

## THE INTERPLANETARY MAGNETIC FIELD *Leverett Davis, Jr.* An invited review

This paper examines the large-scale properties of the interplanetary magnetic field as determined by the solar wind velocity structure. The various ways in which magnetic fields affect phenomena in the solar wind are summarized. The dominant role of high and low velocity solar wind streams that persist, with fluctuations and evolution, for weeks or months is emphasized. High velocity streams are almost invariably identified with a single magnetic polarity, and most patterns of large scale, regularly recurring phenomena in interplanetary space are best organized by relating them to the high velocity streams. It is suggested that for most purposes the sector structure is better identified with the stream structure than with the magnetic polarity and that the polarity does not necessarily change from one velocity sector to the next. Several mechanisms that might produce the stream structure are considered. The interaction of the high and low velocity streams is analyzed in a model that is steady state when viewed in a frame that corotates with the sun. A number of observed features are well explained, but typically the regions of high plasma density appear to occur too soon. Long-term average deviations from the expected spiral structure have been reported. Those in the azimuthal direction should be explainable in terms of the mechanisms that transport angular momentum in the interplanetary medium. The meridional deviations identified by *Ness and Wilcox* [1964] and *Coleman and Rosenberg* [1970] raise serious difficulties that seem to require that we either modify the usual theoretical treatments significantly or question the data.

### ABSTRACT

### INTRODUCTION

The source of the interplanetary magnetic field is the solar magnetic field, in particular the photospheric field that is swept out by the solar wind. In the absence of the solar wind, the interplanetary magnetic field near 1 AU from the sun would be weaker by several orders of magnitude and would have a completely different configuration. Thus the field we observe owes its existence to the solar wind. Nonetheless, the interplanetary magnetic field plays a significant role in many of the phenomena associated with the solar wind. Therefore, let us first review briefly some of the situations in which the magnetic field is important.

1. The magnetic field organizes the plasma into a fluid in regions where collisions become unimportant, roughly beyond  $10 R_{\odot}$ . Thus, solar wind streams of different velocities cannot interpenetrate.
2. At distances larger than about  $20 R_{\odot}$  from the sun, the radial bulk velocity is greater than the Alfvén velocity and hence the energy density in bulk motion is greater than the magnetic field energy density. Thus signals cannot be propagated upwind toward the sun and the field structure near the sun is not affected directly by anything that happens farther out. The flow pattern determines the magnetic field structure and field lines near 1 AU are like paper streamers in a gale that mark the flow lines but do not determine them. Similarly, in and below the

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photosphere the energy density in bulk motion is usually greater than the magnetic field energy density, although here the determining factor is the independent photospheric velocity patterns, rather than the velocity with which the gas is rising up to supply the solar wind. Thus (except in sunspots) the magnetic field patterns observed in the photosphere may be regarded as produced by fluid motions that convect frozen-in field in response to mainly non-magnetic forces. But in the corona out to about  $20 R_{\odot}$  the magnetic field dominates the flow. Alfvén waves carry signals both inward and outward. The magnetic field pattern tends to require a rough balance of magnetic stresses (i.e., a force-free field), and the fluid flow tends to follow the magnetic field lines. Even in this region the plasma can have a significant indirect effect. Suppose small local pressure gradients stretch out an arched structure to the point where it is swept outward into a bipolar radial pattern leading out to the normal spiral pattern at large distances. This pattern will then be maintained right through the region where the magnetic field dominates because the upper and lower ends of the field lines are anchored in regions where the plasma dominates, and in the intermediate region the only effective magnetic forces merely compress the plasma in the interface between the field lines running in opposite directions. Thus a reliable calculation of the magnetic field at a distance  $1/2 R_{\odot}$  above the surface requires as boundary conditions a knowledge not only of the radial component of the field at the photosphere but also of which tubes of force extend to infinity and which return to the photosphere.

3. The magnetic field makes Alfvénic and magneto-acoustic waves possible. The energy in these waves is mainly convected, but to a smaller extent it is propagated. It can be converted to other forms of energy. Ways in which this wave energy and momentum can significantly affect the motion and other properties of the solar wind are discussed in chapter 5, p. 309).
4. The magnetic field profoundly influences the thermal conductivity and hence the energy flow in the solar wind.
5. The magnetic stresses are essentially as important as bulk motion in any discussion of the angular momentum transport of the solar wind.
6. Any anisotropy of the thermal gas or of the cosmic ray gas will have a high degree of axial symmetry about the direction of the local  $\mathbf{B}$ .
7. The irregular magnetic field, nonstatic in a frame

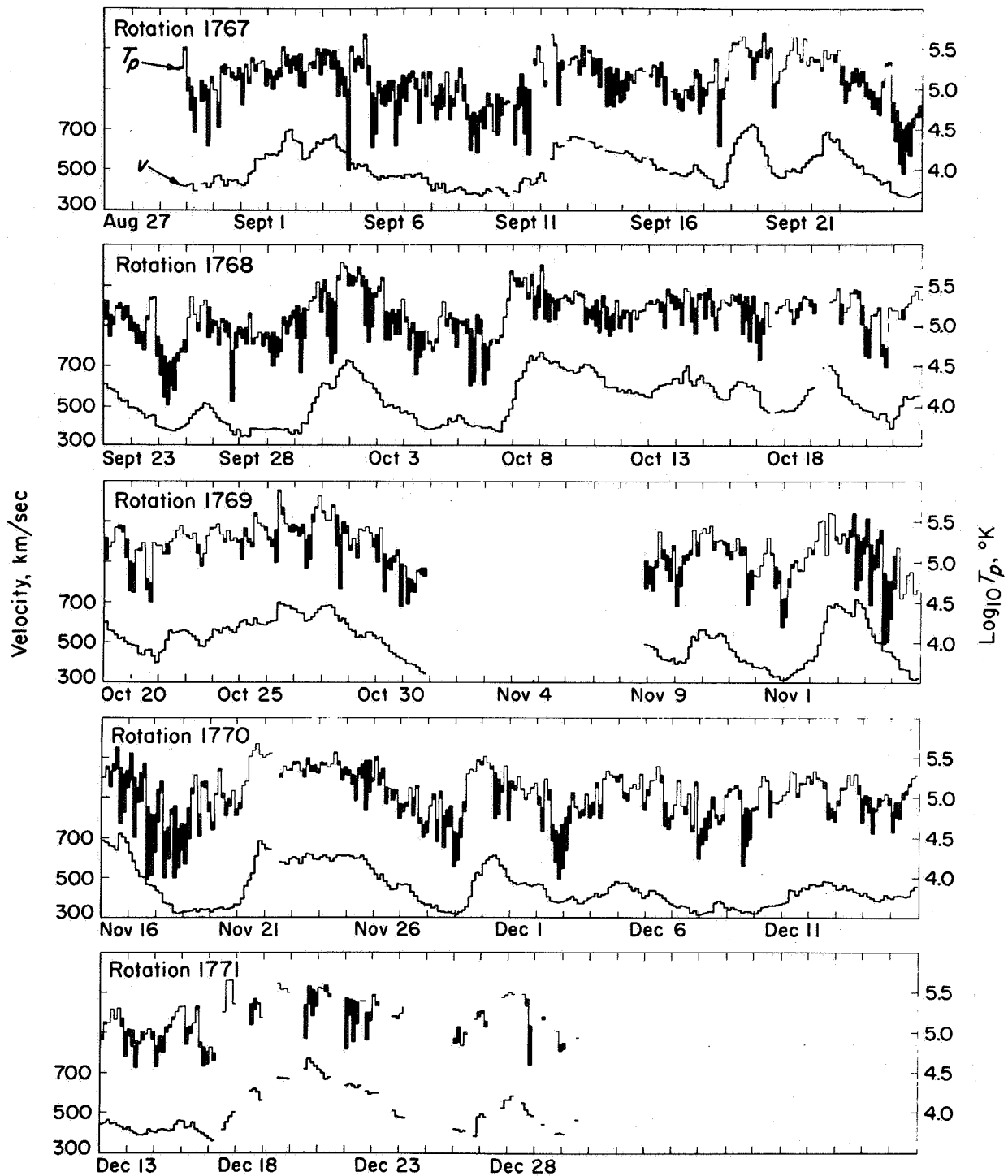
moving with the wind, is embedded in outwardly flowing plasma and partially screens galactic cosmic rays from the inner solar system. This can be described in terms of cosmic ray diffusion and energy change, processes that are important for both galactic and solar cosmic rays.

8. The interplanetary magnetic field is more easily observed than most other properties of the solar wind and provides valuable clues to other phenomena of interest.

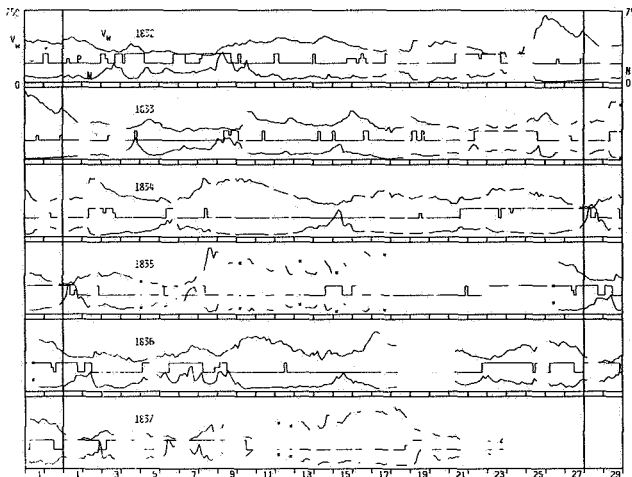
### HIGH VELOCITY WIND STREAMS

For the purposes of this conference, the most important feature of the interplanetary region, at least between the orbit of Mercury and the asteroid belt, is the alternation between high and low velocity solar wind streams. Almost all other features except the basic average spiral pattern seem best organized by reference to the wind streams, and most are either dominated by or are greatly modified by the wind structure. The kinetic energy density in the solar wind is the largest energy density in interplanetary space, and the energy available from fluctuations in velocity is considerably larger than any other energy density.

Let us consider the evidence for the existence and nature of the solar wind streams. The Mariner 2 data on wind velocity in 1962 as observed by *Neugebauer and Snyder [1966a]* were presented at the first Solar Wind Conference in 1964. Mariner 2 was the first spacecraft to make such measurements completely removed from the influence of the magnetosphere, and it was clear at once that during the part of the solar cycle when these observations were made high velocity streams tended to recur at approximately the solar rotation period (figure 1). Hence it was argued persuasively that many such streams flow continuously, each from its own source on the sun, for periods of several months. The obvious changes in character of a stream from one appearance at a spacecraft to the next made it clear from the beginning that they were fluctuating and presumably evolving features. Half a solar cycle later, the Mariner 5 plasma data of *Lazarus and Bridge* shown in figure 2 reveal a somewhat different situation. In any single solar rotation the alternation between high and low velocity regimes is very similar to that observed 5 years earlier, but it is much more difficult to find any features that clearly repeat for several rotations. The streams clearly last a few days and presumably longer, perhaps a few weeks, but the whole stream pattern evolves substantially in a month or less.



