# MICROSTRUCTURE OF THE INTERPLANETARY MEDIUM   L. F. Burlaga
## An invited review

High time resolution measurements of the interplanetary magnetic field and plasma reveal    ABSTRACT
a complex microstructure which includes hydromagnetic wave and discontinuities. This
paper discusses the identification of hydromagnetic waves and discontinuities, their
statistical properties, their relation to large-scale structure, and their relative contribution
to power spectra.

## INTRODUCTION

This review is an up-to-date description of the microstructure of the solar wind and its relation to the large-scale structure. The term *microstructure* refers to the features with a scale length of $\approx 0.01$ AU or less and the fluctuations with Doppler-shifted periods of $\lesssim 1$ hr.

The basic problems concern the interpretation of high time resolution data in terms of hydromagnetic waves and discontinuities. The process of interpreting magnetic field and plasma measurements is not straightforward, and several controversies have developed. Questions to which this review is addressed include: Are the frequently observed discontinuities in the direction of B predominantly tangential or rotational? Are power spectra levels due to discontinuities, Alfvén waves, and/or some other type of structures? Are microscale fluctuations related to $\beta$? What are filaments?

Theoretical results and ideas concerning the physical processes that occur on the microscale and cause the microscale features are reviewed by Barnes later in this chapter (p. 333). *Burlaga* [1971] reviews the theory of hydromagnetic waves and discontinuities appropriate for the solar wind, and the experimental evidence for the existence of such waves and discontinuities in the solar wind.

## DISCONTINUITIES

Discontinuous changes in the magnetic field and plasma parameters are frequently observed on the microscale. It

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is generally agreed that these are hydromagnetic discontinuities. There are several types of hydromagnetic discontinuities [*Landau and Lifshitz*, 1960; *Jeffrey and Taniuti*, 1964; *Colburn and Sonett*, 1966; *Hudson*, 1970; *Burlaga*, 1971]. They are fast shocks, slow shocks, contact discontinuities, rotational discontinuities, and tangential discontinuities. Most types have been identified in the solar wind [*Burlaga*, 1971].

Given a complete set of measurements, $n_p$, $n_\alpha$, $T^p_{\parallel}$, $T^p_{\perp}$, $T^e_{\parallel}$, $T^e_{\perp}$, $T^\alpha_{\parallel}$, $T^\alpha_{\perp}$, V, and B, made with a time resolution of several seconds at four or more spacecraft, the interpretation of the measured discontinuities is relatively simple [*Hudson*, 1970]. Such complete measurements have never been made, however. In practice, it is necessary to introduce an operational definition of a discontinuity that describes the incomplete measurements. This is usually subjective and somewhat arbitrary, but ideally it is sufficiently clear and quantitative that it can be used by different observers with different data to identify the same type of discontinuities.

The operational definitions of discontinuities that appear in the literature are given below, followed by discussion of the nature of these discontinuities (such as tangential or rotational). The statistical properties of these discontinuities and their morphology also are discussed. The concept of a *filament* is related to that of a discontinuity. The history of filaments is reviewed.

### Definitions

Several definitions of discontinuities have been used,

primarily based on magnetic field measurements. These are as follows:

*Filament-discontinuity.* Ness et al. [1966] were the first to observe the frequent occurrence of discontinuities in the magnitude and direction of interplanetary magnetic field. Examples from Pioneer 6 are shown in figure 1. Note the scale. These discontinuities were not defined quantitatively.

*Directional discontinuities* [*Burlaga and Ness*, 1968; *Burlaga*, 1969]. This term was introduced in reference to the type of discontinuities discussed by *Ness et al.* [1966]. It refers to changes in the magnetic field direction $\gtrsim 30°$ that occur in less than 30 sec and are preceded and followed by relatively uniform fields. A more detailed operational definition is given by *Burlaga* [1969]. Some examples from Pioneer 6 are shown in figure 2, which shows 30-sec averages plotted on a scale of 1 hr.

*Simple discontinuities* [*Siscoe et al.*, 1968]. In studying Mariner 4 data, it was observed that the

magnetic field components sometimes change from one more or less steady direction to another in a time short compared with the time that it previously or subsequently remains nearly constant, as shown by the examples in figure 3. *Siscoe et al.* [1968] called such changes "simple discontinuities." Other types of rapid changes identified by Siscoe et al. are also shown in figure 3. For computational purposes, they required that $|\mathbf{B}(t_2) - \mathbf{B}(t_1)| \geq 4\,\gamma$ for simple discontinuities. They found that most of the transitions associated with simple discontinuities had durations of less than 15 sec.

*Possible tangential discontinuity* [*Turner and Siscoe*, 1971]. This type of discontinuity was identified using plasma points obtained at 5-min intervals and corresponding magnetic field averages. The resolution is an order of magnitude lower than that used for identifying the discontinuities discussed above. The procedure for identifying this type of discontinuity is as follows: (1) select intervals in which the density changes by $\geq 20$ percent between two consecutive readings; (2) select the
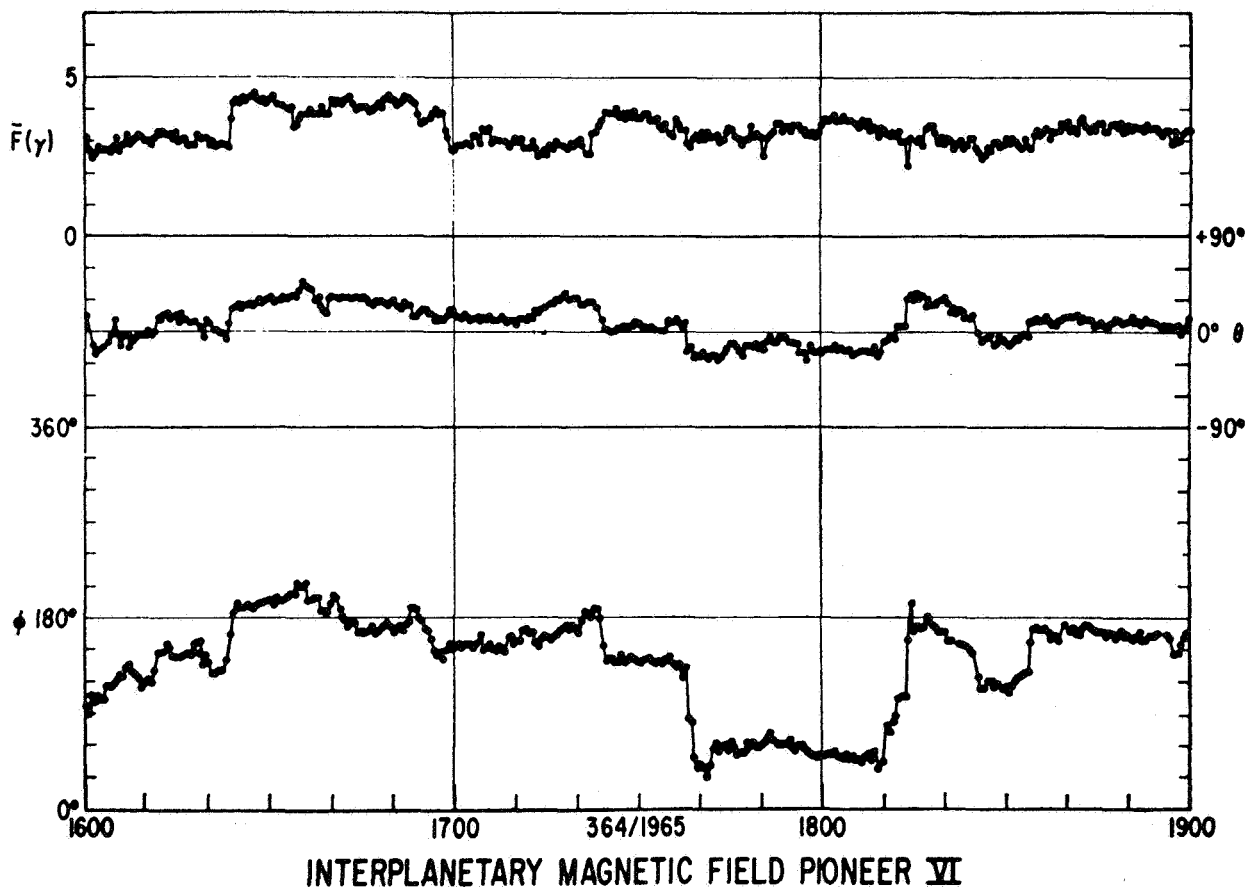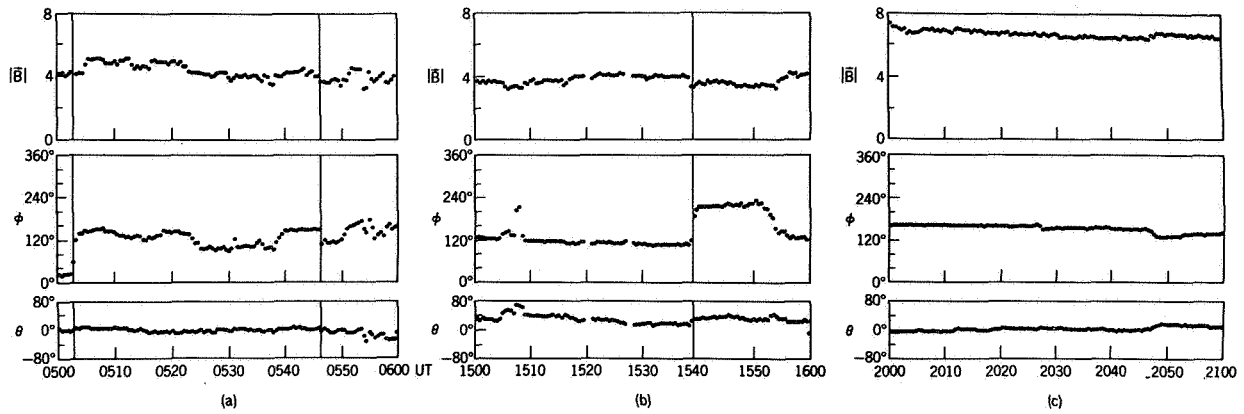


**Figure 1.** *Filament discontinuities. F is the magnetic field intensity and $\theta$ and $\phi$ are solar ecliptic latitude and longitude of B. The field is plotted versus universal time.*

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**Figure 2.** *Directional discontinuities. Three examples of directional discontinuities are shown by the vertical lines. Note the small changes in (c) and the gradual changes in (a) and (b) which are not directional discontinuities.*
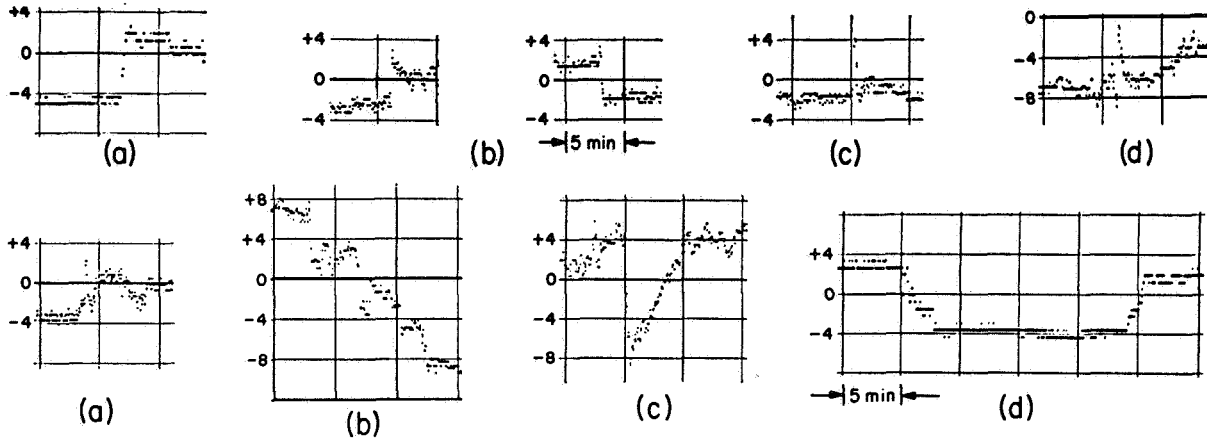


**Figure 3.** *Simple discontinuities and other types. Simple discontinuities are shown in (a), spiked discontinuities in (b).*
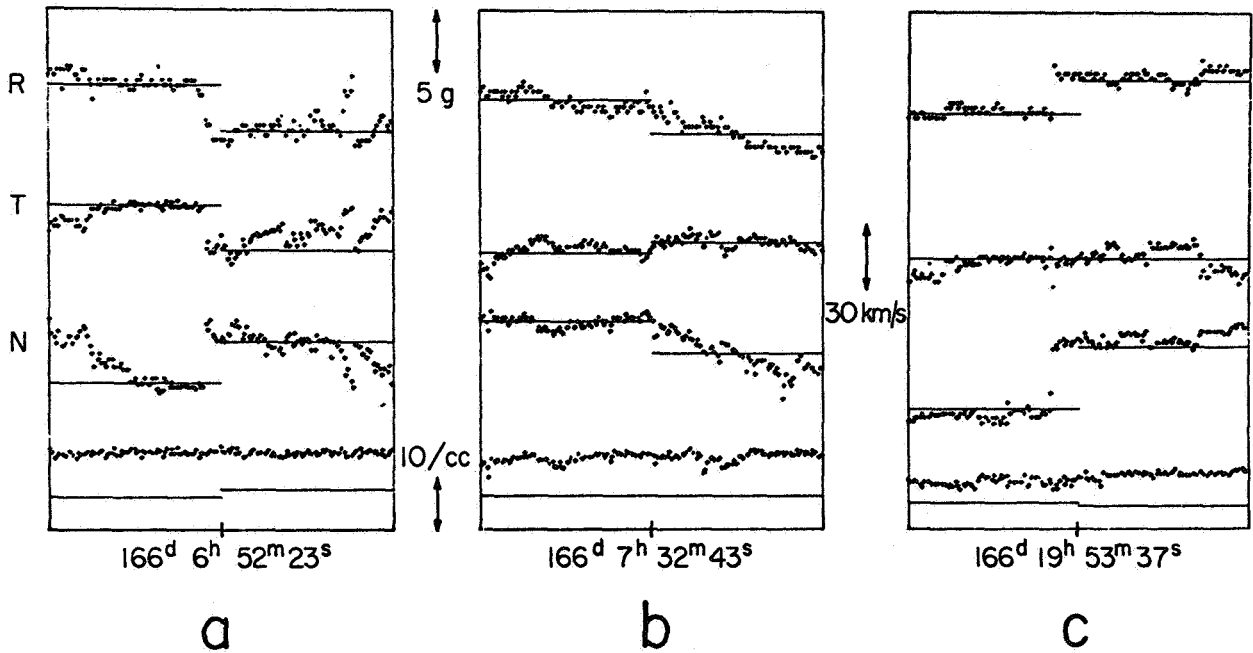
subset for which the density is nearly constant for the three measurements before the discontinuity and for the three measurements after the discontinuity; (3) select those discontinuities for which the magnetic field direction changes by a sufficiently large amount, meaning that the larger of $\sin^{-1}(3\sigma_1/B_1)$, $\sin^{-1}(3\sigma_2/B_2)$, where $\sigma_1$ and $\sigma_2$ refer to standard deviations in the measurements of the components [*Turner and Siscoe*, 1971], should be less than the angle between $B_1$ and $B_2$; and (4) eliminate those discontinuities with a shock signature.

