and Ness (1968), and Burlaga (1968), it is also known that these discontinuities have preferential orientations in space. We will show a tendency should therefore occur for the solar-wind speed and direction (East–West) to be correlated.

The three papers referred to above reveal that the line formed by the intersection of a tangential discontinuity and the ecliptic plane tends to lie along the spiral field direction. This situation, shown in Figure 1, was found with both the Mariner 4 and Pioneer 6 magnetometer experiments.

It can be seen from Figure 1 that if a tangential discontinuity separating two streams has the preferred orientation, plasma in the faster stream, which must travel a greater radial distance than that in the slower one in the same time, will 'climb up' the discontinuity by moving eastward with respect to that in the slower stream. The argument applies regardless of whether the fast or slow stream leads. Thus the orientation of tangential discontinuities implies a tendency for the plasma in fast solar-wind streams to come from the West, that in slow ones from the East, with respect to the *average* East–West component of velocity.

Non-mixing of streams. It has been known since the flight of Mariner 2, which monitored solar wind parameters for more than four solar rotations, that the solar-wind speed is highly variable (NEUGEBAUER and SNYDER, 1966). As an example, Mariner 2 at one time observed the speed to increase from 350 km/sec to 700 km/sec in 18 hours. Such variations were common; and subsequent experiments have confirmed this behavior.

These observations lead to the notion of intermingling or mixing of streams. Fast streams must eventually overtake and penetrate preceding slow ones. The penetration is believed likely to generate shocks or turbulence which dissipates the energy of relative motion and which eventually produces uniform radial motion.

The present results suggest an alternative picture. We have seen that fast and slow streams can exist side-by-side by slippage along a discontinuity. In effect, they get out of each other's way by sideways movement in opposite directions. Thus, the observed velocity variations do not necessarily imply mixing of streams, and the velocity pattern may be maintained to greater distances than expected in the former picture. The presence of discontinuities is not necessary for this argument. The sideways adjustment can just as well be made gradually, as will be discussed in a forthcoming paper by Carovillano and Siscoe.

The existence of tangential discontinuities and the non-mixing of streams can be related to the concept of freezing of the magnetic field in the highly conducting solar-wind plasma. The merging of one stream with another will be opposed by magnetic forces produced by current sheets at their interface. These current sheets are tangential discontinuities. That is, if the magnetic fields in the two streams are not connected, they will act to keep the plasma in the streams separate and distinct.

Origin of the East–West asymmetry. The 'fast from the West, slow from the East' pattern, which was derived here from the observed asymmetry in the orientations of tangential discontinuities, is in fact imposed by the sense of rotation of the sun. If a constant velocity stream emitted from the sun *did not* interact with neighboring streams, it would generate an Archimedes spiral due to the solar rotation. This is the familiar 'rotating lawn sprinkler' phenomenon. If, however, the preceding stream were slower, it would try to spiral more tightly; thus, the two streams would push against each other at their spiral interface. The fast plasma would push the slow plasma away from the sun and to the West, and would in turn be pushed in toward the sun and to the East. The pushing is done by an increased thermal and magnetic pressure at the interface. If the preceding stream plasma were faster, it would try to spiral less tightly; thus, the two streams would tend to separate leaving a low pressure along their spiral interface. The pressure deficit will act to pull the two streams together, thus pulling the faster stream plasma toward the sun and to the East and pulling the slower stream plasma away from the sun and to the West. In either case the fast plasma is accelerated to the East, the other to the West, by forces acting along a spiral interface. Thus, the existence and the sense of the asymmetry follow from the effect of the solar rotation on streams of different velocity.

North–South component. We have till now ignored the North–South component of velocity mainly because it is poorly resolved by the Pioneer 6 experiment. There is evidence that this component is sometimes large, and it will, therefore, obscure somewhat the correlation described above. Explorer 33, which measures the North–South flow directly since its spin axis is in the ecliptic plane, commonly observes flow out of the ecliptic plane by 5 and occasionally by more than 10 (Lyon *et al.*, 1968). Also the studies mentioned earlier on the orientations of tangential discontinuities reveal that their normals tend to lie well out of the ecliptic plane. Therefore, a change in the North–South velocity component across a discontinuity will generally be attended by a change in speed in just the same way as described for the East–West component. This possibility probably accounts for some of the scatter present in Figure 2. However, from another viewpoint, the strong correlation displayed in Figure 2 suggests that slip in the East–West direction across discontinuities is more pronounced than in the North–South direction.

Acknowledgments

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