**Figure 1.** Three-hour average values of plasma velocity (lower curve) and proton temperature (upper curve, logarithmic scale) versus time from the Mariner 2 data for September through December 1962. Features on the same vertical line in the different panels are separated by multiples of 27 days [Neugebauer and Snyder, 1966b].



**Figure 2.** Three-hour averages of Mariner 5 data on plasma velocity,  $V_w$  (upper curve), proton number density,  $N$  (lower curve), and magnetic polarity,  $P$  (middle curve), where the upper level corresponds to positive (outward) polarity, the lower level to negative (inward) polarity, and the intermediate level to intervals when the polarity is not well defined. Each panel shows the data for one solar rotation plus two days overlap at each end. The abscissas are day number of the solar rotation; the time covered is June 15 through November 21, 1967 (solar rotations 1832–1837).

Summarizing these and other observations, one concludes that high velocity streams often persist for several months but also often change substantially from one solar rotation to the next. The low velocity is almost always somewhere near 300 km/sec while the high velocities typically range from 450 to 750 km/sec if we characterize them by 3-hr averages to suppress shorter period fluctuations. Because the low velocity regions seem more uniform in velocity than the high, and because any changes in the magnetic polarity usually occur in low velocity regions, we can think of the sun as having a more or less uniform low velocity steady state on which are superposed a number of high velocity streams. But it could well be the other way around, or the velocity distribution could just be irregular with no background and no isolated streams.

Our direct observations give information only on the streams coming from equatorial regions on the sun. Observations of comet tails demonstrates that the solar wind extends to high latitudes with apparently much the same properties as at low. Since it typically takes a particular velocity regime from 1 to 4 days to sweep past a spacecraft, we must think of streams as extending from  $15^\circ$  to  $60^\circ$  or more in solar longitude. We have no good

idea of how far they extend in solar latitude; the differential rotation of the sun might lead to the conjecture that the width in this direction is somewhat less, at least for long-lasting streams.

Let us now consider the relation of magnetic fields to these solar wind streams. The basic pattern of these fields in interplanetary space is the well-known spiral on which irregular fluctuations are superposed. The polarity of the field is said to be positive when the vector field is, on the average, directed outward along the spiral and to be negative when the field direction is inward. The polarity can fluctuate back and forth in a few hours but typically it stays the same for extended periods, for periods of four days, a week, or even two weeks (fig. 2). As demonstrated so beautifully by *Wilcox and Ness* [1965], this polarity of the interplanetary magnetic field correlates well with the observed polarity of the average radial field in the photosphere and hence shows that the spiral structure extends into the photosphere. From the observations near 1 AU or from the photospheric observations, we conclude that the polarity in the photosphere is patchy but that the regions of one polarity tend to be larger than individual high velocity streams. It was pointed out at the first Solar Wind Conference that at least one such stream always had the same polarity, and subsequent observations have confirmed that changes in polarity usually occur *between* high velocity streams and only rarely, if ever, in them.

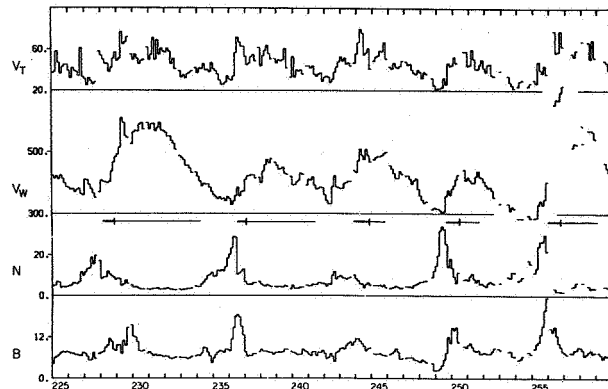
Thus a model that seems very attractive is one in which there is an irregular distribution of high velocity streams over the surface of the sun, each stream situated in a larger region of one dominant polarity from the outer parts of which come low velocity solar wind. The polarity changes in an irregular way from one high velocity stream to the next, sometimes alternating, as in the IMP 1 data [*Wilcox and Ness*, 1965], and sometimes not, as in the Mariner 5 data shown in figure 2. Perhaps the polarities of the streams are distributed at random. It makes little difference to most phenomena whether or not the polarity changes between streams. The only obvious effect is on the nature of the presumably thin interface layer, which will consist of a current sheet when the polarity reverses and be very inconspicuous when it does not. Until we know more about non-equatorial regions, the assumption that the high velocity streams have the same distribution at high latitudes as at low is as plausible as any other. However, the magnetic polarity of polar streams seems unlikely to be as random as that of equatorial streams.

Like the origin of the solar wind, the origin of the stream structure will be found in conditions near the

surface of the sun. One suggestion is that the magnetic field patterns in the corona may act like nozzles of different degrees of divergence that produce streams of different characters. One can consider either an exaggerated or a mild form of this model. In the exaggerated form, all the wind might come from a small fraction of the surface area with small nozzles directed along the axes of the high velocity streams and the low velocity flow between them originating from the fringing field of the central part of the nozzle. This model has never seemed attractive since it does not easily explain the observed tendency for low velocity streams to have high densities and low proton temperatures. Also it is inconsistent with the observed relations between interplanetary and photospheric fields. In the mild version of the nozzle hypothesis there would be only a small variation in the ratio of the cross-sectional area of a tube of force at 1 AU to that at the photosphere. As Parker pointed out, this would introduce an extra degree of freedom into his equations for the solar wind, and would give a greater variety of solutions, facilitating the fit to the great variety of observations. In particular, it would make it easier to explain why high velocity regions do not have the highest densities as in simple models.

Alternatively, since the material in high velocity streams has greater kinetic energy and higher temperatures, one can argue that these streams arise where the energy supply to the corona is greater than normal. The source of coronal energy is believed to be waves that transmit mechanical energy from the photosphere to the corona, where dissipation converts the ordered motion into thermal motion. If the waves are stronger over active regions, then such regions should be the ultimate source of the high velocity wind streams. In considering which coronal regions get the maximum net energy supply, one must allow for the redistribution of energy by thermal conductivity. This is strongly modified by the magnetic field, whose structure will therefore modify the possible correlation between active regions and sources of the solar wind.

Recently, *Belcher* [1971] has demonstrated that high velocity wind streams near 1 AU are usually associated with Alfvén waves propagating outward from the sun. This association is evident in the Mariner 5 plasma and magnetometer data of figure 3, which shows the main features of 5 high velocity wind streams occurring in a 35-day period in 1967. Note from the bars between the  $N$  and  $V_w$  curves that each stream is associated with an enhancement of Alfvénic wave activity. It is possible that these waves are generated in the high velocity streams far from the sun, but then, as *Belcher* has pointed out, they should propagate both inward and



**Figure 3.** Mariner 5 data for 35 days plotted using 3-hr averages and showing the large scale stream structure of the solar wind.  $B$  is the magnetic field strength in gamma,  $N$  is the proton number density in  $\text{cm}^{-3}$ ,  $V_w$  is the proton bulk radial velocity, and  $V_T$  is the most probable proton thermal speed, both in km/sec. The horizontal bars between the  $N$  and  $V_w$  curves show the times when Alfvén waves were prominent, the heavier bars to the left of the short vertical strokes identifying periods of the highest amplitude waves [*Belcher, 1971*].

outward. Since the outward component is all that has been identified, he concludes that they are the remnants of waves that were present in the lower corona. He suggests that they may be the Alfvénic component of the waves that heat the corona and that it is to be expected that such remnants would preferentially be found in gas coming from the coronal regions receiving the greatest energy supply—i.e., the bases of the high velocity wind streams.

### SECTOR STRUCTURE

It is of interest to note how all the data in figure 3—the magnetic field strength, the plasma density, and the proton temperature—may be organized by correlation with the high velocity solar wind streams. This emphasis on the wind streams as the key to the organization of the data is very natural since they must provide the basis for the physical understanding of the phenomena shown. Historically this organization was first discovered and expressed as a correlation with the polarity of the magnetic field. After the initial work of *Neugebauer and Snyder* [1966a,b], the development of these ideas was dominated for several years by the beautiful work of *Wilcox and Ness* [1965] and their collaborators on the sector structure. They showed the connection between the magnetic fields observed in space and those observed in the photosphere. They showed how a great variety of phenomena could be organized on the basis of the sector

structure. They showed how, at times, the sector structure persisted for a number of solar rotations and how, at other times, as also emphasized by Coleman and his collaborators, there was substantial evolution of the polarity patterns from one solar rotation to the next. Much of this was discussed in the preceding paper.

Sectors were originally identified [Ness and Wilcox, 1964] by the polarity of the magnetic field. At that time, each sector contained one high velocity solar wind stream, i.e., the polarity changed from each stream to the next. A good deal of the time, perhaps the majority of the time, this is not the case. It seems clear that the basic physical structure is the high velocity wind stream, not the magnetic polarity. It is thus natural to question whether we should continue to identify a sector as a region of uniform magnetic polarity or as a region containing a single high velocity stream plus the appropriate surrounding low velocity boundary region. Identification by polarity is more useful if one's main interest is the correlation of interplanetary and photospheric fields or if it is the current layers and, perhaps, neutral sheets that separate regions of different polarity. For most other purposes, identification in terms of the velocity structure seems more useful. If it is decided not to use the term *sector* with this modified sense, and a term similar to *polarity region* for the original sense, then new terms should be devised. Perhaps *velocity sector* and *magnetic sector* would be appropriate. In any case, it seems safe to predict that the term identifying the high velocity streams will be more basic than that identifying magnetic polarity.

### COROTATING STREAM STRUCTURES

Now consider the interaction of these streams emitted with different velocities from different regions of the sun. Assume a steady state in which there are no changes with time. If the sun did not rotate, each stream would flow purely radially in a cone and, except for the shear between adjacent streams and possible pressure inequalities, there would be no interaction. But the sun does rotate and a nonrotating, slender radial cone that at one time starts from a low velocity source will, at a later time, be fed from a high velocity source. As time goes on, the high velocity plasma will overtake the slow, compressing the adjacent parts of both. Even if the sources on the sun do not vary with time, the flow pattern in an inertial coordinate system will. The velocity will be nearly radial everywhere, and the field lines will spiral.