*Possible rotational discontinuities* [*Turner and Siscoe*, 1971]. This is based on 5-min magnetic field averages and plasma measurements made at 5-min intervals. The selection procedure is as follows: (1) choose changes in the bulk speed $\Delta V > 25$ km/sec between consecutive measurements; (2) eliminate those discontinuities for

which the bulk speed changed appreciably in the 15 min before or after the discontinuity; (3) eliminate those discontinuities across which the magnetic field intensity changed; (4) require that the change in the magnetic field direction be sufficiently large, as discussed above for possible tangential discontinuities; and (5) choose those for which $\Delta \mathbf{V} \cdot \Delta \mathbf{B} > 0.7 \mid \Delta \mathbf{V} \mid \mid \Delta \mathbf{B} \mid$.

*Sharply crested Alfvén waves, abrupt Alfvén waves* [*Belcher and Davis*, 1971]. These terms are used by Belcher and Davis without a definition. They call a rotational discontinuity a "sufficiently sharp crested Alfvén wave" (see fig. 4).

*Appreciable discontinuities* [*Quenby and Sear*, 1971]. This refers to field magnitude changes > 20 percent and direction changes $\gtrsim 30°$.

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R

T

N

5 g

30 km/s

10/cc

166$^d$ 6$^h$ 52$^m$23$^s$

166$^d$ 7$^h$ 32$^m$43$^s$

166$^d$ 19$^h$ 53$^m$37$^s$

a

b

c

**Figure 4.** *"Sufficiently sharp-crested Alfvén waves."* The time scale is $\approx 10$ min. The dots show the components of **B** in RTN coordinates [Belcher and Davis, 1971]. The corresponding velocity components are shown by the horizontal lines, normalized to give the fits shown here. The density is shown by the horizontal lines at the bottom.

It is clear from the definitions and from figures 1, 2, and 3, that filament discontinuities, directional discontinuities, and simple discontinuities are similar. Further similarities are discussed below. The definitions of *possible tangential discontinuities* and *possible rotational discontinuities* are very restrictive and are likely to give two distinct sets. The definitions of the terms *filaments*, *directional discontinuities*, and *simple discontinuities* do not distinguish between tangential and rotational discontinuities [Burlaga, 1969].

### The Nature of Discontinuities

The discontinuities are likely to be shocks, rotational discontinuities, tangential discontinuities, or a combination of these. The number of shocks is sufficiently small that they can be considered negligible. One question then is: What is the ratio of tangential to rotational discontinuities for each of the classes defined above?

*Ness et al.* [1966] suggested that filament discontinuities are all tangential. Some supporting evidence from simultaneous cosmic ray and magnetic field data was given by *McCracken and Ness* [1966].
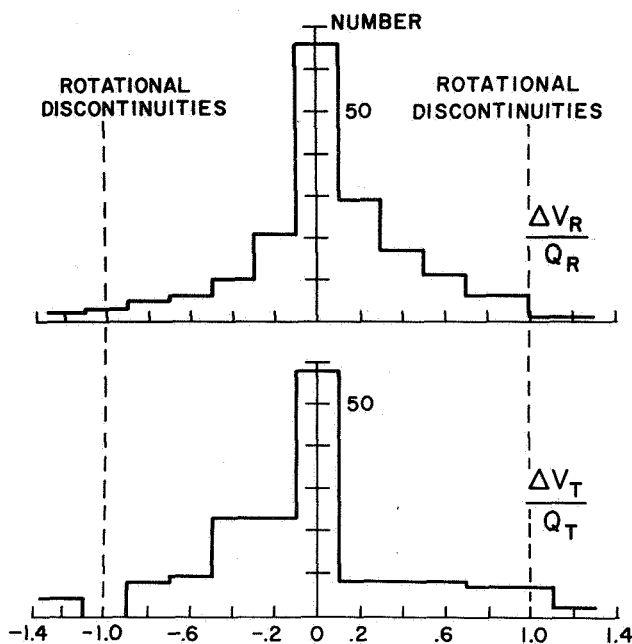
*Burlaga* [1971] showed that most (but not necessarily all) directional discontinuities observed in the period December 18 to 25, 1965, were tangential. The argument is as follows. The discontinuities are probably either tangential, rotational, or a mixture of both. If they are rotational, then necessarily they satisfy the condition

$$V_2 - V_1 = \pm\left(\frac{B_2}{\rho_2} - \frac{B_1}{\rho_1}\right)\left(\frac{\rho_1}{4\pi}\right)^{1/2} \times A, \equiv QA$$

where $A = 1$ for an isotropic plasma and $A \approx 0.9 \pm 0.1$ for the anisotropies typically measured in the solar wind.

The above condition is not satisfied for most of the directional discontinuities (fig. 5). The peak occurs at 0 rather than at $\pm 0.9$. Thus most of the discontinuities are not rotational; they must be tangential. Burlaga shows that the fraction of rotational discontinuities in the set of directional discontinuities must be less than 0.25. *Smith et al.* [1970] have recently suggested that the ratio is greater than 0.5.

*Siscoe et al.* [1968] analyzed the structure of current sheets associated with *simple discontinuities* and concluded that they correspond to tangential discontinuities

**Figure 6.** *Change in magnetic field intensity across simple discontinuities (left) and directional discontinuities (right).*



**Figure 5.** *If most directional discontinuities were rotational, then the distribution of $\Delta V_i/Q_i$, where $Q_i \equiv 21.8\left(\frac{B_{1i}}{n_1}-\frac{B_{2i}}{n_2}\right)\sqrt{n}$ would be peaked at $\pm0.9$. The fact that it is peaked at zero implies that most directional discontinuities are not rotational discontinuities.*

rather than rotational discontinuities. The reason for the difference between this result and that of *Smith et al.* [1970] is not clear.
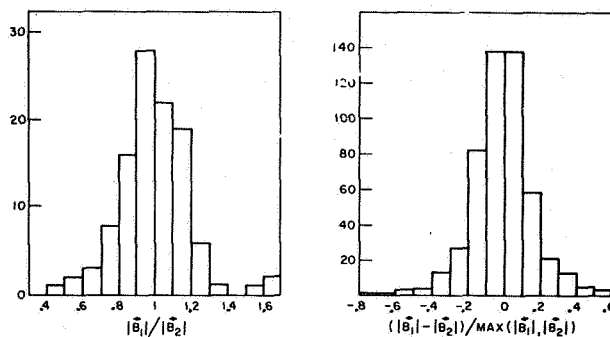
In view of the many constraints involved in using both plasma and magnetic field data in the definition of *possible tangential discontinuities*, there is little reason to doubt that most are in fact tangential. Similarly, most probable *rotational discontinuities* are indeed likely to be rotational, if they can actually be classified as discontinuities. They should be studied with higher time resolution data.

The nature of the appreciable discontinuities discussed by *Quenby and Sear* [1971] has not been studied directly using both plasma and magnetic field measurements. They suggest from a theoretical argument based on cosmic ray measurements that most appreciable discontinuities are rotational.

### Statistical Properties of Discontinuities

*Directional and simple discontinuities.* The basic distributions are for $B_1/B_2$, $\omega$ (the angle between $B_1$ and $B_2$), the time interval between successive discontinuities, and the directions $\hat{n} = B_1 \times B_2/\,|B_1 \times B_2|$.

The distributions of $B_1/B_2$ for planar simple discontinuities and $(B_1-B_2)/\max(B_1,B_2)$ for directional discontinuities are shown in figure 6. It is clear that for

both types, the most probable case is that the magnetic field intensity $B$ does not change across the discontinuity; and increases and decreases in $B$ are equally probable.

The distribution of $\omega$ for directional discontinuities is shown in figure 7. An empirical fit gives



$$365\,(65) - 5\,(66)$$

$$406 \times e^{-\left(\frac{\omega}{75°}\right)^2}$$
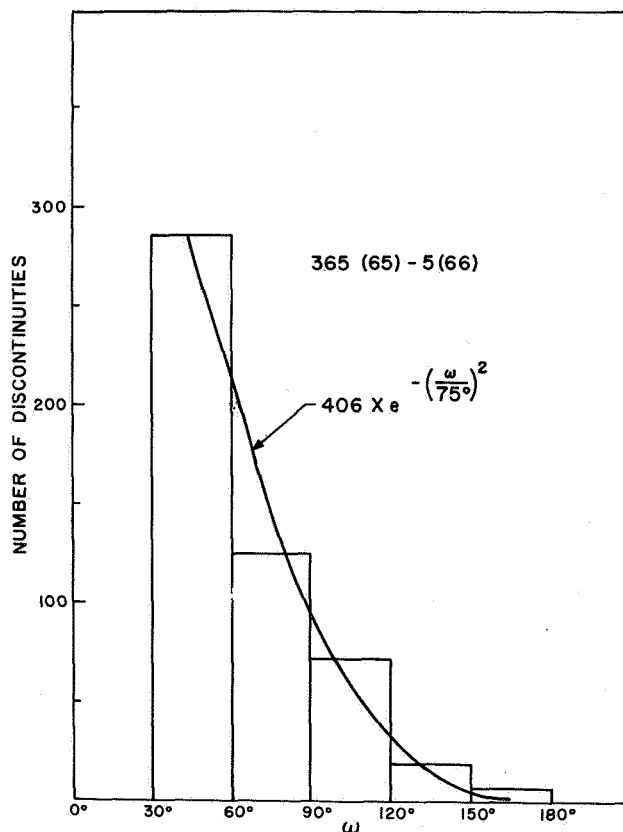
**Figure 7.** *Distribution of $\omega$ for directional discontinuities.*

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$dN/d\omega \sim \exp{-(\omega/75°)^2}$. Clearly, most directional discontinuities have small $\omega$. The lower limit $\omega = 30°$ is a result of the definition of a directional discontinuity and was used to avoid confusing discontinuities and the fluctuations that are usually present. The corresponding distribution of $\omega$ for simple discontinuities is shown in figure 8. For $\omega > 60°$ it is very similar to that for directional discontinuities. The decrease for $\omega < 50°$ is due to the selection criterion, $|B_2 - B_1| > 4\gamma$. Note that for the usual case, $B_1 = B_2 \approx 5\gamma$, this criterion gives a discontinuity with $\omega > 50°$.

The distribution of time intervals between successive directional discontinuities is given in figure 9 for four classes of these discontinuities, those with $30° < \omega \leq 60°$, $60° < \omega \leq 90°$, $90° < \omega \leq 120°$, $120° < \omega \leq 150°$. The distributions are of the form that would be expected if they occurred with a Poisson distribution. They occur at the rate of $\approx 1/\text{hr}$. The probability of finding a simple discontinuity in any time interval $T$ is shown in figure 10. The probability of finding a simple discontinuity in an arbitrary 5-min interval is 0.1. Thus, they occur at the rate of $\approx 1/\text{hr}$. Again we find that the characteristics of directional discontinuities and simple discontinuities are very similar.

The distribution of "normals" for directional discontinuities is shown in figure 11. They tend to be perpendicular to the spiral direction and out of the ecliptic plane. The distribution of "normals" of the current sheets associated with simple discontinuities is shown in figure 12 from *Siscoe et al.* [1968]. Here a sector-dependent asymmetry is also shown. Although figures 11 and 12 are not directly comparable, it is clear that the normal tends to be out of the ecliptic in both cases. The orientation of $\hat{n}$ with respect to the spiral field is not clearly shown by the projection in figure 11.

The distributions described above show that directional discontinuities and simple discontinuities have essentially the same statistical properties. Since their definitions are also similar, and since different, independent analyses show that each type consists predominantly of tangential discontinuities, we may infer that directional discontinuities and simple discontinuities are essentially equivalent.