It is instructive to consider all of this in a reference frame that corotates with the sun. In this frame, nothing appears to change with time, the velocity is truly steady state but nonradial. The stream lines coincide with the

magnetic field lines, which have the same spiral pattern as the inertial frame. Near the sun, all spirals are nearly radial; but far out the spirals of slow streams become flatter than those of fast streams. If there were no modification of the spiral patterns they would intersect. Since this is impossible, there is an interaction region where both spirals are deflected (fig. 4). The flow is still

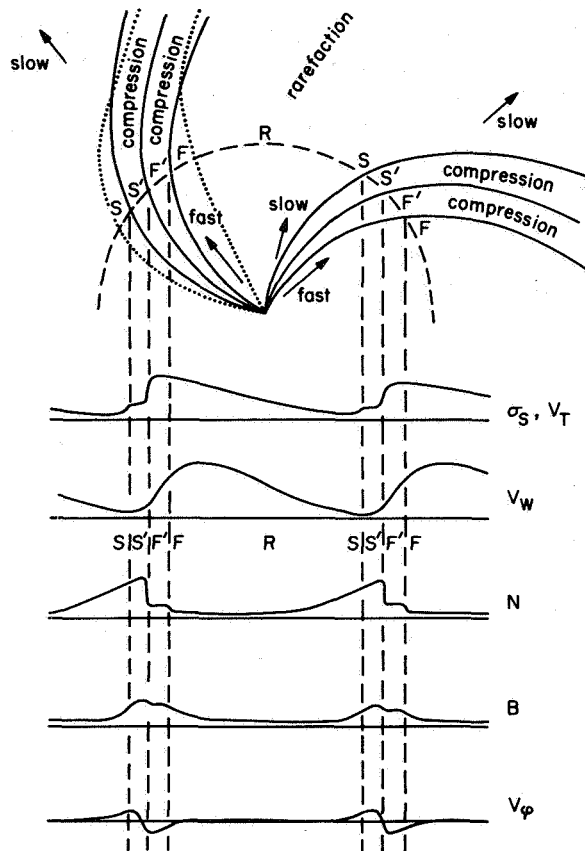


Figure 4. Top: two compression regions and one rarefaction region produced by the interaction of high and low velocity wind streams. Arrows indicate wind velocities in an inertial coordinate system; solid lines bound the various regions; dotted lines are field and stream lines in a system that corotates with the sun and in which the patterns shown are stationary. The circular dashed line at approximately 1 AU is the trajectory of an observing spacecraft in this corotating frame. Bottom: typical schematic curves showing, as functions of time, the changes in solar wind parameters as observed by the spacecraft.  $V_\phi$  and  $V_W$  are azimuthal and radial solar wind velocity components, respectively.  $B$  is the magnetic field strength,  $N$  the proton density,  $V_T$  the most probable proton thermal speed, and  $\sigma_S$  the square root of the sum of the variances over 5.04 min of the three orthogonal components of the field [Belcher, 1971].

steady state out along the magnetic tubes of force but as the gas passes a point where a tube is deflected, the gas is compressed and its velocity changes, becoming slightly nonradial. This happens both to the gas in the slow stream as it passes from region  $S$  to region  $S'$  in figure 4 and to the gas in the fast stream as it goes from  $F$  to  $F'$ . The farther out one goes from the sun, the larger is the fraction of the gas, and of the field lines, that have entered the interaction or compression region. Alfvén waves propagating outward from the sun will follow the field lines and go from  $S$  to  $S'$  as well as from  $F$  to  $F'$ , just as the gas does. Any waves generated at the interface will be swept into the compressed region by the superalfvénic flow (superalfvénic in the tangential if not in the normal direction) whether the direction of propagation is inward or outward along the field lines.

In constructing such a model [Dessler and Fejer, 1963] or drawing a figure, it is natural to introduce surfaces of discontinuity where the stream lines are deflected and at the interface between the fast and slow gas. The former should be shocks and the latter a contact surface through which neither plasma nor field lines penetrate and which has different tangential velocities on the two sides. However, such shocks are rarely, if ever, observed; instead, the transitions are gradual. In a way, this is not surprising since the transitions from low to high velocity on the sun must be gradual. It is not clear whether the velocity gradients are sufficiently small that they would not be expected to evolve into shocks by the time they reach 1 AU or whether various dissipative processes must be invoked to prevent the generation of a discontinuity. Even though the shock is replaced by a gradual but still short-scale transition, the integrations of the equations that yield the usual jump conditions across a shock should yield similar jump conditions across the transition region, and moderately large scale phenomena should be essentially the same as though there were a shock.

In the regions such as  $R$  of figure 4 where fast wind is radially outside slow wind, a gap would tend to form between the simple spirals. Actually, the magnetic and thermal pressures normal to the tubes of force cause them to expand and fill the region. Since the flow tubes will thus have larger than normal cross sections, the plasma density should be lowered.

Belcher [1971] and Belcher and Davis [1971] have used this corotating, steady-state model to analyze the magnetometer and plasma data from Mariner 5. This model turns out to be very helpful in understanding what can be understood and in showing clearly what some of the puzzles are. If the top half of figure 4 is regarded as corotating with the sun, then an observing

spacecraft will appear to move along the circular dashed trajectory with a period of about 27 days. If its observations are plotted as functions of time, one obtains the curves shown in the lower half of figure 4, correspondence with the model being indicated by the vertical dashed lines. The data plots shown are not those for any particular 10-day period but instead are schematic, smoothed curves showing features that Belcher finds to be typical for the entire 160-day period.

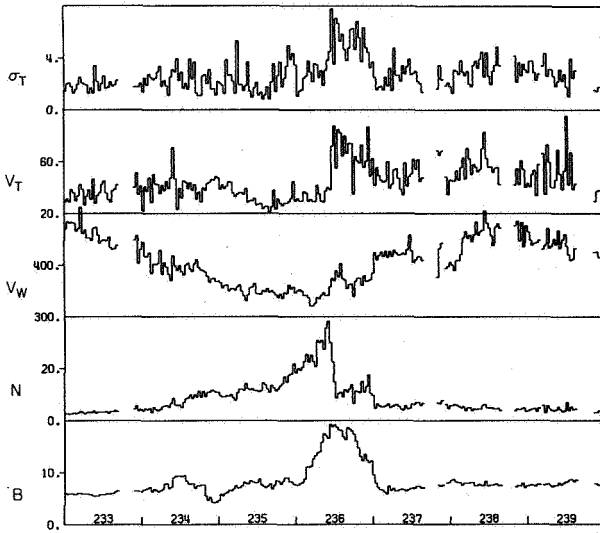
One of the interesting features is that the density ( $N$ ) starts to rise while the spacecraft is still in the slow region and before the velocity indicates that compression should start. It appears that the region of the sun near the source of a high velocity stream is influenced in such a way that it emits streams of higher density than normal. This might be expected if its temperature were higher than that in the center of the low velocity region. However, there is no evidence for similar phenomena on the other side of the fast stream; perhaps a better explanation should be sought. Note, however, that the region where the magnetic field strength is high fits much better the compression region defined by the velocity structure than does the density, which drops rapidly shortly after the velocity increase starts.

The thermal velocity of the plasma and the magnetic fluctuations with periods less than 10 min show approximately the same pattern and hence are represented by a single curve in figure 4. Both are much greater in the compressed high velocity gas than in the compressed low velocity gas, perhaps because the compression ratio should be higher in the high velocity gas than in the low because its original density tends to be lower. This partial summary should make it clear why so much attention is given to the influence of the high velocity solar wind streams in a discussion whose primary aim is an understanding of the interplanetary magnetic field.

Figure 5 shows 1 week of reasonably typical Mariner 5 data. Essentially all the phenomena seen more clearly in the schematic curves of the previous figure can be found here and in numerous other simple plots.

#### DEVIATIONS FROM EXPECTED SPIRALS

Parker's [1963] original discussion of the solar wind pointed out that a radially flowing, highly conducting solar wind ejected from a rotating sun would comb out any solar magnetic fields into spirals wound on circular cones whose vertices are the center of the sun, whose axes are the sun's rotation axis, and whose half angles are the polar angle of the source on the sun. Typical interplanetary magnetometer data for periods of a few hours show many fluctuations but little evidence for the



**Figure 5.** An example of detailed stream structure from 7 days of Mariner 5 data, using 40.4-min averages. The quantities plotted are as defined in figures 3 and 4.

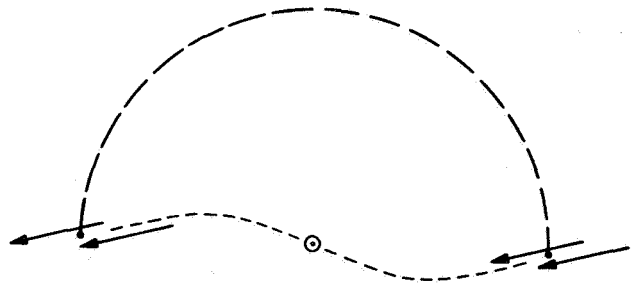
expected spiral pattern. If the data are suitably averaged over longer periods, it becomes evident that the basic spiral pattern is present but that superposed on it are large amplitude fluctuations due to waves and convected magnetic structures. In addition to these fluctuations, the averages suggest the presence of systematic deviations from the spirals computed from the observed radial velocity of the solar wind. It is these systematic deviations, not the superposed shorter period fluctuations, that are discussed here.

If the pitch of a spiral field line does not have quite the average value expected on the basis of the radial velocity, it must be explained in terms of  $V_\phi$ , the azimuthal velocity component of the solar wind. This is associated with the angular momentum transport from the sun and will be discussed in a later session. First, with the usual mathematical treatment, substantial deviations in average pitch of the spiral, and hence substantial average azimuthal velocity, implies a substantial torque applied as a boundary condition at infinity. This could be torque exerted by the galactic magnetic field, but it is more likely associated with transverse momentum imparted to solar gas as it reaches the outer boundary of the heliosphere *Davis* [1971]. The deviations of the magnetic spirals on entering the compression regions shown in figure 4 lead us to expect azimuthal velocity components which seem to be consistent with those observed by *Lazarus* [1970] and by *Wolfe* [1970].

There are also observations that indicate the presence of a long-term average component of the interplanetary

magnetic field that is normal to the cone on which the spiral should be wound; there is a  $B_\theta$  component. We shall now see that this has much more puzzling consequences than an unexpected  $B_\phi$  component. Since most observations are made near the ecliptic, which is inclined at only  $7^\circ.25$  to the solar equatorial plane, the cone is very flat.

The best known observations of this kind were made by IMP 1, where *Ness and Wilcox* [1964] found a southward component that averaged a substantial part of a gamma over a 3-month period. The field lines had a modal angle with the equatorial plane of the order of  $20^\circ$ , and whether they were inward or outward along the spiral they also pointed a bit southward more often than a bit northward. That this raises difficulties of a very basic character can be seen in a number of ways. For example, consider a circle in the ecliptic whose radius is 1 AU and which bounds a hemispherical cap whose center is the sun, as indicated in meridional cross section in figure 6. Magnetic tubes of force are shown to the left in an outward pointing sector. As they are swept



**Figure 6.** Schematic meridional projection of the average interplanetary magnetic field, as based on IMP 1 data, and of a northern hemisphere bounded by the earth's orbit. With this model, the outward flux through this hemisphere tends to increase rapidly.