*Possible tangential discontinuities.* One expects the properties of these discontinuities to be similar to directional and simple discontinuities, since physically they seem to be the same. However, one expects "probable tangential discontinuities" to occur less frequently because of the more stringent requirements involved in their definition.
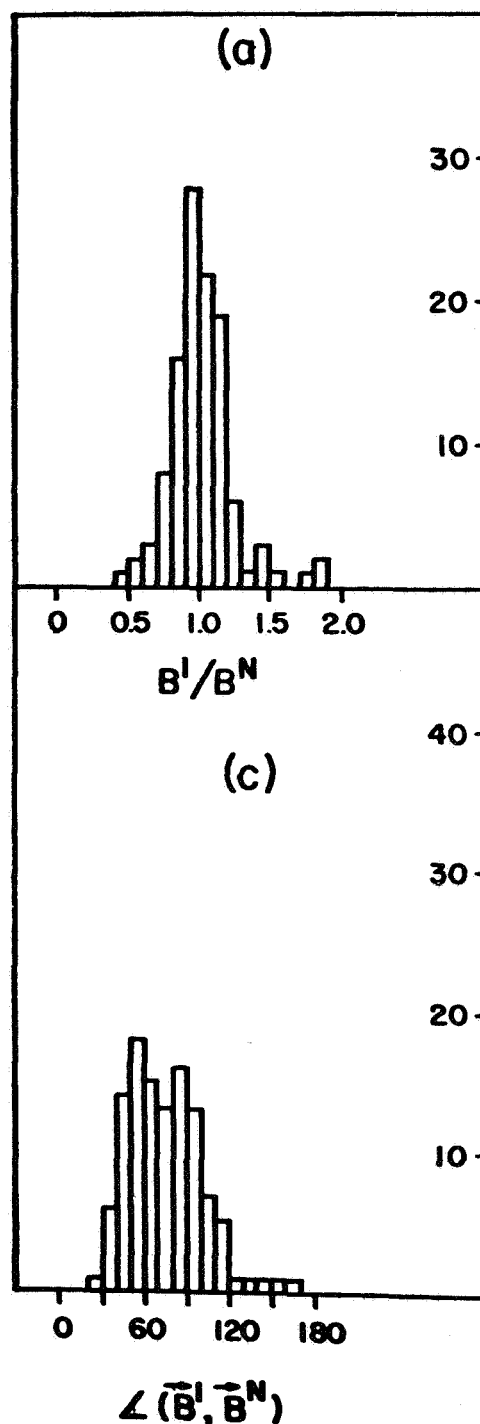


**Figure 8.** *Distribution of magnitude changes (a) and $\omega$ (c) for simple discontinuities.*

The rate at which possible tangential discontinuities passed Mariner 5 is $\approx 1/25$ hr, which is to be compared to $\approx 1/\text{hr}$ for simple and directional discontinuities.
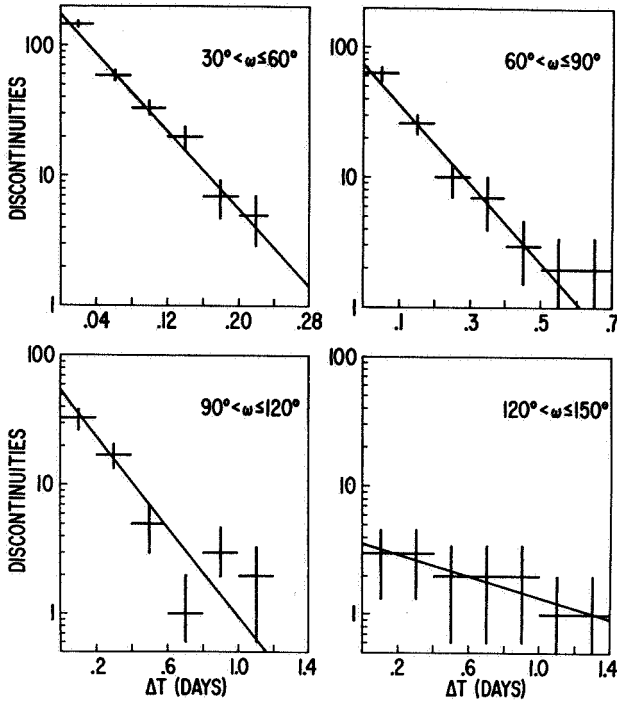
**Figure 9.** *Distribution of time intervals between successive directional discontinuities.*
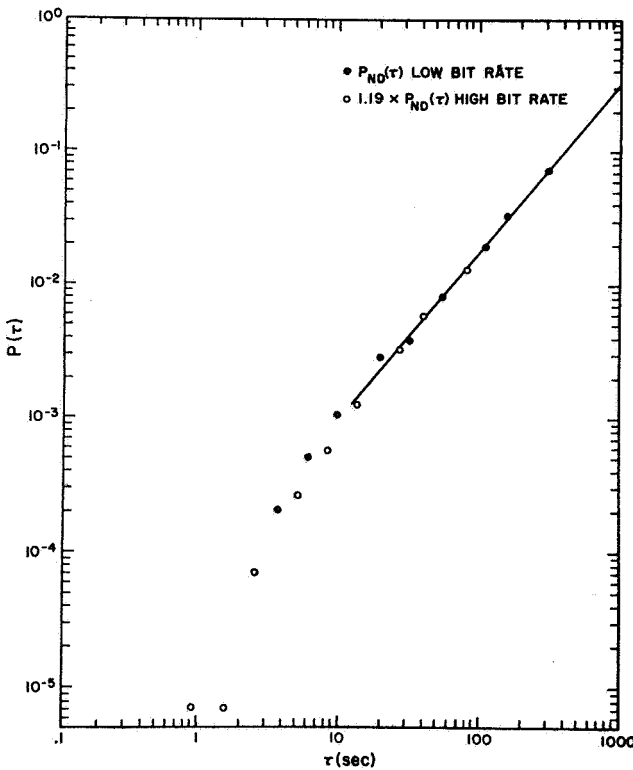


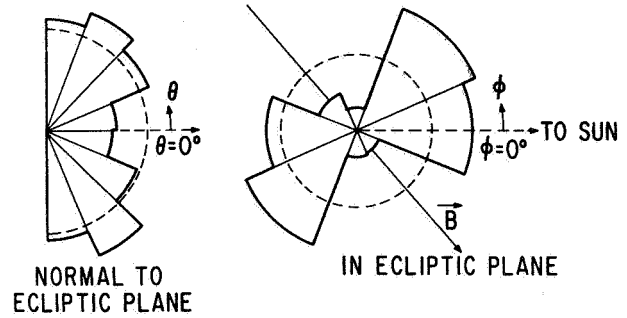**Figure 10.** *Probability of finding a simple discontinuity in any time interval $\tau$.*

**Figure 11.** *Distribution of the vectors $B_1 \times B_2 / |B_1 \times B_2|$ for directional discontinuities.*

*Turner and Siscoe* [1971] did not give the distributions of $B_1/B_2$ and $\omega$ for possible tangential discontinuities. The distribution of the polar angles of the normals normalized to obtain the number per unit solid angle is shown in figure 13. The normals of possible tangential discontinuities tend to be normal to the spiral direction and in the ecliptic plane. Recall that the "normals" associated with directional discontinuities also tend to be normal to the spiral direction, but they tend to be out of the ecliptic.

*Possible rotational discontinuities.* Forty of these were found in 40 days of data from Mariner 5, but most occurred in three intervals of $5 \pm 1$ days. Thus, the maximum rate is $\approx 0.1$/hr which is only 10 percent of the rate of directional and simple discontinuities. Most of the time the rate is much less than this. Although the ratio of possible rotational discontinuities to possible tangential discontinuities is $\approx 1$, it does not mean that this is the ratio of rotational to tangential discontinuities in the set of directional discontinuities. One can only say that at times up to 10 percent of the directional discontinuities might be possible rotational discontinuities.

The $\omega$ and $B_1/B_2$ distributions were not given by *Turner and Siscoe* [1971]. The distribution of average normals for three subsets of discontinuities is given in figure 13. This is different from that of probably tangential discontinuities.

*Changes in plasma parameters at discontinuities.* The early models assumed that the plasma parameters change across most magnetic field discontinuities. This is probably not so, but the matter has not been studied extensively. *Burlaga* [1968] found no change in $n$, $V$, or $T$ across directional discontinuities with $B_1 \approx B_2$, which according to figure 6 is the most probable case. Changes in plasma parameters do sometimes occur, however. Burlaga classified discontinuities according to changes in

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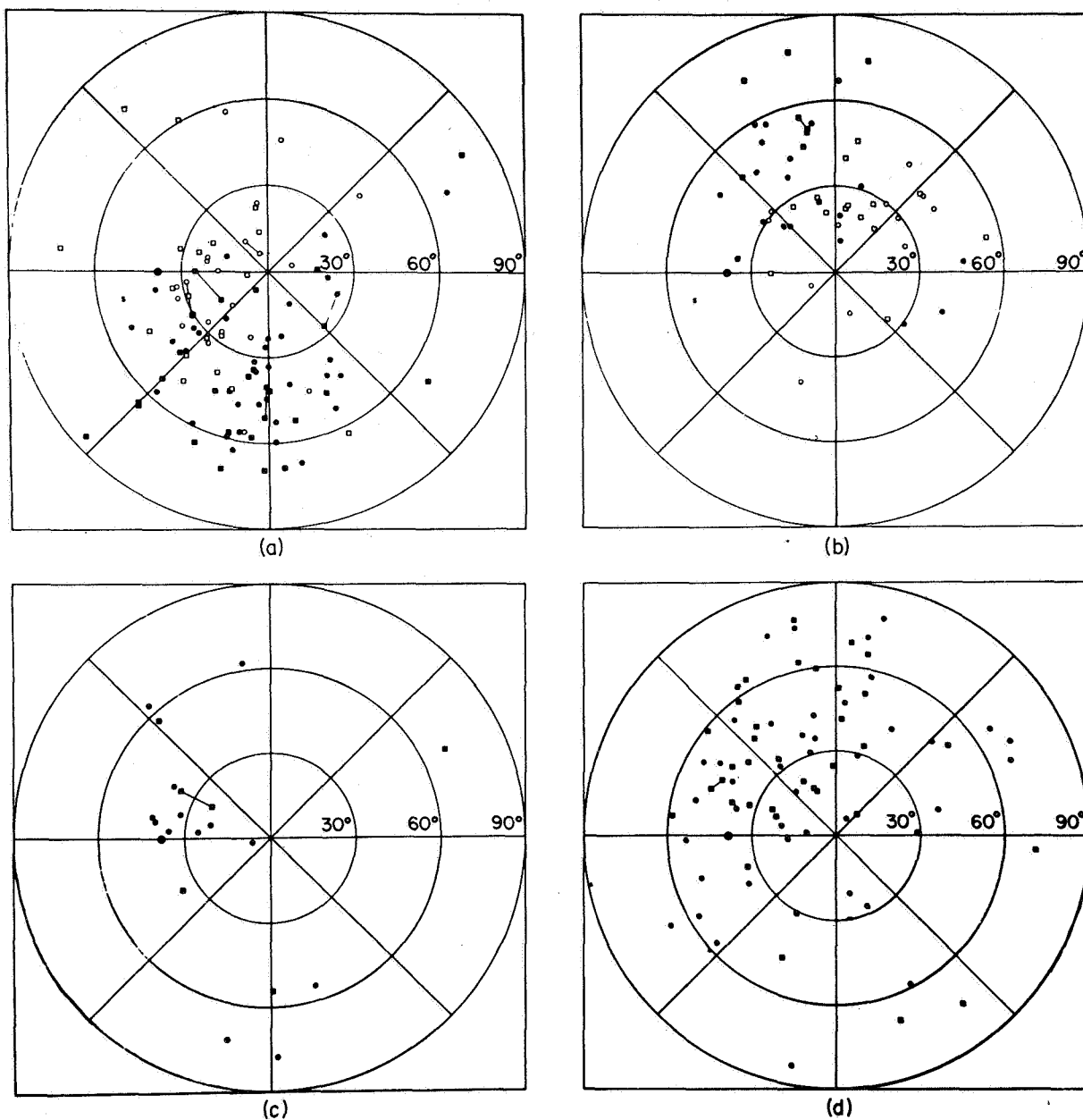
**Figure 12.** *Distribution of current sheet normals associated with simple discontinuities.*

*B*, *n*, and *T*, as shown in table 1. The symbol (+,−,0) implies an increase in *B*, a decrease in *n*, and no change in *T*. The other symbols have similar meaning. Nine of the 13 possible signatures were found in the Pioneer 6 data. This scheme may be useful for discussing the statistical properties of discontinuities when more data become available. It has been used to discuss interaction of discontinuities with the earth [*Burlaga*, 1970*b*]. *Hudson* [1970] has pointed out that it cannot be used for identifying tangential or rotational discontinuities in

an anisotropic medium such as the solar wind. Recently, *Burlaga and Chao* [1971] showed that the discontinuities in *B* which they selected ($\gtrsim$ 20 percent in $\lesssim$ min) are essentially always accompanied by changes in *n* and possibly *T* (fig. 14). However, figure 6 shows that the probability of such a change in *B* across *A* directional discontinuity is small.

**Morphology of Simple and Directional Discontinuities**
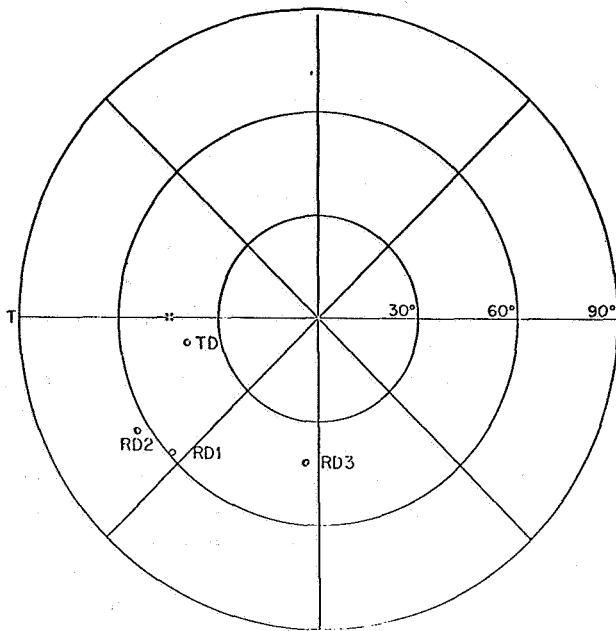
This section aims to present a mesoscale ($\approx$ 1 AU)

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**Figure 13.** *Average normals for "probable tangential discontinuities" and "probable rotational discontinuities."*

**Table 1.** *Tangential discontinuities*

| TO | $( \ 0 \ \ 0 \ \ 0 \ )^a$ | | |
|---|---|---|---|
| T2 | $( \ + \ - \ 0 \ )^a$ | $( \ 0 \ + \ - \ )^a$ | $( \ - \ 0 \ + \ )^a$ |
| | $( \ - \ + \ 0 \ )^a$ | $( \ 0 \ - \ + \ )$ | $( \ + \ 0 \ - \ )^a$ |
| T3 | $( \ + \ - \ + \ )^a$ | $( \ + \ + \ - \ )^a$ | $( \ - \ + \ + \ )$ |
| | $( \ - \ + \ - \ )^a$ | $( \ - \ - \ + \ )$ | $( \ + \ - \ - \ )$ |

[a] *Observed in Pioneer 6 data*

picture of the topology of the discontinuity surfaces and the variations of plasma parameters between them. This is intended to be a zeroth approximation; details must be supplied by later work.