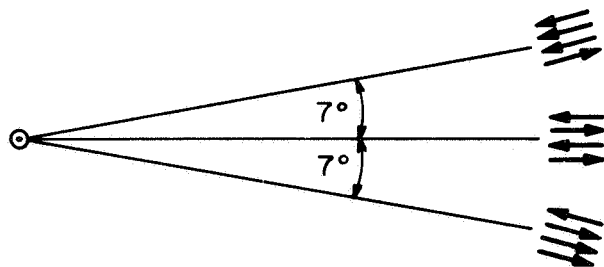
outward radially by the solar wind, they are carried across the circle and increase the outward flux through the hemisphere. On the right are tubes of force in an inward pointing sector. As they are swept radially outward across the circle, they remove inward flux through the hemisphere and hence increase the net outward flux. Hypothetical connections of these tubes to the sun are shown, but they are irrelevant to the argument. However they are arranged, the flux through the hemisphere must increase steadily.

An approximate estimate of the time constant of this increase is easily made, the result being that it takes



about 40 days for the total flux through the hemisphere to increase by the equivalent of a uniform  $5\gamma$  radial component of  $\mathbf{B}$  over the entire hemisphere. It is literally incredible that this can continue for long and it seems likely that a rather unpalatable modification either of the data or of our theoretical understanding of the solar wind will have to be accepted. Among the modifications that might be contemplated are (1) the IMP 1 data grossly misrepresent the true situation because of statistical fluctuations; (2) the magnetometer zero level is in error; (3) the wind does not flow radially but has a southward velocity component that matches the observed inclination of the magnetic field; (4) the conductivity of the solar wind is so much lower than is usually believed that the plasma need not slide along the lines of force; or if all the preceding are rejected because each is very unpalatable to someone, (5) Maxwell's equations are invalid.

A different and to this author more intriguing proposal for nonspiral mean fields is that made by *Rosenberg and Coleman* [1969] and *Coleman and Rosenberg* [1970]. Figure 7 summarizes in schematic fashion their deductions from an extensive body of observations made between  $7^\circ S$  and  $7^\circ N$  solar latitude. In the equatorial



**Figure 7.** Schematic meridional projection of the average interplanetary magnetic field based on the analysis by *Coleman and Rosenberg* [1970]. The multiple arrows at  $7^\circ S$ ,  $0^\circ$ , and  $7^\circ N$  solar latitude indicate roughly the fraction of the time that the meridional projection of the average field in these locations is directed as shown. The median line is the solar equatorial plane. Note that the upper and lower sets of arrows are inclined at a greater angle than the corresponding radial vectors.

plane, positive and negative polarities are of essentially equal frequency. Rosenberg and Coleman find that the spacecraft goes to north solar latitudes, the fraction of the time spent in negative polarity sectors increases until at  $7^\circ N$  latitude it is roughly three-fourths. As the spacecraft goes to  $7^\circ S$  latitude, the fraction of the time spent in positive polarity regions increases to roughly three-fourths.

There is no basic difficulty in accepting these observations. If we were to map on the surface of the sun the patches of positive and of negative polarity, we could find them equally frequent along the equator but with a substantial preponderance of patches of negative polarity to the north and of positive polarity to the south. This would probably require that the patches be smaller in latitude than was suggested earlier, but there were no strong grounds for that suggestion. There is probably no good reason to extrapolate these observations to conclude that twice as far from the equator there will be only patches of a single polarity. However, if one wishes, one could easily reproduce the observations using a model in which at middle latitudes the northern hemisphere is exclusively of negative polarity and the southern hemisphere exclusively of positive polarity with a single wavy boundary between, although this is not at all the model that is usually deduced from photospheric observations.

A second, more puzzling deduction made by Coleman and Rosenberg is that on the average the field lines, when projected on the meridional plane, are not precisely radial; on the average they make a larger angle (very roughly by a factor of  $3/2$ ) with the solar equatorial plane than does the radius from the center of the sun to the point of observation. It is apparent from figure 7 that the latitude dependence of polarity then implies an average southward net flux, although not as large as that implied by the IMP 1 data. (The point under consideration is not the clearly apparent preponderance of lines that are directed southward with respect to the solar equatorial plane; it is that they are directed southward with respect to the local radius from the sun.) If the solar wind is radial, this excess tilt of the field lines means that tubes of force that at one time emerged through portions of a sphere at 1 AU lying either north of  $7^\circ N$  latitude or south of  $7^\circ S$  latitude are being swept into a belt  $14^\circ$  wide around the equator. The total net flux through this belt need not change since as much negative flux is convected inward over its northern boundary as positive flux is convected inward over its southern boundary. However, the only way to keep the flux of each sign from growing and thus rapidly increasing the field strength is to have some kind of field merging by which tubes of opposite polarity "eat each other up." The time constant for this must be of the order of 10 days, which seems unacceptably short.

Another way of looking at the difficulty is that the negative flux in the cap north of  $7^\circ N$  latitude is being convected into the equatorial belt at a rate that would reduce the flux through the cap to zero in approximately 100 days. This flux cannot be regenerated by the

drawing out of loops from the lower corona unless the positive leg of each loop comes from south of  $7^\circ\text{N}$  and the negative leg comes out from the north of  $7^\circ\text{N}$ . But if this happens, a corresponding amount of north-pointing flux should be observed passing a spacecraft at  $7^\circ\text{N}$  solar latitude.

If the observations are accepted at face value, we seem driven to one of three conclusions: (1) The solar wind, by chance, behaves consistently in one way on the side of the sun where the spacecraft happens to be and on the other side behaves consistently in the reverse way; with the large number of solar rotations involved, this is highly implausible. (2) The effective conductivity of the solar wind is low enough, or our knowledge of plasma physics is so incomplete, that the field lines can remain fixed in space and the wind blows partially across them. (3) The wind velocity is not radial, rather being directed parallel to the field lines.

If we attempt to follow this escape route, we are at once confronted with two further difficulties. First, as pointed out by Schatten in the preceding paper, Rosenberg and Coleman's interpretation disagrees with the perhaps still tentative plasma observations. Further, all the magnetic flux and all the plasma that pass through the  $14^\circ$  belt over which observations have been made at 1 AU would have to come through a narrower belt nearer the sun and follow a path curved away from the equatorial plane. The dynamics of this curved flow requires that forces act on the plasma. It would be very surprising if the gradients in plasma pressure were large enough to produce this deflection. Let us therefore consider electromagnetic forces. Parker's ideal spiral in the solar equatorial plane is a force-free configuration. But out of the equatorial plane it produces a small force normal to the cone on which it is wound and away from the equatorial plane. If the force is computed for the ideal spiral, it appears from a crude calculation to be too small by a factor of roughly 3 to 10. This discrepancy may not be important since, in a more complete model in which the  $\theta$  component of the magnetic field is not zero, the force in the  $\theta$  direction may be larger. A similar process occurs for the azimuthal motion, where if the ends of the field lines as  $r$  approaches  $\infty$  are assumed to be pulled in the  $\varphi$  direction, the curvature of the field lines for intermediate values of  $r$  produces forces that deflect the wind in the  $\varphi$  direction. A necessary feature of a model having the desired forces in the  $\theta$  direction is likely to be some process that draws the lines of force toward the axis of rotation when they are very far from the sun and from the equatorial plane. This will require curvature toward the poles all along the field line and might produce the forces necessary to deflect the wind along the curving field lines.

In summary, there appears to be no theoretically acceptable model that is in agreement with all the observations of long-term average components of the magnetic field and of wind velocity in the  $\theta$  direction. If the data are accepted, one must accept very uncomfortable theoretical consequences. If one makes himself comfortable theoretically, he must suffer the unpleasant consequences of disagreeing with those who have worked very hard and skillfully in carrying out difficult experiments to get badly needed data. For the moment it seems best to suspend judgement.

Although it was argued above that there could be no significant rapid cancellation of oppositely directed flux tubes near 1 AU in the solar wind in the equatorial belt, there must be some such phenomena somewhere in the solar system, although with a much longer time scale. From time to time magnetic arches push up through the photosphere with the birth of spot groups. Some of these may later be pulled back down inconspicuously along the border between regions of positive and negative polarity. But many such arches extend high into the corona and their apexes are occasionally swept outward by the solar wind, increasing the number of tubes of force that extend from below the photosphere to the outermost reaches of the solar system. Once the vertex of such an arch passes the Alfvénic critical point, it can never be simply pulled back. Some process must be found to keep the number of tubes of force from increasing indefinitely. The surface currents that flow between regions of opposite polarity will produce some cancellation because of the finite conductivity, but in and above the corona the rate at which this happens is very small. The conductivity, or at least the decay time of surface currents of the significant scale, is smallest in the photosphere. And in the photosphere there are fluid motions driven by mechanical forces that are large compared to the magnetic forces. Thus, from time to time flux tubes of opposite polarity must be driven together, producing very thin current sheets. One result will be a very local cancellation of oppositely directed flux tubes and a reconnection of the parts of the tubes that do not mutually "eat each other up." Below the region of cancellation there will be an arch whose legs go deep down into the sun. This can be submerged below the photosphere by magnetic tension in the legs or by random fluid motions. Above the region of cancellation there will be a field loop that is suspended from above. When enough of the gas in it has risen up and flowed off in the solar wind, the entire loop will rise and blow away. By this somewhat complicated process, two entire oppositely directed tubes of force are removed from interplanetary space. It is necessary only that this process operate rapidly enough to keep up with the new

flux that is added when the tops of arches rise in the solar wind.

As a final comment, it is urged that a Copernican viewpoint be adopted for the interplanetary medium. The earth's orbit has much less influence than the sun's axis of rotation on the phenomena we have been considering. Thus it is better to use solar polar coordinates than ecliptic coordinates. The radial components of field and velocity vectors are the same in the two systems, even when the spacecraft is in neither equatorial plane, but the true  $\theta$  component can be mixed with as much as 12 percent of the  $\varphi$  component if the wrong coordinate system is used. Angles can be shifted by  $7^\circ$ . For example, this may account for a small part of the southward excess found by IMP 1. Unfortunately, there has been a strong, although currently dying, tradition of using ecliptic coordinates even where they are inappropriate. It is to be hoped that this tradition will not long survive.

#### ACKNOWLEDGEMENTS

I am greatly indebted to the generosity of the Mariner 5 plasma experimenters, H. S. Bridge, A. J. Lazarus, and C. W. Snyder, and to the other Mariner 5 magnetometer experimenters for the use of large quantities of carefully reduced data before publication, and for helpful discussions and comments. I am particularly indebted to J. W. Belcher for many discussions and for the use of the results of his analysis. Financial support from NASA under research grant NGR-05-002-160 is gratefully acknowledged.