The separations between discontinuity surfaces can be approximately described by the distribution of time intervals between successive discontinuities, since the discontinuities are convected past the spacecraft at the solar wind speed. This is an approximate description since the solar wind speed changes, but it is a good
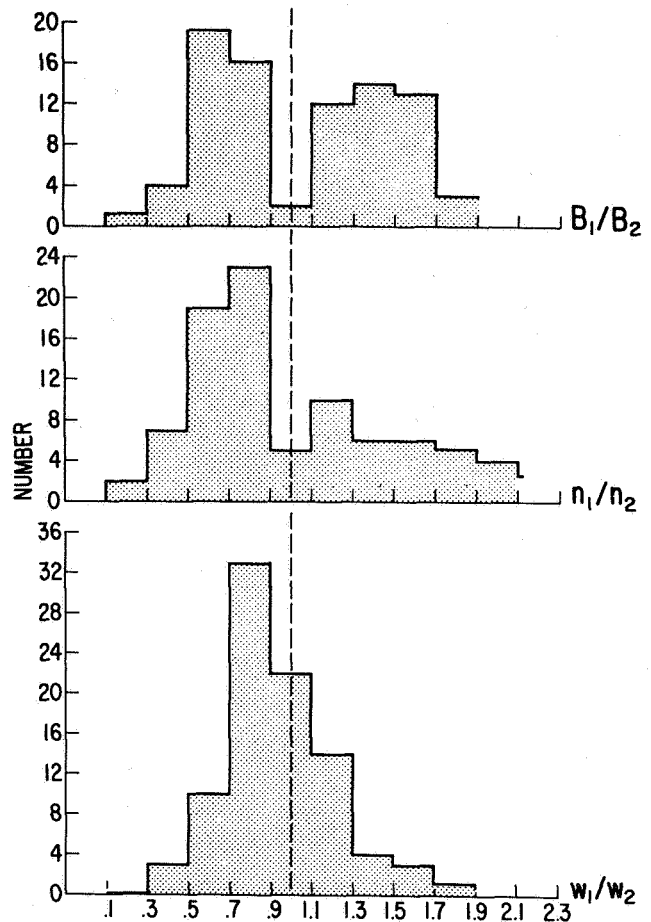


**Figure 14.** *Changes in n associated with changes in* |B| *across discontinuities.*

zeroth approximation because the changes are seldom greater than 50 percent. Figure 9 from *Burlaga* [1969] shows such a distribution of time intervals for four classes of directional discontinuities. The corresponding mean separations in space are shown in figure 15.

The topology of individual surfaces can be studied only with multiple spacecraft observations. *Burlaga and Ness* [1969] and *Ness* [1966] discuss one exceptional surface seen by Pioneer 6 and IMP 3, which was planar and unchanged over a distance of 0.01 AU. *Burlaga and Ness* [1969] studied six surfaces, each of which was observed at three spacecraft, Explorers 33, 34, and 35. These are shown in figure 16 where it is seen that some of them do show an appreciable curvature over distances of 100 $R_E$ = 0.005 AU. These are probably atypical; the curvature is likely to be larger for most discontinuities.

If it is assumed that the surfaces are plane, then their orientations can be computed very simply using the formula $\hat{n} = B_1 \times B_2 \ / \ | \ B_1 \times B_2 \ |$ and measurements
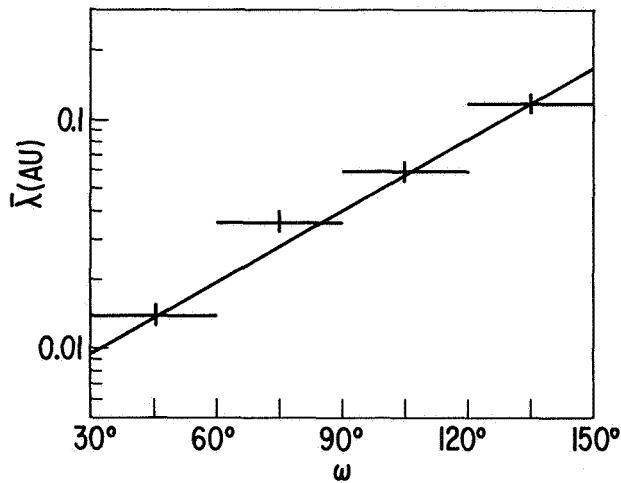
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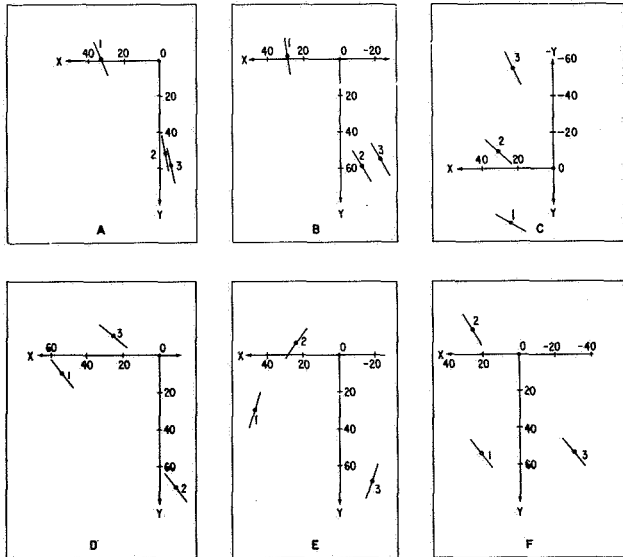**Figure 15.** *Average separation of directional discontinuities.*



**Figure 16.** *Multi-spacecraft observations of discontinuity surfaces. Each panel describes one surface. Each dot represents the position of a spacecraft. The earth is at the origin and units are earth radii. The line segments are ecliptic plane intersection of the discontinuity surface, compiled from* $\hat{n} = \mathbf{B_1} \times \mathbf{B_2} / |\mathbf{B_1} \times \mathbf{B_2}|$. *The surface first passed spacecraft 1, then spacecraft 2, and finally spacecraft 3.*

from just one spacecraft. This procedure shows (unpublished results) that the surfaces associated with directional discontinuities intersect at a distance $\approx 0.01$ AU from the earth-sun line. This should not be surprising, since the autocorrelation length of $\mathbf{B}$ is $\approx 0.01$ AU. The result does not imply that directional discontinuities are not tangential. Rather, it implies that the surfaces are appreciably curved on a scale of $\approx 0.01$ AU.

The picture that is suggested by the above results is illustrated in figure 17. There are numerous discontinuity surfaces (current sheets) in space, separated by $\approx 0.01$ AU. Although the surfaces are shown as planar in figure 17 for simplicity, they are actually appreciably warped and bent on the scale of the figure. Successive discontinuity surfaces are not parallel, but they do tend to scatter about the spiral field direction. The magnetic field direction changes discontinuously across each of the surfaces and varies appreciably between adjacent surfaces. The magnetic field directions are shown as straight line segments in figure 17, but in reality are appreciably bent and "distorted" on the scale shown there. In reality, they are probably additional discontinuities between the directional discontinuities that have $\omega < 30°$ or are obscured by fluctuations and noise.

Figure 17 gives only a rough approximation to reality. There are infinitely many variations of detail, and complexities not yet mentioned. The way that surfaces connect with one another (if they do so) and their extent toward the sun is unknown. The cosmic ray measurements of *McCracken and Ness* [1966] suggest that the magnetic field lines on either side of a discontinuity go directly to the sun; but this does not necessarily imply a similar extent of the current sheet.

The density, temperature, and bulk speed usually do not change across the discontinuity surfaces, but such changes do occasionally occur. The plasma parameters sometimes also vary *between* the discontinuity surfaces. Thus, if one were to use a color code to map plasma parameters in figure 17, he would probably find a weak relation between the color pattern and the directional discontinuities.

### Relations Between Discontinuities and Mesoscale Structure

*Siscoe et al.* [1968] noted that there was a pronounced north-south, sector-dependent asymmetry in the distribution of current sheet normals (fig. 12). They suggested that this is due to velocity shears acting in tangential discontinuities. Another interpretation was given by *Siscoe and Coleman* [1969]. Subsequently, however, *Turner and Siscoe* [1971] offered the hypothesis that the north-south asymmetry is due mainly to rotational discontinuities. This is based on the assumption that more than half of the discontinuities in *Siscoe et al.* [1968] are rotational. At the moment, there is no evidence to support this assumption. The results of *Burlaga* [1970b] argue against it if the discontinuities studied by *Siscoe et al.* [1968] are directional discontinuities. Obviously, the problem needs further study.
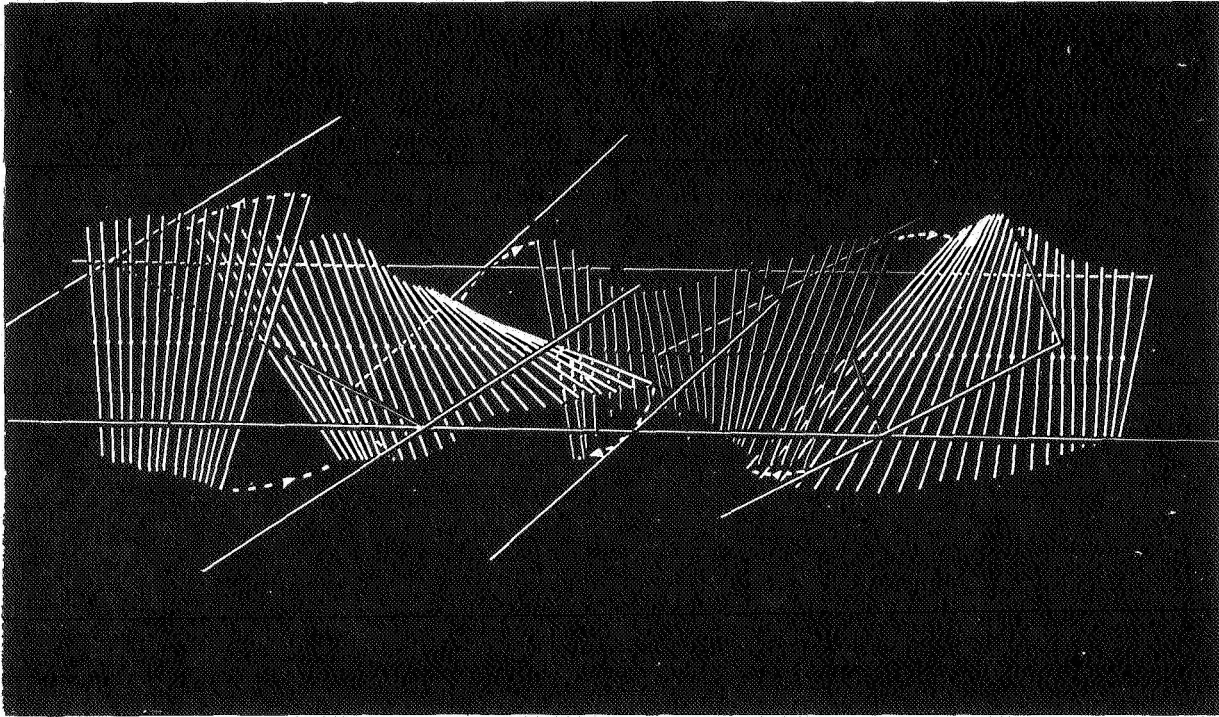
Figure 17. *Simplified view of three discontinuity surfaces and magnetic fields between them illustrating how a 0.05 AU segment of the solar wind might look (see text).*

*Burlaga* [1970a] could not find a relation between the rate of occurrence of directional discontinuities and positive bulk speed gradients. This implies that most of these discontinuities are not caused by the gradients.

### Variation of Discontinuities with Distance from the Sun

The only work on this subject is that of *Burlaga* [1970a] which is based on the Pioneer 6 data of Ness for the region between 0.8 and 1.0 AU. He found that (1) the "density" of discontinuities (number passing the spacecraft per hour) was possibly 35 percent less at 0.8 AU than at 1.0 AU, but this difference could be due to the higher quality data near the earth; and (2) the distributions of $\omega$, the change in the direction of B across a discontinuity, were essentially identical at 0.8, 0.9, and 1.0 AU. The conclusion is that most discontinuities originate within 0.8 AU and their characteristics do not change very much between 0.8 and 1.0 AU.

### Filaments

The concept of a filament is widely used, but never precisely defined. This has caused much confusion. The concept has evolved appreciably during the last 10 years, so a historical discussion is appropriate.

The idea that filaments might exist in the solar wind seems to go back to *Parker* [1963], who suggested that they would be the result of an assembly of fine streamers or temperature striations in the corona. Parker pictured the streamers as more or less discrete flow tubes separated by regions of material with different density, temperature, and magnetic field intensity. The scale of these filaments was set at ≈0.01 AU. Radio observations of Hewish (p. 477) have been interpreted as evidence for such filaments, but this interpretation has been questioned by *Jokipii and Hollweg* [1970]. The observation of filamentary structure in comet tails was also interpreted as evidence for filaments in the solar wind, but more recent work [*Kubo et al.*, 1970] suggests that this might result from turbulence, instabilities, or some other mechanism. The early observations by Explorer 10 showed regions of plasma with density 7 to $20/cm^3$ and $B \approx 10\,\gamma$ alternating at approximately hour intervals with higher field regions $(20\,\gamma)$ with no detectable plasma. This was said to be evidence for filaments in the solar wind, but more recent observations suggest that Explorer 10 was alternately inside and outside the magnetosheath.