#### REFERENCES

- Belcher, J. W.: Alfvén Waves in the Interplanetary Medium. Ph.D. Thesis, California Institute of Technology, 1971.  
 Belcher, J. W.; and Davis, L., Jr.: Large-Amplitude

- Alfvén Waves in the Interplanetary Medium, 2. *J. Geophys. Res.*, Vol. 76, 1971, p. 3534.  
 Coleman, P. J., Jr.; and Rosenberg, R. L.: The North-South Component of the Interplanetary Magnetic Field. *Inst. Geophys. Planet. Phys., Univ. California at Los Angeles*, Pub. 818, 1970.  
 Davis, L., Jr.: The Configuration of the Interplanetary Magnetic Field, in *The Interplanetary Medium*, edited by Roederer and Hundhausen, p. 19, Reidel, Dordrecht-Holland, in press, 1971.  
 Dessler, A. J.; and Fejer, J. A.: Interpretation of  $K_p$  Index and M-Region Geomagnetic Storms. *Planet. Space Sci.*, Vol. 11, 1963, p. 505.  
 Lazarus, A. J.: Pioneer 6 and 7 Observations of Average Solar Wind Properties. *Trans. Amer. Geophys. Union*, Vol. 51, 1970, p. 413.  
 Ness, N. F.; and Wilcox, J. M.: Solar Origin of the Interplanetary Magnetic Field, *Phys. Rev. Lett.*, Vol. 13, 1964, p. 461.  
 Neugebauer, M.; and Snyder, C. W.: Mariner 2 Observations of the Solar Wind. *The Solar Wind*, edited by R. J. Mackin, Jr., and M. Neugebauer, Pergamon Press, New York, 1966a, p. 3.  
 Neugebauer, M.; and Snyder, C. W.: Mariner 2 Observations of the Solar Wind, 1, Average Properties, *J. Geophys. Res.*, Vol. 71, 1966b, p. 4469.  
 Parker, E. N.: *Interplanetary Dynamical Processes*. Interscience, New York, 1963.  
 Rosenberg, R. L.; and Coleman, P. J., Jr.: Heliographic Latitude Dependence of the Dominant Polarity of the Interplanetary Magnetic Field. *J. Geophys. Res.*, Vol. 74, 1969, p. 5611.  
 Wilcox, J. M.; and Ness, N. F.: Quasi-stationary Corotating Structure in the Interplanetary Medium. *J. Geophys. Res.*, Vol. 70, 1965, p. 5793.  
 Wolfe, J. M.: Solar Wind Characteristics Associated with Interplanetary Field Sector Structure. *Trans. Amer. Geophys. Union*, Vol. 51, 1970, p. 412.

*M. Dryer* I have a question about the Alfvén waves [fig. 4]. I'm a little puzzled by looking at the description of the data here or looking at the data and seeing that the deviations of the magnetic field and density and so forth are quite large. When I think of Alfvén waves I think of linear waves where, let's say,  $\delta b$  divided by  $b$ ,  $\delta n$  divided by  $n$ , and so forth, are all much less than one. Is there some explanation for that?

*L. Davis* The Alfvén waves are part of the small-scale structures. The things that I was showing are very large-scale structures, those changes in density which last during periods of the order of a day, where there were substantial changes in density and field strength. Variations on a scale which you couldn't see on this diagram at all would be the Alfvén wave fluctuations.

*C. P. Sonett* On one of the earlier slides, you show the plot with the velocity decreasing in the slow stream. The field changing, the density changing—it all looks sort

#### DISCUSSION

of like a snowplow. The temperature showed a very distinct very large jump very suddenly. Now, it seems this wasn't a velocity jump at that time. Would you attribute that to something like an electric field in a shear layer?

*L. Davis* I wouldn't want to tie myself down now completely on any explanation. What you would like to argue is that at that place where the temperature jumped one had gone from gas on the low temperature side, one was in gas which originally originated in the low velocity stream. When one went to the high temperature one was in a gas which had originally come in the high velocity stream. And I think these gases were different all the way out from the sun, and that it is a remnant of this past history that accounts for the high temperatures. I wouldn't want to say there weren't electric fields involved.

*J. M. Wilcox* With regard to the planning of future spacecraft observations, I would like to point out specifically that in the paper by Schatten there was shown very clearly a difference in what one might expect for observations at a heliographic latitude of  $40^\circ$  and at 1 AU distance from the sun, namely, that on one viewpoint one would expect to find a sector structure very similar to that observed near the earth or in the solar equatorial plane, but on another picture one would expect to find essentially a continuous polarity either always away from the sun or toward the sun. I think this is the kind of specific physical question one likes to have available when thinking about where one might look for new observations.

*B. McCormac* On those velocity jumps, the field plots, wouldn't it be useful to put on there the momentum and energy? It seems like they don't vary nearly as much as the velocity, in some cases might even stay relatively constant.

*L. Davis* Then I would really be getting into talking about the plasma, giving a plasma paper, and I think I should leave that for the people who will talk tomorrow.

*E. J. Weber* I would think, Leverett, you would just have to think about the plasma if you want to talk about your magnetic field at 1 AU. The reason for that is I think of a magnetic field in the plasma flow which is perpendicular to the ecliptic plane, which we seem to have, despite the fact that you tried to average it away a couple of years ago, if I remember, because it couldn't be possible. I think this really is one of the possibilities which might exist, as follows: Suppose you have on the sun temperature gradients along the polar direction and further down these are basically shielded from each other because of strong magnetic fields and you can't conduct the heat perpendicular to them. Further out, though, they act on it and in a sense can give an acceleration to the plasma, and therefore can produce a velocity perpendicular to the ecliptic plane.

*L. Davis* You're going to have to produce something on the general order of 40 km/sec. This gets in the range of acoustical velocities. I think this gets a little large to produce. That is the transverse velocity you will have to have there.

*M. Dryer* You were speaking about trying to get a mechanism for dissipating magnetic flux. Would it be possible if we accepted Alfvén's admonition and ruled out infinite conductivity, and tried to get rid of some of it that way? Would that be sufficient?

*L. Davis* Well, I did rule out infinite conductivity in the photosphere. I think when we say the solar wind is infinitely conducting we don't really mean that, we mean that it has a very high conductivity. I think we have some idea of what it should be, and it is large enough so that it is hard in the interfaces between the positive and negative polarity regions to eat up very much flux there. I think you will have to make some mechanism which reduces the conductivity very greatly before you can manage that way.

*A. J. Hundhausen* In the slide in which you showed some idealized structures for the high speed streams, which I believe was from one of John Belcher's papers, you showed beneath this some structures for various parameters as a function of time. Were those theoretical structures, observed structures, or idealizations of one or the other?

*L. Davis* They were basically an idealization of observed structures.

*A. J. Hundhausen* Well, in your interpretation of that density rise preceding the

velocity rise are you certain that that is really a property of the steady wind that might exist in front of the high speed stream, or is that just the back end of the rarefaction from the previous high speed stream? Can you really distinguish between the two?

*L. Davis* It is hard to distinguish between them. I perhaps should ask John Belcher to give a comment on this if he wishes. I might say that I think the argument I gave, that this high density reflected some different condition in the low velocity stream near the sun, near the high velocity stream—I'll be responsible for that and John may or may not want to partake in it, I don't know. But the observation that many times just before the velocity increases, sometimes when the velocity has been coming down and is about to start right back up, or when the velocity has come down and gone more or less constant for a while and then goes up, each time it is just before the velocity goes up that one gets this high density spike.

*C. P. Sonett* I'm a bit hesitant to bring this particular subject up, but I think in view of the importance of the field measurements in terms of what Leverett has had to say this question at least ought to be aired once more, even though cosmic plasmas are neutral. What I am referring to in particular is that there have been a number of field measurements showing in some cases components out of the ecliptic and in other cases fields in which as far as experimental accuracy permitted the component out of the ecliptic was essentially zero. In the first case, in the case of the IMP 1, if I remember correctly, it was about  $1 \gamma$ . There's another case taken from our data on Explorer 33 and possibly 35 which was carried out by Joan Hirshberg some years ago, in which she constructed histograms of the type that Ness and his group employed in the IMP reduction. In the case that she carried out, which was published in a letter in JGR\*, the residuals were below the error levels, and that means something like two-tenths of a gamma or perhaps less. Joan is here. Would you like to say something about it?

*J. Hirshberg* Perhaps only to add that the results were the same for the equatorial plane or the ecliptic plane.

*A. J. Dessler* This might be an appropriate place to take a short poll among the experimenters. Is there complete agreement between all the experimenters that there is a southward field of 1 to  $2 \gamma$ ? Dr. Ness, can you say something?

*N. F. Ness* It is not unpleasant to hear old data brought back to life, and it certainly has had a good ride since 1963 or '64. I think if you read the papers, if you are interested in this problem, one would specify the quantitative value to the component transverse to the ecliptic plane. I think we should realize, however, that if one studies this problem from a variety of satellite data you would first of all have different intervals of time, in a sense different polarities. You also have different time intervals over which they can be averaged. That is, in some of the work one is averaging over a solar rotation only and then doing this on successive solar rotations. In other cases one is averaging over a period of 3 months or 6 months or perhaps 18 months with gaps interspersed for various reasons. So that in all of this, in attempting to reconstruct what the net view is on the field component transverse to the ecliptic, one is faced with the problem of essentially incomplete data. I think we still believe that for the IMP 1 time interval the perpendicular component of about  $1 \gamma$  was valid within the accuracies quoted in the paper. And since that time I must say it's been interesting to see the turnaround as to how the southward component in the interplanetary field has resurrected itself in the framework of the recent studies of the interplanetary field topology related to the solar field. It is obviously a difficult measurement to make but I caution those of you who simply take scrawls from abstracts or from review papers to be certain that when you are looking for the magnitude of the component transverse to the ecliptic you understand it is over a solar rotation and which solar rotation, because it is clear that it changes.

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\*Hirshberg, J., Interplanetary Magnetic Field during the Rising Part of the Solar Cycle, *J. Geophys. Res.*, 74, 5814–5818, 1969.

*A. J. Lazarus* Just one comment on the interaction between high and low speed streams. I think you can tell where the interaction has occurred by looking at the transverse component of velocity and seeing how it changes as you move from a slow to a high speed. You can therefore talk about an interaction region where perhaps there is some compression; but I think it is important to look at some of these regions in detail, as we will do later in this Conference.

*P. J. Coleman, Jr.* From our data from the Mariners and Explorers and so on, if one averages the north-south flux at the solar equatorial plane, it seems as far as we can tell within our statistical accuracy that it's zero.

*J. M. Wilcox* I should like to mention a matter of terminology. Of course, physics gets involved in it. I would like to propose that the name *sector*, as used in the interplanetary medium, could be saved for an interval in which you have several days of continuous dominant magnetic field polarity in one direction. If a feature lasts for only half a day, then that is a filament or something but it is not a sector. Now, it is certainly true that there is this other kind of structure where you may have two peaks in solar wind velocity, each a few days wide, but all within the same polarity of the magnetic field. One possibility is to call each of these peaks of solar wind velocity a *subsector* or a *stream*. Now, in my opinion it is not clear which is the dominant physical structure, this subsector as I just described it or a sector. In fact, I think the answer to that question depends upon the specific problem that you are thinking about. But if we could have a standard terminology it might help the discussion. I wonder if Leverett Davis could comment.