With the advent of high time resolution magnetic field

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data from Pioneer 6, Mariner 4, and other spacecraft, the concept of filaments was rejuvenated. *Ness* [1966] pointed to two kinds of filaments: those bounded by pairs of nearly identical directional discontinuities (fig. 11) and those characterized by less abrupt changes in magnetic field intensity (fig. 18). It was suggested [*McCracken and Ness*, 1966] that the interplanetary field could be viewed as bundles of intertwined filaments bounded by tangential discontinuities (directional discontinuities) and extending to the sun. This has been referred to as the "spaghetti" model. Support of this model was given by *Siscoe et al.* [1968], who on the basis of Mariner 4 data suggested that the shape of the filamentary tubes is elliptical.

*Michael* [1967] proposed an alternate model, with "entropy fluctuation cells," but this has not been discussed further in the literature. *Burlaga* [1969] pointed out that such filaments are exceptions rather than the rule at 1 AU and suggested that the interplanetary medium should be regarded as discontinuous rather than filamentary. Figure 19 shows a day of Ness's Pioneer 6 magnetic field data with a number of clearly defined directional discontinuities, but it would be difficult for two observers to agree on how it might be divided into filaments. The point is that there is

generally no obvious pairing of directional discontinuities. This does not imply that filaments bounded by similar directional discontinuities never occur, only that they are relatively rare. *Siscoe et al.* [1968] found only nine pairs of nearly identical simple discontinuities separated by 2 to 30 min in the Mariner 4 data. "Filaments" of the kind shown in figure 18 are not uncommonly seen behind driven shocks. These structures resemble more closely than any others the type described by *Parker* [1963]; but their nature might be different. Again, they are the exception rather than the rule.

The current situation is that the term *filament* has many meanings. It seems more appropriate to describe the solar wind near 1 AU as discontinuous rather than filamentary. This does not exclude the presence of waves, fluctuations, or turbulence. Pairs of simple discontinuities and pairs of directional discontinuities do sometimes occur, but their significance is not certain.

## Waves and Fluctuations

Linear hydromagnetic theory predicts three types of waves: fast, slow, and Alfvén waves. It is possible that all three types are present at one time or another in the solar wind as well as larger amplitude nonlinear waves. The observed waves are very seldom periodic and frequently nonlinear, and they are probably coupled
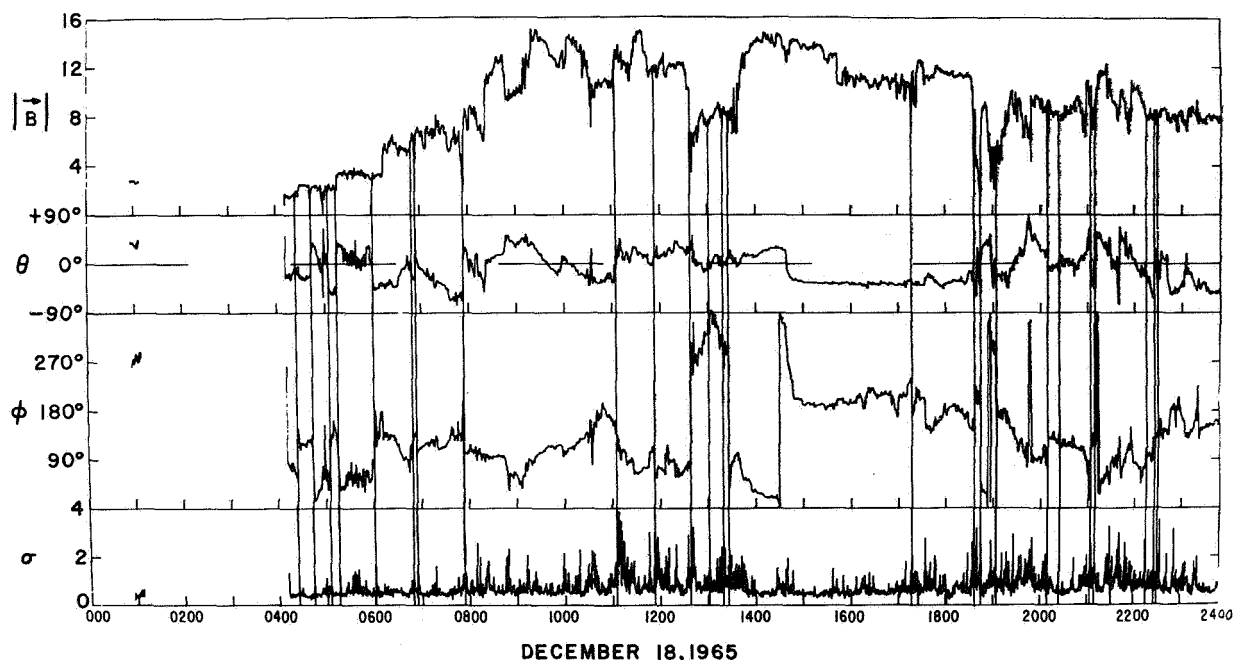
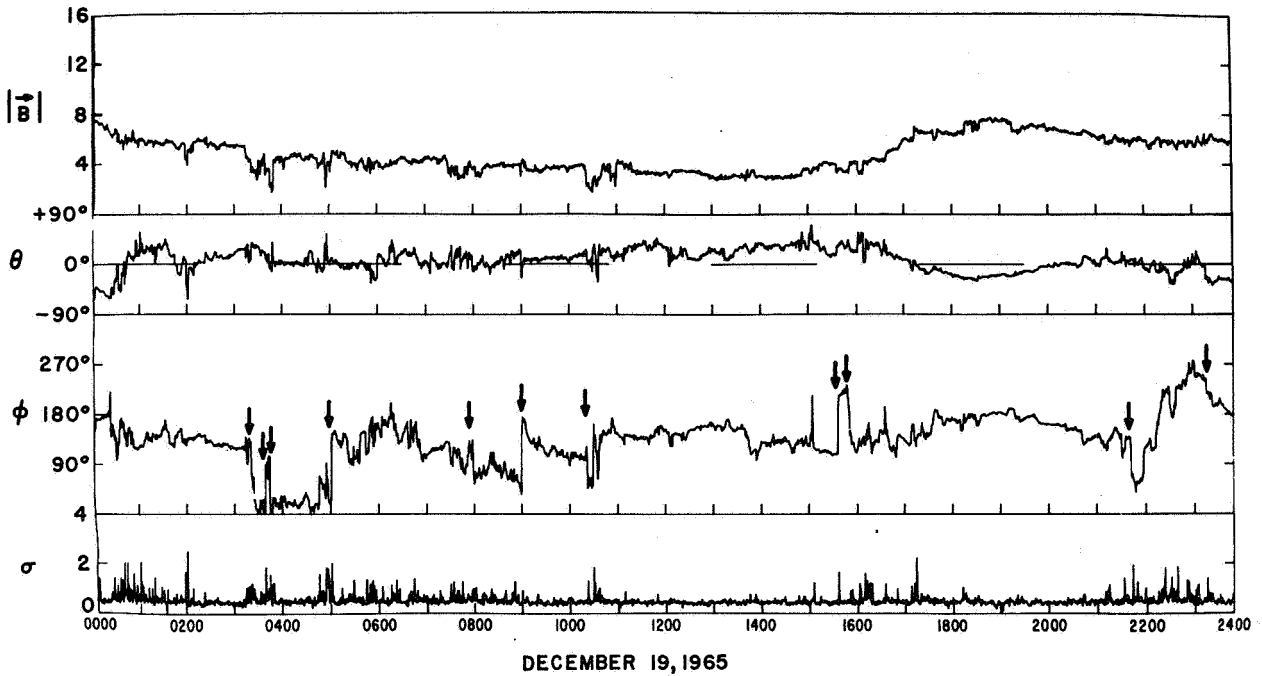

Figure 18. *"Filaments" in* B.

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**Figure 19.** *Directional discontinuities and filaments. The directional discontinuities are marked by arrows. How would one divide this interval into filaments?*

with one another. The interpretation of the observations is thus intrinsically complicated and is further hindered by incomplete plasma observations. The usual approach is to study the fluctuations in the magnetic field and try to interpret them, with the limited available plasma data and/or with idealized models, in terms of the linear hydromagnetic theory.

Much confusion has resulted from the loose or erroneous use of words and definitions. Here we review the various types of waves and fluctuations that have been mentioned in the literature, discuss the interpretation of power spectra and the controversy concerning microscale fluctuations, and present a hypothetical model of the relation between the bulk speed and fluctuations and evidence for the variation of fluctuations with distance from the sun.

### Types of Waves and Fluctuations

*Periodic Alfvén waves.* Unti and Neugebauer [1968] searched Mariner 2 data for *sinusoidal* changes in the direction of **B** that satisfy the conditions for Alfvén waves. One (but only one) such wave, with a Doppler-shifted period of 30 min, was found [*Burlaga*, 1971]. Such waves do not play an important role in the general structure of the solar wind at 1 AU, but their existence is of fundamental physical significance.

*Periodic waves.* Burlaga [1968] found a few sinusoidal wave trains with Doppler-shifted periods of $\approx 5$ min in the Pioneer 6 magnetic field data of Ness. These were compressive waves, probably magnetoacoustic and fast waves [*Burlaga*, 1971]. Again, only a few periodic waves were found in $\approx 6$ months of data, so they are not basic to the general structure of the solar wind at 1 AU.

*Large-amplitude aperiodic Alfvén waves.* Belcher et al. [1969] found in the Mariner 5 data that the bulk speed and radial component of **B** were strongly correlated 30 percent of the time (fig. 20), and argued that the fluctuations during these times were primarily Alfvén waves. An example of such a wave train is shown in figure 21. Note that this plot is based on 5-min averages.

The basic criterion which Belcher and Davis [1971] and Belcher et al. [1969] use to identify Alfvén waves is a strong correlation ($> 0.8$) between $V$ and $B_R$. They consider three subclasses of Alfvén waves:

1. *Pure waves.* Waves are called "pure" if there is no power in B–i.e., no compression oscillations—and the wave is linear. Such a condition seldom, if ever, occurs in the solar wind. Strictly speaking, an Alfvén wave is linear and is characterized by a constant $B$, so it must be a pure wave. Thus, intervals of pure Alfvén waves seldom, if ever, occur in the solar wind.
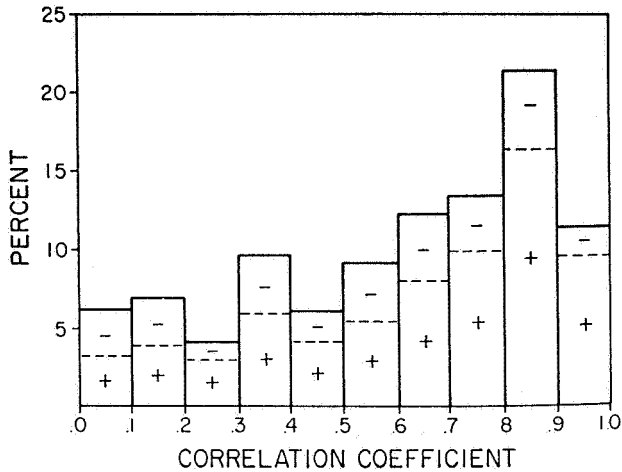
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**Figure 20.** *Correlation between V and $B_R$. Thirty percent of the time the correlation coefficient was >0.8 in the period June 14 to November 21, 1967.*
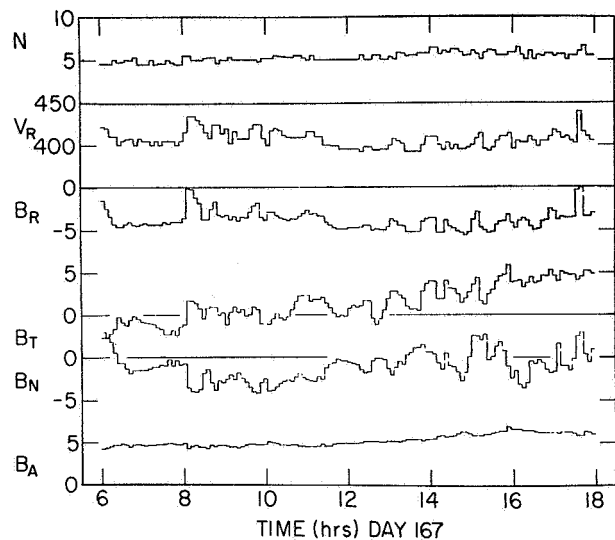


TIME (hrs) DAY 167

**Figure 21.** *Aperiodic Alfvén waves. The density N, bulk speed $V_R$, magnetic field components $B_R$, $B_T$, $B_N$, and magnetic field intensity are plotted versus time on a scale of 12 hr.*

2. *Almost pure waves*. These are periods when the power in B is judged to be much less than that in the components of B. Belcher (private communication) expects the power in the magnitude to be at least an order of magnitude below the power in the components, with a correlation between $\delta V$ and $\delta$B above 0.8, for almost pure waves. There may also be some

nonlinear coupling with other modes. *Belcher and Davis* [1971] sometimes refer to almost pure waves as pure waves.

3. *Good waves*. These show a correlation between $\delta V$ and $\delta$B, but are presumably accompanied by changes in *B* as well. These seem to be the most common type of large-amplitude aperiodic Alfvén waves.

Physically, there is no such thing as an almost pure Alfvén wave or a good Alfvén wave. When *Belcher and Davis* [1971] use these terms they are referring to the fraction of the power that is contributed by Alfvén waves. It might be better to stop using these terms and refer instead to power levels and correlation coefficients.

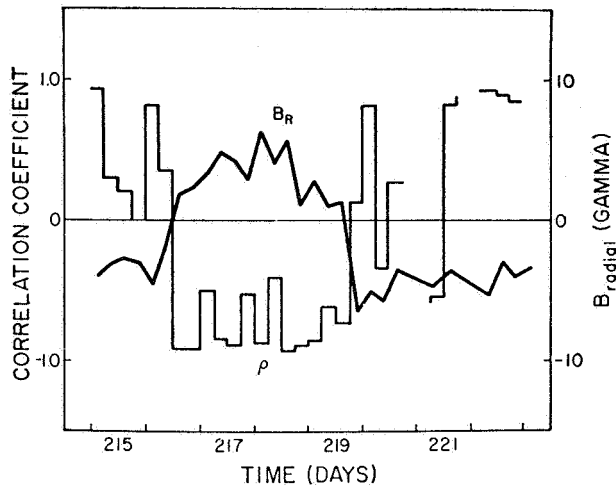Most aperiodic Alfvén waves move away from the sun, as shown by figure 22 from *Belcher et al.* [1969].



TIME (DAYS)

**Figure 22.** *Correlation coefficient and $B_R$ versus time. The anticorrelation indicates outward propagating waves during the period shown here.*

Belcher and Davis further distinguished between "sharply crested waves" and "smooth waves." The distinction was not defined operationally, and it depends on the time scale used (Belcher, private communication).

*Fluctuations.* This is a general term, seldom defined, which is used to describe nearly any kind of change in B. Consider a time series B($t$). For a given interval this may be written B($t$) = $B_{AV}$ + B'($t$) where $B_{AV}$ is the average over that interval. The term "fluctuation" refers to B'($t$). Here we use the term for that which is described by the power spectrum of B($t$). Obviously, B($t$) contains shocks, tangential discontinuities, sector boundaries, Alfvén waves, aperiodic Alfvén waves, and many other phenomena besides. However, the power spectrum may

be dominated by only one of these structures and the dominant type may change with time. This is discussed more precisely below.

*Microscale fluctuations.* Burlaga et al. [1969] noted that there are certain isolated periods, usually an hour or two in length, in which there are large, high-frequency (minutes) fluctuations in both the magnitude and direction of B. These are illustrated in figure 23.

*Belcher and Davis* [1971] also used the term *microscale fluctuations*, but they refer to a phenomenon distinctly different from that described by *Burlaga et al.* [1969]. The microscale fluctuations of Belcher and Davis have frequencies in the range 1/(4.2 hr to 10 min), and they occur more or less continuously. They seem to be essentially the same as the fluctuations discussed above. Belcher and Davis use variances to describe the fluctuations.

*Abrupt Alfvén waves.* Belcher and Davis use this term to describe three discontinuous or nearly discontinuous

changes in B (in the sense defined earlier, which were correlated with V in accordance with the relation $\delta B = \pm D \delta V$. They consider abrupt Alfvén waves to be identical to rotational discontinuities. Belcher and Davis stated that such changes occur at the rate of one per hour; however, they presented no evidence to support this remark.

### Fluctuations and Power Spectra

*Observations.* The standard techniques of spectral analysis are used to describe the magnetic field time series and its relation to other time series such as $V_R(t)$. This method of analyzing interplanetary magnetic field fluctuations was used by *Coleman* [1966a] in his analysis of Mariner 2 data. The basic results are as follows:

1. The power spectra of $B_r$, $B_\theta$, $B_\phi$, and B for 24-hr periods have the approximate form $f^{-\alpha}$, $1 \lesssim \alpha \lesssim 2$, in the range $10^{-5}$ to $10^{-2}$ Hz.
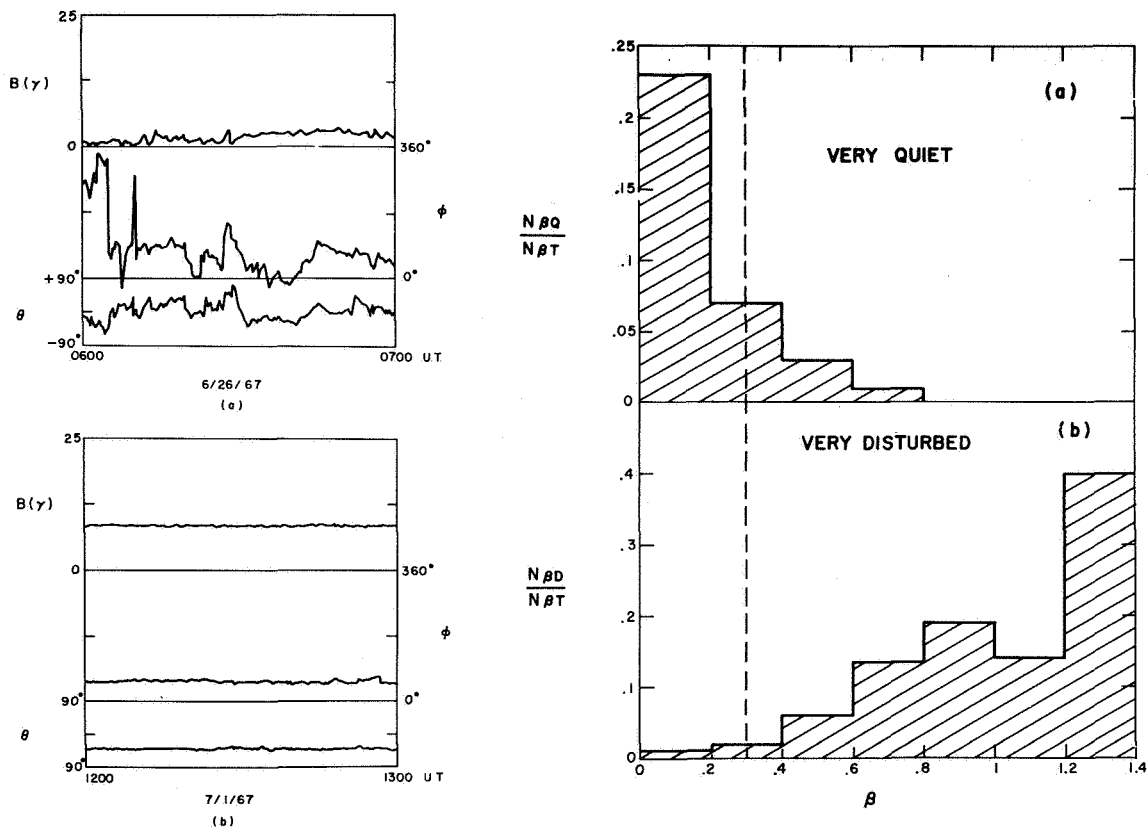


Figure 23.   *Microscale fluctuations and relation to $\beta = 8\pi nkT/B^2$. Burlaga et al. [1969] considered only two extreme conditions: very quiet (b) and very disturbed (a) on a scale of 1 hr. The very disturbed periods show large,"rapid" fluctuations in both the magnitude and direction of B. The very quiet periods occur when $\beta$ is small, the very disturbed periods when $\beta$ is large.*

2. Power levels range from $(10^3$ to $50)\,\gamma^2/\text{Hz}$ at $10^{-3}$ Hz.

3. $P(B_\theta) > P(B_\phi) > P(B_r) > P(|\mathbf{B}|)$—that is, the fluctuations are primarily transverse rather than compressional, and the largest fluctuations are normal to the ecliptic plane. The power in compressional oscillations was typically one-half to one-third that of the power in the components. All six intervals examined by Coleman showed fluctuations in $|\mathbf{B}|$.

4. $V_r$ and $B_r$ were correlated. Their phase difference was $\approx 180°$ when $B_{AV}$ was away from the sun and $\approx 0°$ when $B_{AV}$ was toward the sun. The magnitude of the square of the coherence between $V_r$ and $B_r$ was between 0.05 and 0.49 in the range 1 to 50 cycles per day (cpd); it was typically 5 to 8 times larger than that for $(V_r,B_\theta)$ $(V_r,B_\phi)$ and $(V_r,B)$, although all pairs showed significant coherences.

5. The ratios $P(B_i)/P(V_r)$, $i = r, \theta, \phi$, were essentially independent of frequency in the range 1 to 50 cpd.

Power sepctra from Mariner 4 covering the range $3 \times 10^{-4}$ to 0.5 Hz for six 24-hr intervals in t the period December 7, 1964, to January 2, 1965, were reported by *Siscoe et al.* [1968] (fig. 24). They show the same general characteristics, (1) to (3) above, found by Coleman. *Siscoe et al.* [1968] distinguished active, intermediate, and quiet times; they found an order of magnitude more power at active times than at quiet times (fig. 24).

*Belcher and Davis* [1971] report that they computed power spectra and cross spectra for the high data rate part of the Mariner 5 mission to Venus, and obtained results similar to those of *Coleman* [1966a]. The spectra are not published, however.

*Interpretation of power spectra.* Power spectra are simply statistical descriptions of time series. Their physical interpretation is not straightforward since they do not contain phase information. There are at least four contributors to the power spectra.
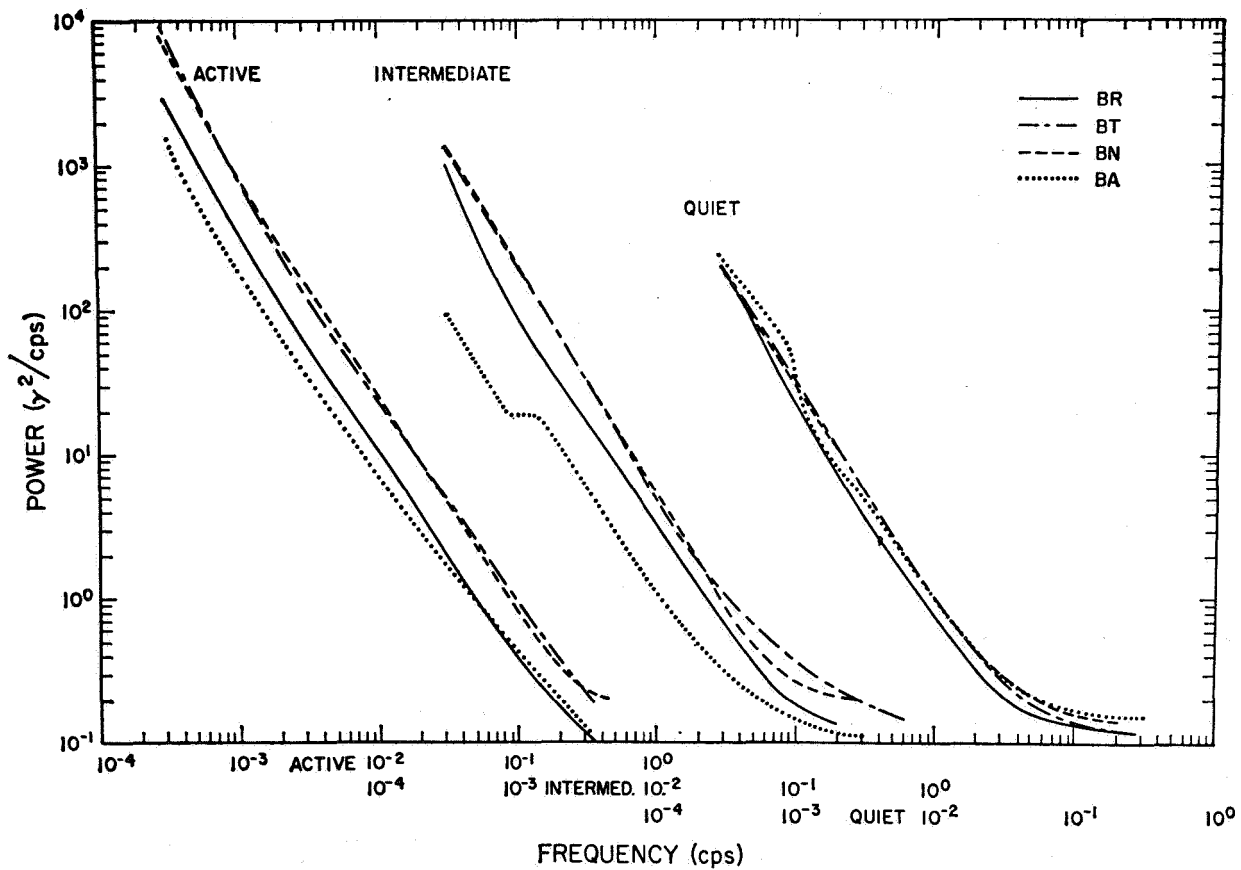


Figure 24. *Mariner-4 power spectra showing relative power in the magnetic field intensity $B_A$ and components. N is the direction normal to the ecliptic, R the radial. direction and T in the direction of the earth.*

Coleman [1966b, 1967] examined the possibility that linear MHD waves are dominant. He concluded that typical spectra are probably due to fast hydromagnetic waves or a mixture of fast waves and Alfvén waves. He could not exclude either of these two possibilities. He did exclude the possibility that the spectra were due to pure Alfvén waves alone, because he always found a significant amount of power in | B |, amounting to nearly one-third or one-half that in the other components. The results of Siscoe et al. [1968] could be interpreted similarly.

Belcher and Davis [1971] imply that "nearly pure" nonlinear, aperiodic, Alfvénic waves dominate the power spectrum ≈ 30 percent of the time. By "nearly pure," Belcher and Davis mean that the power in | B | and n was judged to be much less than that in the components, but not necessarily zero. This seems to be the case in figure 24, for example. The observations of Belcher and Davis that there is a strong correlation between $V_r$ and $B_r$ and that the coherence indicates outward-going waves were also made by Coleman. In effect, Belcher and Davis have taken the further step of discussing the subset of spectra for which $P(B)/P(B_i)$ is very small. This process selects intervals where the ratio of Alfvén waves to compressive waves is large. Referring to figure 24 from Siscoe et al. [1968], this subset would occur at times of intermediate activity. This is consistent with remarks in Belcher and Davis [1971].