*L. Davis* I wouldn't object to that. All I was trying to emphasize was that if you looked at, say, the sector pattern based on the IMP data, where everything was nice and repetitive, and you find that within a sector the polarity reverses from one sector to the next, the field strength has the characteristic pattern across the polarity, velocity has the characteristic pattern across the polarity, you get cosmic rays in one, not the other—all these things—suppose you look at some later period of time and you find that—I'm not claiming that you do but I suspect there will be times when you do—that in one of these subsectors all of these things will go through the characteristic changes but the polarity will happen to be the same for two adjacent subsectors. Then, of course, for these things which fit this pattern the subsector is the dominant thing and it may be convenient to call it a subsector rather than a sector. I think it depends a lot on whether you're thinking about the sector as being traced back to the sun and are worrying very much about what's happening on the sun to make this thing. Then John's use of the word *sector* is clearly the right one.

*J. M. Wilcox* It seems to me that if we could agree to call these things subsectors without in any way judging the physical significance of that term it might help to clarify the discussion.

*A. J. Dessler* Is it correct that the sectors have a particular dominant polarity when you are above the solar equatorial plane?

*L. Davis* That is what you will find in the papers by Coleman and Rosenberg. I should perhaps make it quite clear, I'm somewhat neutral in my own mind as to whether all of these observations mean what they appear to mean. When they don't satisfy the theorist sometimes it's rather awkward to explain the consequences. As a friend of the people who do the experimental work it is difficult to argue with them. It's even difficult to argue with the somewhat convincing data if I weren't a friend of theirs. Like all experimental data there are some bits of it that fit together and some that don't. It depends on what you want to believe, what you finally accept. But I do think that there is enough indication that there are funny things going on here, funny in terms of the simple model, that one should forget for the moment whether he's trying to decide whether you agree with the data or not but just say if it's right what are the

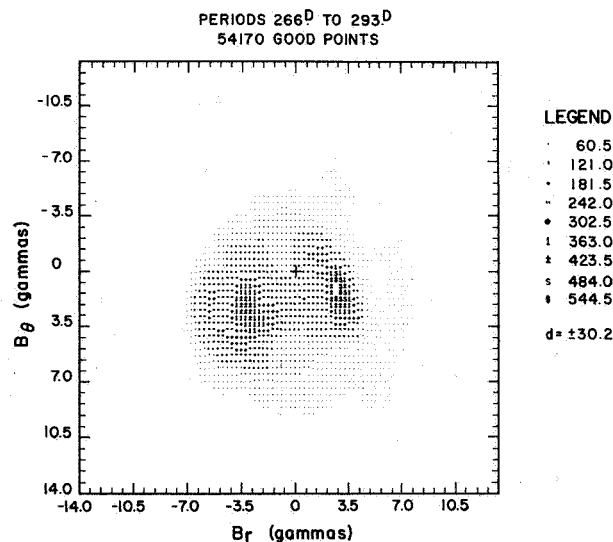
consequences? That's what I was doing.

*A. J. Dessler* I guess one might summarize, then, by saying the existence of a perpendicular component on the average would be a matter of taste.

*K. H. Schatten* I just wanted to make one comment that might be relevant to this discussion. In the Babcock picture of solar magnetic fields, the bipolar magnetic regions separate, one pole drifts to the north and becomes part of the polar field or tries to minimize the polar field and make it change sign; the other pole goes towards the equator and supposedly connects back with the opposite polarity from the opposite hemisphere. This may then be convected out, flux lines merging, this may be convected out through the solar wind and possibly cause some north-south asymmetries. I don't know, I haven't looked into the magnitudes. This has just crossed my mind, and it might relate to this type of analysis.

*P. J. Coleman* I would like to make two points concerning the north-south component of the interplanetary magnetic field. First, the average *magnitude* apparently depends upon heliographic latitude and, second, the mean value of this component in the equatorial plane is probably zero.

Figure 1 shows the effect that we are dealing with. It's a skewing of the distribution of the field in the  $r\theta$  plane of the spherical polar coordinate system. Here the solar equatorial plane is the plane of reference. For the particular distribution, the outward field ( $B_r > 0$ ) is more northward than the inward field.



**Figure 1.** Joint distribution of  $B_r$  and  $B_\theta$  for a 27-day interval of the Mariner 2 flight. The zero level of  $B_\theta$  is arbitrary [after Coleman and Rosenberg, *J. Geophys. Res.*, Vol. 76, 1971, p. 2917].

As a measure of the skewing we use the quantity  $B_{\theta S} = (\langle B_{\theta+} \rangle - \langle B_{\theta-} \rangle) / 2$  where, for a 27-day distribution,  $\langle B_{\theta+} \rangle$  is the mean value of  $B_\theta$  for the outward field and  $\langle B_{\theta-} \rangle$  is the mean value of  $B_\theta$  for the inward field. Figure 2 shows  $B_{\theta+}$ ,  $B_{\theta-}$ , and  $B_{\theta S}$  versus time, heliocentric range, and heliographic latitude from Mariner 5. Here  $B_{\theta S}$  is

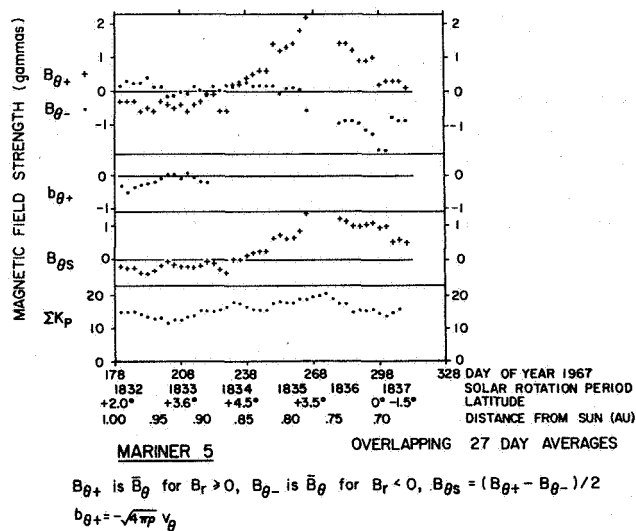


Figure 2. Plots of  $\langle B_{\theta+} \rangle$ ,  $\langle B_{\theta-} \rangle$ , and  $B_{\theta S}$  versus time, heliocentric range, and heliographic latitude for the Mariner 5 flight. These three quantities are defined in the text. The others shown are not pertinent here [after Coleman and Rosenberg, *J. Geophys. Res.*, Vol. 76, 1971, p. 2917].

from 27-day distributions taken at 3-day intervals. We see that  $B_{\theta S}$  changes sign sometime before Mariner 5 crossed the equator. This is an active period, but there is still a clear reversal despite the activity.

Figure 3 shows  $B_{\theta S}$  from Mariner 4 data. We had a longer stretch of data at a quieter time. The spacecraft was below the equatorial plane for most of the interval. But as Mariner 4 crossed the equatorial plane  $B_{\theta+}$ ,  $B_{\theta-}$ , and  $B_{\theta S}$  reverse polarities. The problem

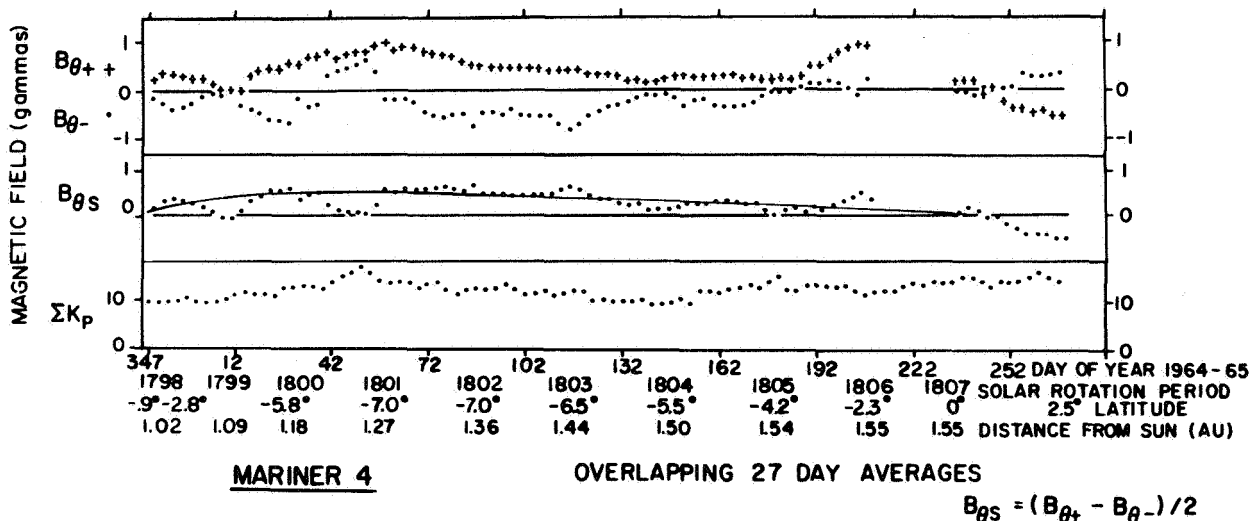
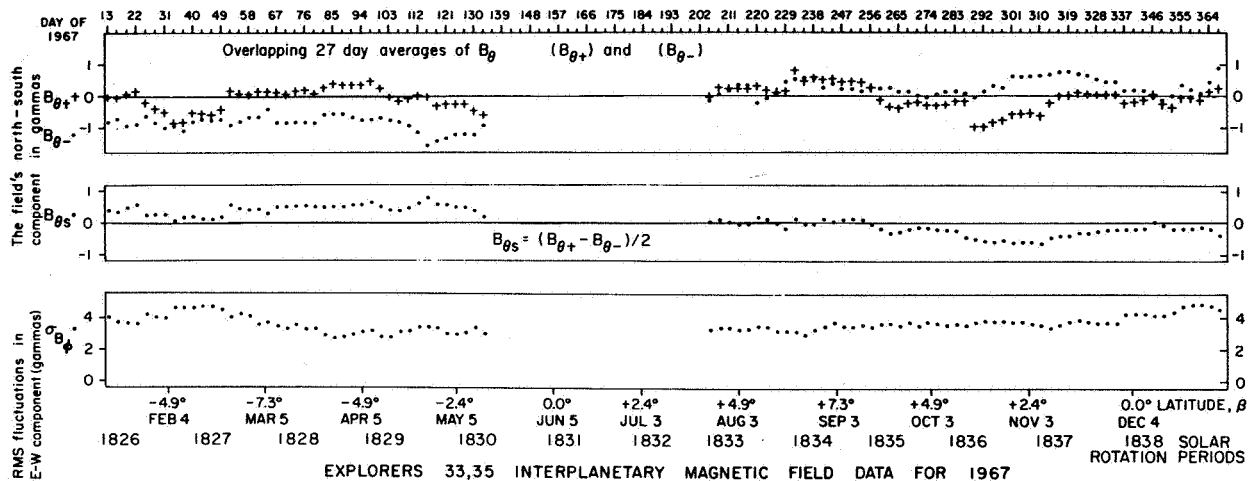


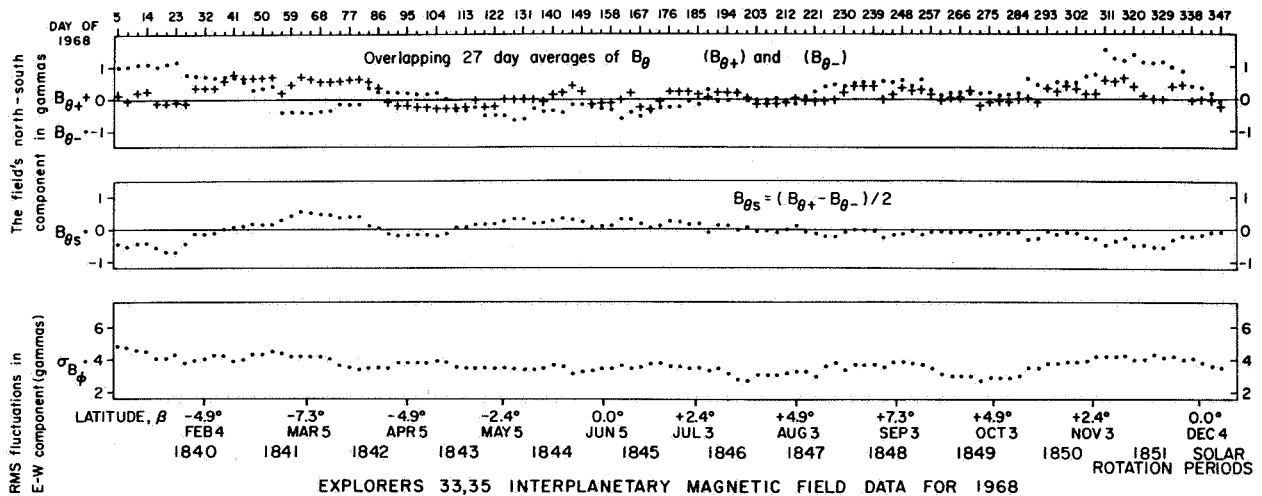
Figure 3. Plots of  $\langle B_{\theta+} \rangle$ ,  $\langle B_{\theta-} \rangle$ , and  $B_{\theta S}$  versus time, heliocentric range and heliographic latitude for the Mariner 4 flight [after Coleman and Rosenberg, *J. Geophys. Res.*, Vol. 76, 1971, p. 2917].



with the Mariners is that they simultaneously move in heliocentric range and heliographic latitude. So, with the cooperation of Dave Colburn and his colleagues at Ames, Ron Rosenberg and I used the Explorer 33 and 35 data to test for the dependence on heliographic latitude. The results are shown in figures 4 and 5. We found the least-squares



**Figure 4.** Plots of  $\langle B_{\theta+} \rangle$ ,  $\langle B_{\theta-} \rangle$ , and  $B_{\theta S}$  versus time, heliocentric range, and heliographic latitude for the Explorers 33 and 35, 1967 [after Rosenberg, Coleman, and Colburn, *J. Geophys. Res.*, Vol. 76, 1971, p. 6661].



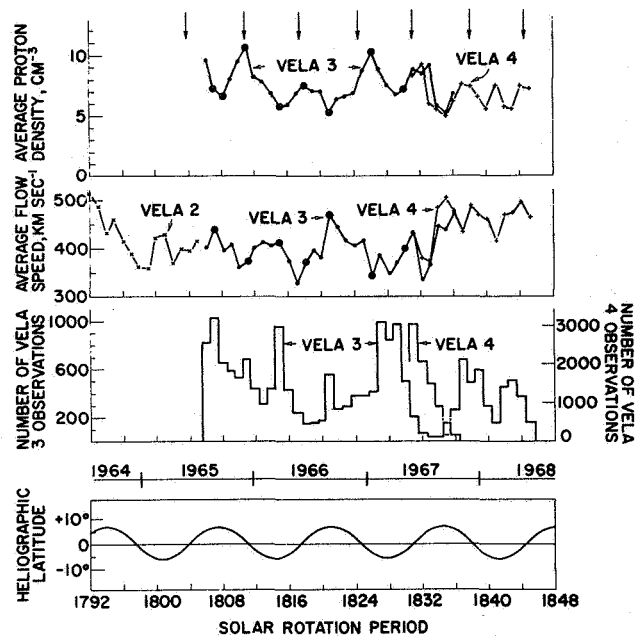
**Figure 5.** Plots of  $\langle B_{\theta+} \rangle$ ,  $\langle B_{\theta-} \rangle$ , and  $B_{\theta S}$  versus time, heliocentric range, and heliographic latitude for the Explorers 33 and 35, 1968 [after Rosenberg, Coleman, and Colburn, *J. Geophys. Res.*, Vol. 76, 1971, p. 6661].

best-fit sinusoid to be one with a period in the range  $1.0 \pm 0.1$  years. For 1967 the amplitude of the sine wave is about  $0.4 \gamma$ . For 1968 it is about  $0.2 \gamma$ . For Mariner 4, which is complicated by radial effects, we estimated the amplitude to be  $0.6 \gamma$  using another model. So it's conceivable that during more active periods such as 1962, when Mariner 2 was launched the amplitude could have been as high as  $1 \gamma$  or something close to that.

Finally, I want to stress once again that these results indicate that the observations of a nonzero north-south component can be accounted for without requiring that the sun lose flux transverse to the equatorial plane. In other words, they indicate that  $\langle B_{\theta} \rangle$  would be zero everywhere in the equatorial plane if the sun were axially symmetrical.

*A. J. Hundhausen* I must confess to feeling somewhat out of place speaking in this session, but as the plasma observations I will describe are relevant to the present discussion, Alex Dessler has convinced me that I should get up here despite the risk of getting caught in a magnetic crossfire. I will briefly describe a search for heliographic latitude dependence in plasma flow properties, based primarily on Vela 3 data obtained between July 1965, and mid-1967, but also using earlier Vela 2 data and Vela 4 data obtained between May 1967 and mid-1968. A more complete discussion of this study will be published in the *Journal of Geophysical Research*.

Figure 1 shows 27-day averages of the solar wind proton density (uppermost frame) and



**Figure 1.** Solar wind observations made by Vela satellites between July 1964 and mid-1968. Twenty-seven day averages of the proton density observed by Vela 3 and 4 and of the solar wind speed observed by Vela 2, 3, and 4 are shown in the top two frames. The third frame gives the number of Vela 3 and 4 observations made within each 27-day solar rotation interval. The heliographic latitude of observation is shown in the fourth frame; the times of crossings of the solar equator are also indicated in the top frame by arrows.

flow speed (second frame) obtained by these various satellites. By averaging over 27 days we have presumably taken out longitude effects and can look for seasonal or latitude variations. The third frame of figure 1 shows the number of observations made by Vela 3 or Vela 4 during each 27-day averaging period. The lowest frame of the figure shows a familiar plot of the heliographic latitude of the earth as a function of time during this

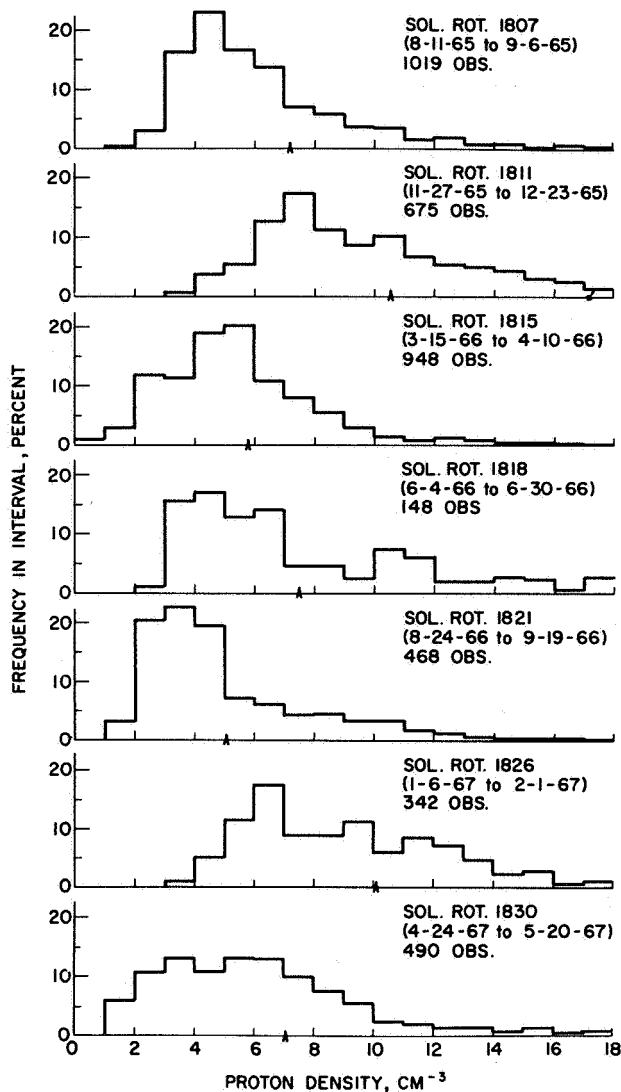
4-year period. In the uppermost frame crossings of the solar equatorial plane are indicated by arrows.

The average density curve of figure 1 clearly hints at a seasonal variation. Maxima in the solar wind density occur near the crossings of the solar equatorial plane; minima occur near the extremes of the latitude excursion. The pattern is less evident in the flow speed averages but the flow speed is generally high when the density is low (away from the solar equatorial plane) and conversely low when the density is high (near the equatorial plane).