Coleman [1967, 1966b] assumed that the power in $B$ was due to some kind of wave. He inferred that fast waves were the principal contributors. A compressive wave implies a positive correlation between $n$ and $B$. Such a correlation was not examined by Coleman. However, Burlaga and Ogilvie [1970b] showed that changes in magnetic and thermal pressures tend to be anticorrelated on a scale of 0.01 AU. This is illustrated for a particular period in figure 25, which shows many
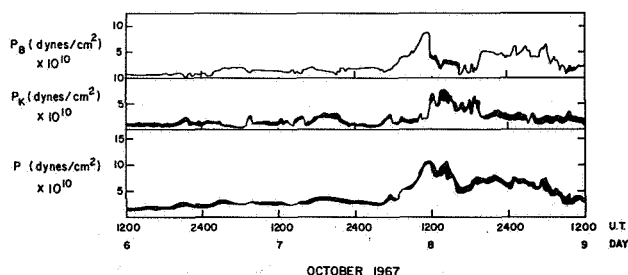


**Figure 25.** The magnetic pressure $P_B$ and thermal pressure $P_k$ tend to be anticorrelated on a scale of 0.01 AU, tending to keep the total pressure $P_T$ constant on the scale, even though $P_T$ changes on a larger scale. The anticorrelation suggests static features. These will contribute to the power spectrum of B.

changes in the magnetic pressure $P_B = B^2/(8\pi)$ accompanied by opposite changes in the thermal pressure $P_K \equiv nk(T + T_e)$. Thus, it is possible that much of the power in $B$ is due to convected structures (not necessarily discontinuities).

Sari and Ness [1969] showed that there are also times when the power levels in the components of $B$ are due primarily to discontinuities. This is shown in figure 26,
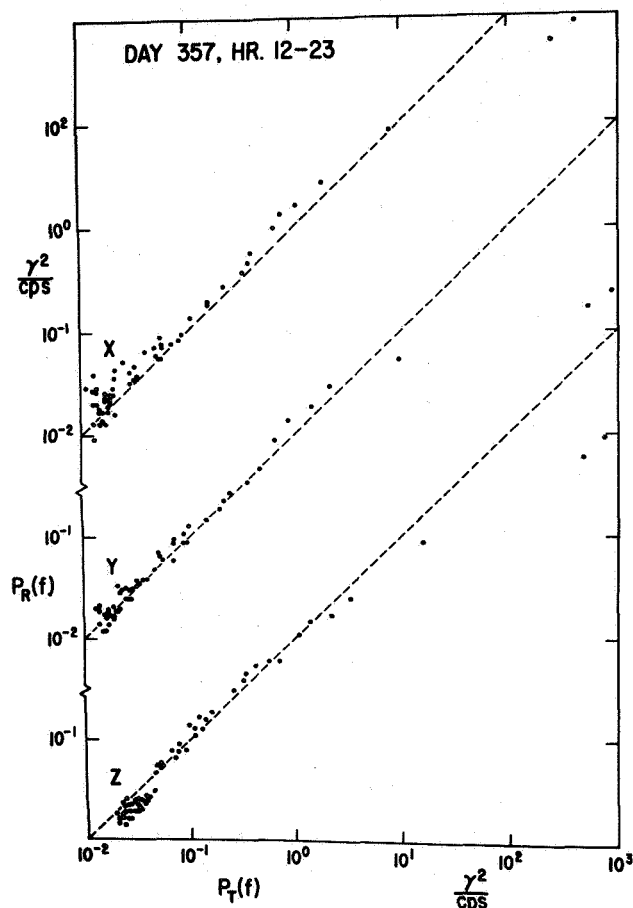


**Figure 26.** Discontinuities may dominate the power spectrum. The observed power $P_R$ equals the power $P_T$ computed from the observed discontinuities for the period indicated. Thus, the discontinuities alone can account for all of the power at this particular time.

which compares the observed power in the interval 1200–2400 UT on December 23, 1965, with the power computed from the discontinuities that were present. Clearly, the observed power can be accounted for by the discontinuities alone. The actual power spectrum for this time is shown in figure 27. The spectrum has the form $f^{-2}$, as predicted for a series of discontinuities. The power levels are rather low and geomagnetic

Figure 27. The observed power spectra for the period discussed in figure 26. The slopes are −2, as predicted for discontinuities.

spectrum. *Sari and Ness* [1970] themselves show that discontinuities are not always dominant. It seems to be agreed [*Belcher et al.,* 1970], that discontinuities can dominate the spectrum at times; the evidence is that given by *Sari and Ness* [1969].
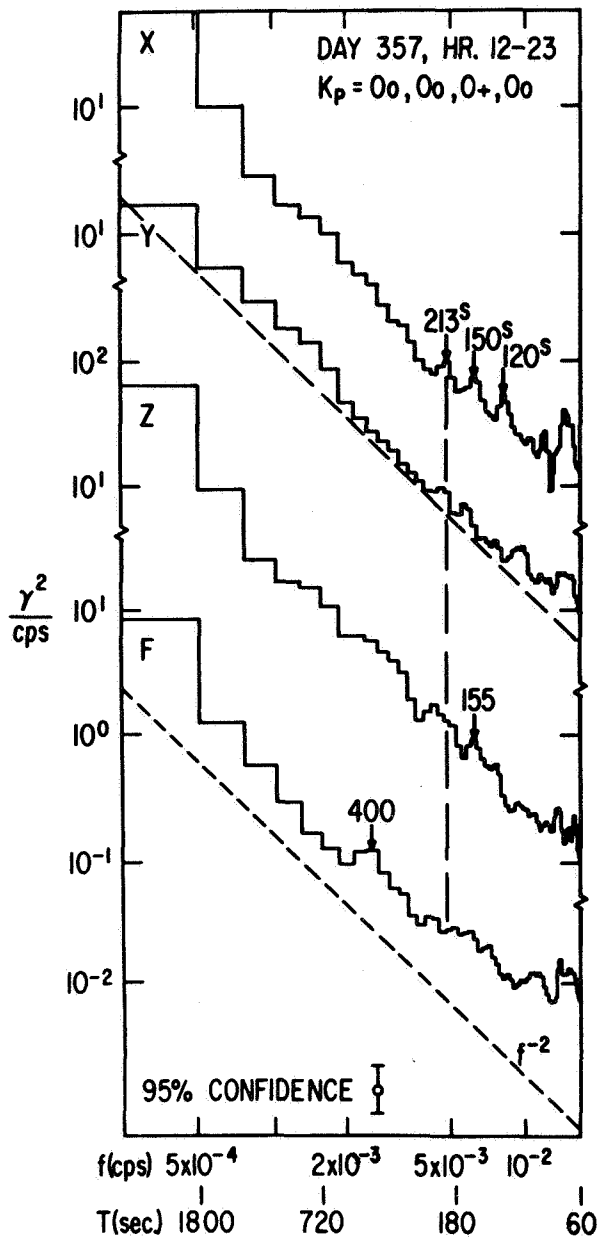
### Microscale Fluctuations of Burlaga et al. [1969]

The most important feature of these fluctuations is a strong correlation with the local value of $\beta \equiv 8\pi nkT_p/B^2$, as shown in figure 23. Very disturbed intervals are associated with high $\beta$, very quiet conditions with low $\beta$. The high $\beta$ were due primarily to high temperatures.

Microscale fluctuations such as those shown in figure 23 are not common features of the data; out of ~2500 hr examined, only 126 hr contained such fluctuations. Hour intervals with such fluctuations tend to be isolated. Less than 24 percent of such disturbed intervals occurred in pairs, and less than 20 percent in groups of more than 3-hr intervals.

*Belcher and Davis* [1971] challenged the result of *Burlaga et al.* [1969]. They assumed that the power in microscale fluctuations is measured by $\sigma_{S_1}$, the square root of the 3-hr average of the 168.75-sec total variances in the magnetic field *components*. They found a low correlation between $\sigma_{S_1}$ and $\beta$ (−0.12), and suggested that this implies a conflict with the results of *Burlaga et al.* [1969]; an alternative, and correct, inference is that $\sigma_{S_1}$ is not a good measure of the type of fluctuations studied by *Burlaga et al.*

*Burlaga et al.* [1969] inferred that microscale fluctuations are generated locally. *Belcher and Davis* [1971] suggested that microscale fluctuations are generated by nonlocal properties such as stream structure.

### Relation of Fluctuations to Bulk Speed of the Solar Wind

Many characteristics of the solar wind can best be organized and understood in reference to the bulk speed. Here we shall attempt to relate fluctuations and waves to the bulk speed. Unfortunately, little has been published on this as yet.

*Neugebauer and Snyder* [1966a,1967] and *Davis et al.* [1966] showed that the 3-hr variances of the magnetic field from Mariner 2 were sometimes appreciably larger than average at the leading edge of high speed streams— where the bulk speed increases. The interpretation is that the fluctuations are abnormally large there. As pointed out earlier, it is not clear what physical characteristics $\sigma$ really measures. Moreover, the magnitude of **B** also increases at positive bulk speed gradients,

activity, as indicated by *Kp*, was very low. The solar wind speed at that time was decreasing from 375 to 350 km/sec. *Siscoe et al.* [1968] also considered the possibility that discontinuities might dominate the spectrum, but found no evidence for it. *Belcher et al.* [1970] have challenged the results of *Sari and Ness* [1969]; see the reply by *Ness et al.* [1970]. Actually, they challenged a misinterpretation of the results in Sari and Ness, namely that discontinuities *always* dominate the power

so it is not clear that the relative level of activity $\sigma/B$ is unusually high there. As shown by Belcher and Davis [1971], there is a strong correlation between $\sigma$ and $B$.) Nevertheless, it is probably true that the power levels are unusually high in the interaction regions. Figure 28 from
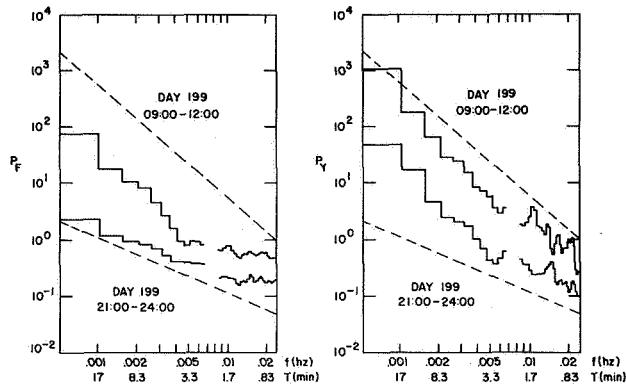


**Figure 28.** *Power inside and outside an interaction region. The left panel shows power in $|B|$, the power in the right panel shows power in one of the ecliptic plane components. The top histogram in each panel is the power in the interaction region.*

*Burlaga et al.* [1971] compares the power in the longitudinal and transverse fluctuation in an interaction region with that just outside the interaction region. The power is an order of magnitude higher in the interaction region. Belcher and Davis give some examples of the greater disturbances in **B** in interaction regions. They state that the largest Alfvénic fluctuations are found in interaction regions, but it is not clear how they identify Alfvén waves in an interaction region where $|\, B\, |$ fluctuates appreciably. In any case, no matter how one measures the fluctuations, it is generally true that the magnetic field is highly disturbed in the interaction regions, both compressive and transverse fluctuations being present.

Belcher and Davis [1971] state that there is no discernible pattern of association between the *presence* of aperiodic Alfvén waves and high speed streams or sectors; i.e., $\rho$ is not related to the large-scale structure of the solar wind. However, Belcher and Davis offer the interesting hypothesis that the largest amplitude "pure" aperiodic Alfvén waves are found in high speed streams and on their trailing edges. This might be due to an association of such waves with high temperatures, since $T$ is related to $V$ [*Neugebauer and Snyder*, 1966b; *Burlaga and Ogilvie*, 1970a].

The lowest wind speeds are probably relatively free of magnetic field fluctuations, although the evidence to

support this is rather meager. Belcher and Davis state that Alfvén waves in low speed regions have smaller amplitude and are "less pure" than elsewhere. The intervals of low fluctuation intensity in *Sari and Ness* [1970] were associated with low bulk speeds.

In summary, the relation between fluctuations and bulk speed is poorly understood, but published results suggest the following working model. There are large fluctuations in **B** at positive gradients, presumably representing inward and outward propagating transverse and compressive waves generated there. There are transverse waves in the high speed streams and on their trailing edges whose intensity is proportional to the proton temperature. They may be remnants of a wave-heating process near the sun [*Alfvén*, 1947; *Parker*, 1963; *Burlaga and Ogilvie*, 1970a; *Hartle and Barnes*, 1970; *Belcher and Davis*, 1971; *Barnes et al.*, 1971]. Between streams, where the solar wind is in its base state in which there is presumably little or no wave heating beyond $2\, R_\Theta$ [*Burlaga and Ogilvie*, 1970a; *Barnes et al.*, 1971], wave-like fluctuations in **B** but not discontinuities might be essentially absent. Again, this is a tentative working model, and further work is needed to substantiate it (fig. 29). *Hundhausen* [1970] discusses some of the problems with the Hartle-Barnes model.
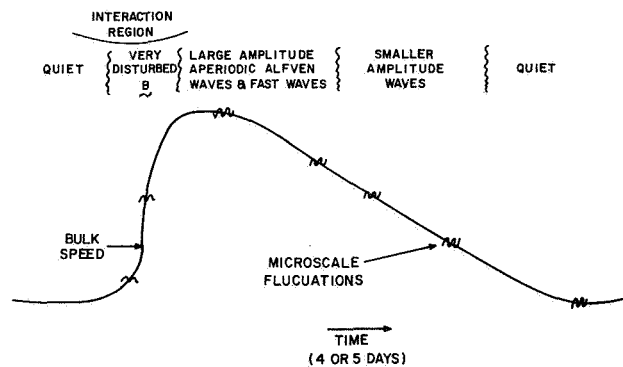


**Figure 29.** *Hypothetical model of relations between the waves and fluctuations and the bulk speed.*

**Variation with Distance from the Sun**
The only report of changes in the characteristics of fluctuations (as measured by power spectra) with distance from the sun is that of *Coleman et al.* [1969] based on Mariner 4 measurements over the distance 1 to 1.43 AU made in the period November 28, 1964, to July 14, 1965. The basic result is shown in figure 30, which gives the ratio of the power at 1.43 AU, $[P_i(A)]_2$, to that at 1.00 AU, $[P_i(A)]_1$, as measured by $k$, where $[P_i(A)]_2/[P_i(A)]_1 = (1.43)^{-2k}$. The positive $k$ imply a

decrease of power with increasing distance from the sun. The decrease is seen in all components and at all frequencies in the range $\approx 10^{-6}$ to $\approx 10^{-2}$ Hz. The power in the magnetic field intensity decreases appreciably less rapidly than the power in the components. Thus, the ratio of power in the compressive fluctuations to that in the transverse fluctuations increases with distance from the sun. In other words, the compressive mode tends to become dominant and the Alfvén mode less significant as one moves away from the sun and earth. This assumes that the observed variations are not temporal changes.

*Coleman et al.* [1969] report that the average field intensity decreases as $(r/r_0)^{-1.25}$ This decrease is more rapid than that of the square root of the power. Thus, the magnetic field becomes increasingly disturbed and disordered as one moves from 1.0 to 1.4 AU. This result tends to support models of cosmic ray propagation that postulate a diffusing shell near the earth and beyond [*Lüst and Simpson*, 1957; *Burlaga*, 1969].

Figure 30 shows that the power in the fluctuations in $B_\theta$, normal to the ecliptic plane, decreases more rapidly than that in the ecliptic plane components $B_r$ and $B_\phi$.

If the compressional oscillations studied by *Coleman et al.* [1969] are related to $\beta$ as the microscale fluctuations studied by *Burlaga et al.* [1969], then one
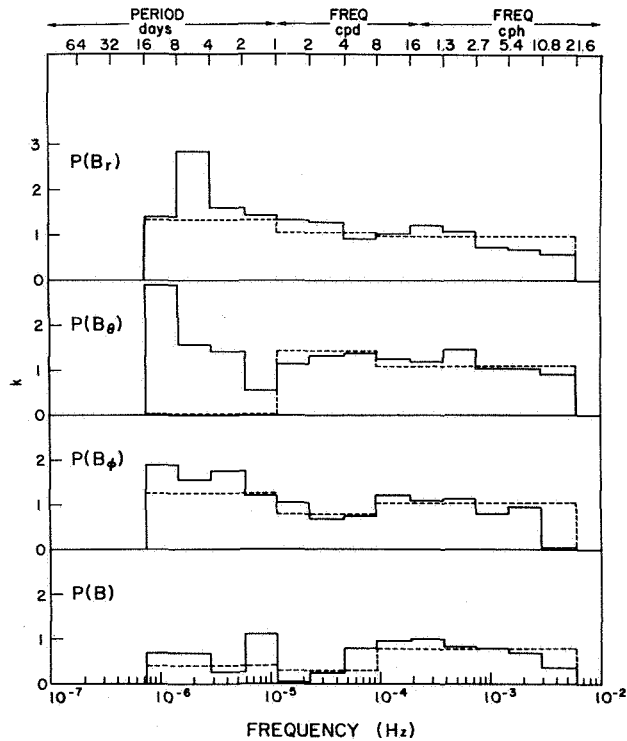


**Figure 30.** *Ratio of the power densities at 1.4 and 1 AU, as parameterized by k (see text).*

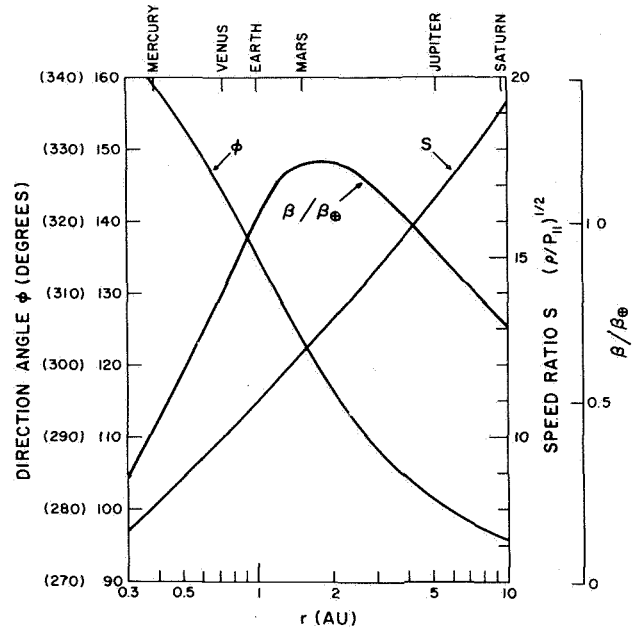would expect the power in these fluctuations to be maximum just beyond the orbit of Mars (fig. 31). The



**Figure 31.** *Variation of $\beta$ with distance from the sun, relative to $\beta$ at earth. The spiral angle and $(\rho/P_{\parallel})^{1/2}$ are also shown. The results are based on Whang's model of the solar wind.*

figure indicates the corresponding shell should extend somewhat farther outward from Mars than inward toward the earth, unless other effects associated with the spiral angle $\phi$ or sound speed ratio $S$ become important. This hypothesis also implies a decrease in the power in compressional oscillations as one moves from earth to Venus (a point that could be tested with existing data), and it implies that this power would be very small at the orbit of Mercury and closer to the sun (a point that will be tested in 1973 and 1974 when the MVM and Helios spacecraft are launched.)

## SUMMARY

There are numerous tangential discontinuities in the solar wind, more or less evenly distributed between 0.8 and 1.0 AU. The discontinuity surfaces are separated by $\approx 0.01$ AU and are probably appreciably bent and curved on that scale. They tend to be alined along the spiral direction, but the orientation changes from one surface to the next. There is generally no obvious pairing, so it is more appropriate to say that the solar wind is discontinuous than to say that it is filamentary. Filamentary forms do sometimes occur, however. Most discontinuities are characterized by changes in the magnetic field

direction with little or no change in the magnitude. When the magnitude does change, there is usually a corresponding opposite change in the plasma density. Rotational discontinuities may occur at the rate of ≈1/day, corresponding to separations ≈0.25 AU. *Belcher and Davis* [1971] and *Smith et al.* [1970] suggested that rotational discontinuities occur at the rate of 1/hr but they gave no evidence for this. The observations discussed by *Burlaga* [1970a] and by *Siscoe et al.* [1968] suggest that tangential discontinuities are present every day. The failure of *Belcher and Davis* [1971] to observe tangential discontinuities is probably due to the fact that they used 5-min averages (or longer), which would tend to obscure any microstructural discontinuities that were present.

Sinusoidal waves are very seldom seen in the solar wind, but random fluctuations seem to be the rule. These fluctuations are best described by power spectra when there is little damping of them. The principal contributors to the power are probably (1) Alfvén waves, (2) fast waves, (3) static structures in which $B$ and $n$ are anticorrelated, and (4) discontinuities. Discontinuities dominate the power spectra occasionally in the range ≈5 × $10^{-4}$ to ≈$10^{-2}$ Hz, but probably they usually make only a small contribution. Usually the power in $B$ is only a fraction ($\lesssim 0.3$) of that in the components, and fluctuations in $\underset{\sim}{V}$ are often correlated with the fluctuations in B. This has led *Belcher and Davis* [1971] to imply that Alfvén waves are the principal contributors to the typical power spectrum. Coleman has pointed out that pure Alfvén waves are never present for periods of 12 hr or more, since there is always appreciable power in $B$, and he suggested that the compressive fluctuations are due to fast waves. The relative contribution of fast waves and static structures to the power in $B$ remains to be determined, however.

Little is known about the relation of discontinuities and fluctuations to the large-scale structure. There is evidence that discontinuities show a sector-dependent north-south asymmetry, and they are not associated with positive bulk speed gradients. It has been suggested that fluctuations can be related to the bulk speed, having the largest amplitudes when the speed is high and decreasing amplitudes with decreasing speeds. This hypothesis fits in nicely with the idea that the fluctuations originate in the region close to the sun which heats and accelerates the solar wind. But a comprehensive study of the relation between power levels or wave amplitudes and bulk speed has not yet been made. There appears to be more than average power in both transverse and compressional oscillations at positive bulk speed gradients, presumably due to the collision of a high speed stream with slower plasma, but the fluctuations generated in this way do not propagate away from the interaction region.

There are also isolated "patches" of enhanced, high frequency transverse and compressional fluctuations, which are correlated with $\beta$, some of which might be due to local instabilities.

Very little is known about the radial dependence of discontinuities and fluctuations. No significant radial dependence of discontinuities has been observed between 0.8 and 1.0 AU. A relative increase of compressional fluctuations from 1.0 to 1.4 AU has been suggested, and might be related to an increase with $\beta$. Basically, however, the question of radial dependence will not be answered until observations from deep space probes are available.

We now know more or less how to interpret B($t$) in terms of hydromagnetic structures. The next step will be to analyze discontinuities and power spectra for extended periods of time, to relate these results to the larger scale structures of the solar wind, and to identify the origin of these structures.

## ACKNOWLEDGMENTS

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*J. R. Jokipii* Would you care to estimate the relative contributions to the power spectrum, say at periods of about 10 min, of the tangential discontinuities and the rotational or wave type?   DISCUSSION

*L. F. Burlaga* We will have to look at the data to find out.

*C. P. Sonett* I was under the assumption that Alfvén waves are linear, no matter what their amplitude. Am I correct?

*L. F. Burlaga* I see heads nodding yes, and heads shaking no. I think that shows the problem. What are we going to call an Alfvén wave? Perhaps Professor Davis can give us his opinion.

*L. Davis* I will give my own personal definition of an Alfvén wave. I start with perhaps the oldest definition, which implies an incompressible fluid in which the wave amplitude is not important and Alfvén waves of very high amplitude are possible. Historically, I think the Alfvén wave in a plasma came next. This is usually derived by a linearized treatment, and the restriction to small amplitude is probably important. However, the Alfvén disturbance does not produce any compression of the plasma and you can't tell from the behavior of the fluid whether or not it is compressible. There is a second-order change in field strength which changes the total pressure; if the medium is compressible, large-amplitude Alfvén waves will be modified. The observations in space reveal waves which have the characteristics of Alfvén waves in their correlation between velocity and magnetic field fluctuations, but they are large amplitude and the plasma in space is not incompressible. I would still like to characterize them as Alfvén waves, using an extended definition of the term, although I agree that we have to explore the problem mathematically much more than we have.

Turning now to a question of my own, there seems to be considerable confusion as to the dividing line between microscale and mesoscale structures. Is a feature with a length of approximately 0.01 AU that takes a half hour to go by microscale or mesoscale? In the discussion we just heard there was some indication that the 1 hr referred to the length of the plot that was used, not to the length of the feature, and that the feature had to be significantly shorter than an hour. This is a matter that the people who invent these definitions should make clear to those who want to use them.

*L. F. Burlaga* Let us agree to use the term *microscale* to refer to features with a scale length of $\approx$0.01 AU or less, and fluctuations with Doppler-shifted periods $\lesssim$1 hr. *Mesoscale* features are from 1 to $\sim$ 100 hr.

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*M. Dryer* I recall a definition of rotational discontinuities, given by Landau, in which the Alfvénic Mach number normal to the discontinuity is equal to 1 on both sides of the discontinuity. If no component of the field gives unity Alfvén Mach number normal to the discontinuity, then the discontinuity is a *tangential* or *contact* discontinuity.

*L. F. Burlaga* I know that's a necessary condition for an isotropic medium. I don't know if it's sufficient to define a rotational discontinuity.

*M. Dryer* I guess what I'm trying to advocate is the use of some of these fundamental descriptions as given in the classical literature.

*L. F. Burlaga* The trouble is, Murray, that the data are not mathematically precise. We might have, say, a nonzero normal component that is less than the experimental uncertainties. In this case we can't distinguish between a rotational and tangential discontinuity. That's why we used directional discontinuities and other simple discontinuities which showed relatively large changes. I think the accuracy of the data is sufficient that we can test the necessary conditions in such cases.

*M. Dryer* In your first figure there's a small perturbation. Is that a rotational discontinuity?

*L. F. Burlaga* If there is a component of $B$ normal to the discontinuity surface, then it is probably a rotational discontinuity. The rotational part is then the projection of **B** in the plane of the discontinuity surface. If it's a tangential discontinuity, there is no component of **B** normal to the surface or the current sheet.

*L. Davis* Is it strictly a question of whether there's a normal component?

*L. F. Burlaga* No, that's just one necessary condition. There are others. The condition that I was referring to in figure 5, the histogram, is the necessary condition that relates the change in velocity to the change in the field. Essentially, it is the type of condition that you see for an Alfvén wave: $\Delta$**V** is proportional to $\Delta$**B**. The proportionality constant involves the Alfvén speed. That is a necessary condition for a rotational discontinuity. What I showed is that that condition is not generally satisfied for the directional discontinuities, therefore they are not rotational.

*L. Davis* I think part of our confusion arises because the term *rotational discontinuity* is used in a variety of ways and some of us are trying to find out how you are using it.

*L. F. Burlaga* I'm using it the way Landau and Lifshitz used it.

*C. P. Sonett* If these waves are nonlinear, then I would assume that they must steepen with time and ultimately become shocks, infinitesimal or finite shocks, depending on the particular situation. I suppose this depends also on their lifetime.

*L. F. Burlaga* I don't know if they necessarily do steepen. It's been argued that Alfvén waves don't steepen into shocks, and I think that's just one of the questions one must answer by a nonlinear treatment.

*D. S. Intriligator* In reference to your illustration of the power spectra for the different components of the magnetic field, a similar analysis for the velocity of the plasma shows no comparable effect as a function of whether the intervals are quiet or disturbed. We find that, in general, the level of power and the slope is the same for each component of the velocity, $V_r$, $V_\theta$, and $V_\phi$.

*L. F. Burlaga* That would imply, then, that they are not Alfvén waves? Do you agree?

*D. S. Intriligator* We haven't yet looked at the simultaneous power spectra for the magnetic field.

*P. A. Sturrock* Have any structures been detected similar to the "solitary waves" discussed by Adlam and Allen, *Phil. Mag.* 3, 448, (1958) and others?

*F. L. Scarf* I think there are certain structures seen near the bow shock that look very much like these solitary pulses that they discussed. I would, however, like to defer this discussion. Our program includes many more talks on Alfvén waves and other low-frequency turbulence in the solar wind, so we will all have an opportunity to continue with the questions and comments later.