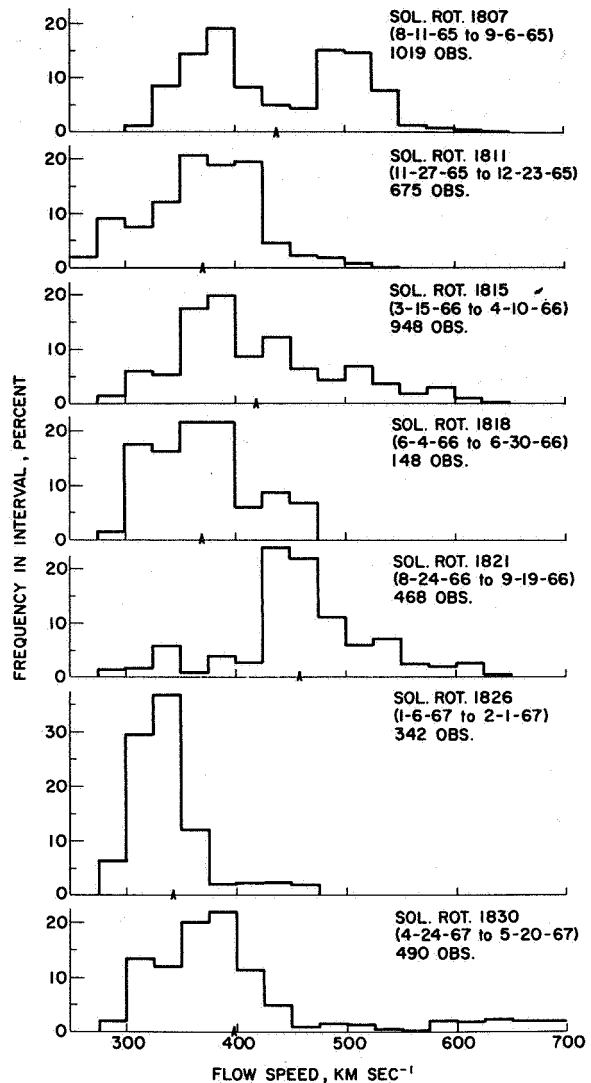
Before interpreting these variations as a latitude dependence in the plasma flow, one should consider several other possibilities. For example, could this be an instrumental effect? Fortunately, we are limited to *very* short contributions at this meeting, so no thorough discussion of such effects can be given. In fact, careful consideration must be given to this possibility, as the spin axes of Vela 3 spacecraft are not normal to the ecliptic plane and thus undergo annual precessions that could lead to an apparent annual variation in an observed quantity. The density variation could result from the spin axis precession if the Vela 3 analyzer systems were to transmit incoming particles at  $\sim 30^\circ$  from the entrance aperture normal with an efficiency 30 to 40 percent higher than particles at normal incidence. Such transmission characteristics are not expected and have not been encountered in laboratory calibrations of these instruments. Further, the Vela 4 spacecraft, earth-oriented and thus subject to a different spin axis variation, measures the same density variation as Vela 3 in mid-1967.

The statistical significance of the variations must also be considered. Figure 2 shows distributions of the observed proton densities from the solar rotations at the maxima and minima of figure 1 (indicated on fig. 1 by circles). Now, the difference between the averages (indicated by the arrows along the abscissae) for these differential solar rotations are about equal to the *standard deviations* of the individual distributions. The *standard error* in the determination of the average density in a given rotation is some fraction of the standard deviations. Therefore, the density variations under discussion are probably statistically significant. The possibility that these variations are random but accidentally resemble a periodic variation for the  $\sim 4$  cycles of figure 1 can be examined using standard statistical tests on runs. The probability of this accident is somewhere between one in a hundred and one in a thousand. Thus both of these possible statistical sources of the density variations are improbable. Figure 3 shows the flow speed distributions observed for the same solar rotations. Again, the variation in the average flow speeds results from large changes in the distributions. Note that high solar wind speeds, say above  $400 \text{ km sec}^{-1}$ , are much rarer near the solar equator.

Having thus dismissed instrumental and statistical sources for the observed variations, can we find a plausible physical explanation? The simplest such interpretation would envision a steady solar wind with high density and low velocity near the solar equatorial plane, and low density and high velocity at higher latitudes, produced by a coronal expansion that is not spherically symmetric. In fact, the Vela observations appear to show that such an interpretation is incomplete. Figure 4 shows 3-hr averages of the proton density and flow speed as a function of time from a solar rotation in 1965 when the satellite is approaching the maximum northern excursion from the solar equatorial plane. Note the presence of pronounced high velocity streams, each of which produced a very pronounced but short-lived density compression followed by a longer period of low densities that very much suggests a rarefaction. In averaging over such a solar rotation, the longer periods of low density dominate and lead to a low average density. Figure 5 shows the same observed quantities from a solar rotation three months later, that includes the crossing of the solar equator. The high velocity stream structure is not nearly so well defined as in figure 4, nor does the most prominent high velocity feature involve as large a velocity excursion. The pattern of density compressions and rarefactions is present but



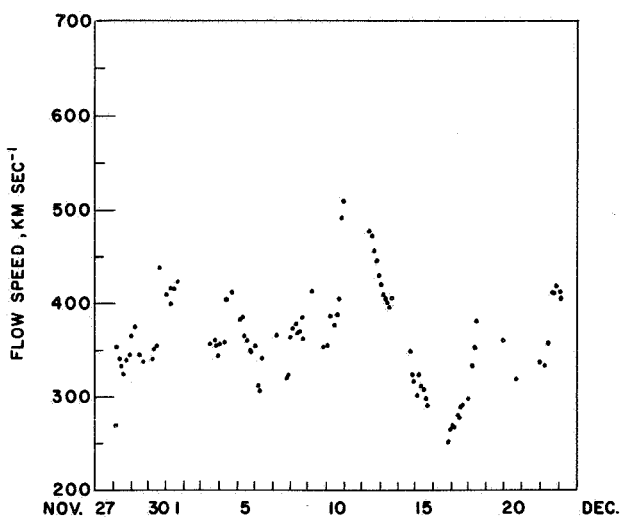
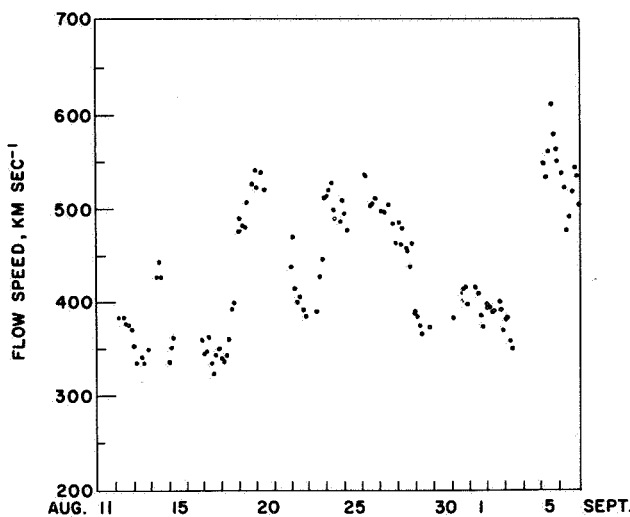
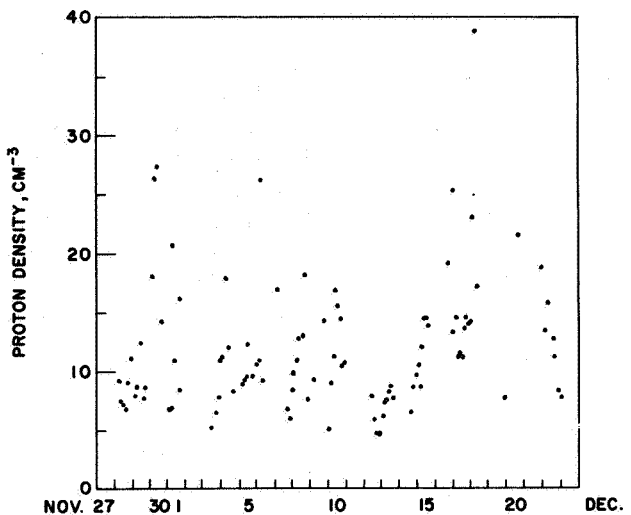
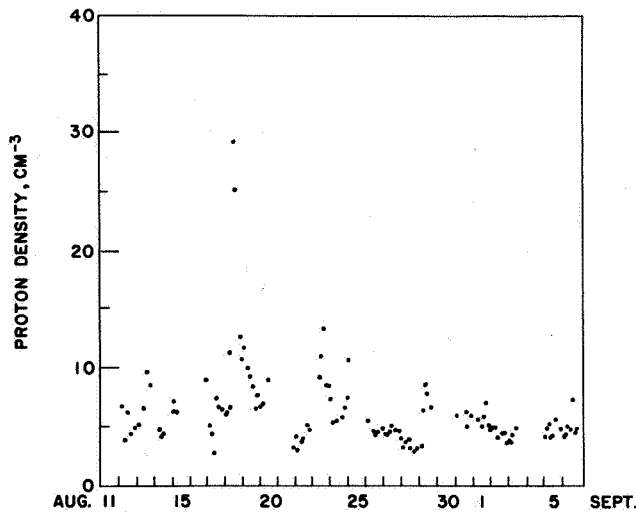
**Figure 2.** Histograms of the Vela 3 proton density observations made during the 27-day solar rotations indicated by circles around the density averages on figure 1. The arrows along the abscissae indicate the averages derived from each distribution.



**Figure 3.** Histograms of the Vela 3 solar wind flow speed observations made during the same set of solar rotations as in figure 2.

less pronounced. In averaging over this rotation one naturally obtains a higher average density. The difference between these two solar rotations might well reflect a latitude dependence in the *solar activity* that presumably produces the high speed stream structure. For the early portion of a solar cycle (when these observations were made), it is well known that solar activity occurs at solar latitudes near 30 to 40°, not near the equator. One might interpret our observations as showing that the high speed streams observed at 1 AU are also confined to latitudes away from the solar equator.

These observations were made during the same period in which Rosenberg and Coleman observed a latitude structure in the magnetic field polarity. Wilcox has pointed out that the structure described by Coleman seemed to disappear sometime in late 1967. Note from figure 1 that our apparent latitude variation in the plasma flow also seemed to



**Figure 4.** *Three-hour averages of the proton density and flow speed observed during a solar rotation in Aug.-Sept., 1965—that is, near  $+7^\circ$  heliographic latitude.*

**Figure 5.** *Three-hour averages of the proton density and flow speed observed during a solar rotation in Nov.-Dec., 1965—that is, near the solar equator.*

disappear near this same time. A simple and plausible explanation of this change can be proposed on the basis of the above discussion. As the solar cycle progresses, the centers of solar activity move toward the equator. That very motion of the sources of the streams might lead to their penetration into the equatorial region.

I should also mention that part of Rosenberg's interpretation of the magnetic field observations has been that the dividing surface between the north and south "regions" might at times be depressed because of the greater solar activity in the northern solar hemisphere. If the Vela 3 observations are used to compare the regions north and south of the solar equator, one finds the flow speeds are about 10 percent higher in the northern solar hemisphere than in the southern solar hemisphere. This may lend some plausibility to Rosenberg's speculation.

In conclusion, the presence of the structures I have described in the plasma flow may add to the plausibility of magnetic fields organized in solar latitude. The next task should

be to search for direct relationships between the plasma flow and magnetic field structures.

*J. M. Wilcox* In Rosenberg's analysis the change from positive to negative dominant polarity occurs sometimes when the earth is at zero heliographic latitude. At other times the change occurs when the earth is several degrees away from this. It is at these latter times when they would like to invoke a southward flow of the solar wind. Do you have the ability to check that from your data?

*A. J. Hundhausen* For this particular period, yes. That is the kind of detailed thing we haven't done yet. But you will note that many of our density maxima were not directly lined up with those equatorial crossings, either. If in fact this variation does depend on solar activity, then since solar activity does not vary smoothly you would expect such offsets.

*E. J. Smith* Did you make any comments at all about flow direction, or would you like to comment on what you see or whether you are able to say anything about flow direction?

*A. J. Hundhausen* As far as the latitude density is concerned, I don't think we see anything. But, remember, we only measure the flow roughly in the ecliptic.