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THE INTERPLANETARY MAGNETIC FIELD

Leverett Davis, Jr.

Physics Department

California Institute of Technology

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ABSTRACT

This review 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 which 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 by Coleman and Rosenberg raise serious difficulties that seem to require either that we significantly modify the usual theoretical treatments or that we question the data.

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 A.U. 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. Let us first, therefore, 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 A.U. are like paper streamers in a gale that mark the flow lines but do not determine them. Likewise, in and below the photosphere the energy density in bulk motion is usually greater than the magnetic field energy density although here it is the independent photospheric velocity

patterns rather than the velocity with which the gas is rising up to supply the solar wind that matters. Thus (except in sun spots) 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 be determined by requiring a rough balance of magnetic stresses (i.e., a force-free field); the fluid flow tends to be constrained 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 that leads out to the normal spiral pattern at large distances. This 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 magnetoacoustic 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. I believe that later in this conference Dr. J. W. Belcher will discuss ways in which this wave energy and momentum can significantly effect the motion and other properties of the solar wind.

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 $\underset{\sim}{B}$.

7. The irregular magnetic field, non-static 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; most such features 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. Among the things we should all recall from the record of the first Solar Wind Conference are the Mariner 2 data on wind velocity in 1962 as observed by Neugebauer and Snyder [1966a]. Mariner II was the first spacecraft to make such measurements completely removed from the influence of the magnetosphere; and it was at once clear, as we see from Figure 1, 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. 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 from one appearance of a stream 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 five 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.

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 hour 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, I like to 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. It may be like asking whether a zebra is a white animal with black strips or a black animal with white stripes.

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 one to four days to sweep past a spacecraft, we must think of streams as extending from 15° to 60° 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 as seen in Figure 2. As demonstrated so beautifully by Wilcox and Ness, 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. Either from the observations near 1 A.U. 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 observations since have confirmed that changes in polarity usually occur between high velocity streams, 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], 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 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 A.U. 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 A.U. 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. You will 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 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 Aflvénic 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

Is 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. But you do not need to be reminded that 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, the development of these ideas was dominated for several years by the beautiful work of Wilcox and Ness, 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 review paper by Schatter, which we have just heard.

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 ones 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 non-rotating, slender, radial cone which 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, 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 non-radial. The stream lines coincide with the magnetic field lines, which have the same spiral pattern as in 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, as shown in the top half of Figure 4, an interaction region where both spirals are deflected. The flow is still 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 is changed, becoming slightly non-radial. 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 having 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 A.U. 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] [Belcher and Davis, 1971] has 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 gets the curves shown in the bottom 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 N, the density, 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 though 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 minutes 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.

Turning from these schematic plots to actual data, Figure 5 shows one week of Mariner 5 data that is reasonably typical. Essentially all the phenomena seen more clearly in the schematic curves of the previous figure can be found here and in numerous other similar plots that we have studied.

DEVIATIONS FROM EXPECTED SPIRALS

Parker's 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 shows many fluctuations but little evidence for the expected spiral pattern. If the data are suitably averaged over longer periods, it becomes very 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 I will now discuss.

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_φ, 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. For the present there are only two brief points I wish to make. First, substantial deviations in average pitch of the spiral and hence substantial average azimuthal velocity implies, using the usual mathematical treatment, a substantial torque applied as a boundary condition at infinity. This could be torque exerted by the galactic magnetic field, but it is perhaps more likely that it is associated with transverse momentum imparted to solar gas as it reaches the outer boundary of the heliosphere Davis, [1970]. Second, 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_θ component. We shall now see that this has much more puzzling consequences than an unexpected B_φ 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, being nearly the solar equatorial plane.

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 three month period. The field lines had a modal angle with the equatorial plane of the order of 20° 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, one of which is the following. Consider a circle in the ecliptic whose radius is 1 A.U. and which bounds a hemispherical cap whose center is the sun, as indicated in meridional cross-section in Figure 6. On the left are indicated magnetic tubes of force in an outward pointing sector. As they are swept outward radially by the solar wind, they are carried across the circle and increase the outward flux through the hemisphere. On the right are indicated 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 5γ radial component of $\underset{\sim}{B}$ 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 that the IMP 1 data grossly misrepresent the true situation because of statistical fluctuations, or that the magnetometer zero level is in error, or that the wind does not flow radially but has a southward velocity component that matches the observed inclination of the magnetic field, or that 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, that Maxwell's equations are invalid.

A different, and to me more intriguing, proposal for non-spiral 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°S and 7°N solar latitude. In the equatorial plane, positive and negative polarities are essential equally frequent. As the spacecraft goes to north solar latitudes, they find that the fraction of the time spent in negative polarity sectors increases until at 7°N latitude it is roughly three-fourths. As the spacecraft goes to 7°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 preponderence 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 if you go 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 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 preponderence 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 A.U. that lay either north of 7^{o}N latitude or south 7^{o}S latitude are being swept into a belt 14^{o} 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^{o}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^{o}N and the negative leg comes out from the north of 7^{o}N. But if this happens, a corresponding amount of north-pointing flux should be observed passing a spacecraft at 7°N solar latitude.

If the observations are accepted at face value, we seem driven to one of three conclusions. The first possibility is that 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. The second possibility is that 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 blow partially across them. The third possibility is that 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 previous paper, this disagrees with the perhaps still tentative plasma observations. Second, this means that all the magnetic flux and all the plasma that passes through the 14° belt over which observations have been made at 1 A.U. must come through a narrower belt nearer the sun and must 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 θ-component of the magnetic field is not zero, the force in the θ-direction may be larger. A similar process occurs for the azimuthal motion, where, if the ends of the field lines as r approaches ∞ are assumed to be pulled in the φ-direction, the curvature of the field lines for intermediate values of r produces forces that deflect the wind in the φ-direction. A necessary feature of a model having the desired forces in the θ-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 θ-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 A.U. 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. This will produce 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 my final comment, I would like to urge 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 θ-component can be mixed with as much as 12% of the φ-component if the wrong coordinate system is used. Angles can be shifted by 7°. 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.

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Figure Captions

Fig. 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]

Fig. 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; i.e., solar rotations 1832-1837.

Fig. 3 35 days of Mariner 5 data plotted using 3-hour 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 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]

Fig. 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 A.U. 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_φ 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 σ_S the square root of the sum of the variances over 5.04 minutes of the three orthogonal components of the field. [Belcher, 1971]

Fig. 5 An example of detailed stream structure from 7 days of Mariner 5 data, using 40.4 minute averages. The quantities plotted are as defined in Figures 3 and 4.

Fig. 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.

Fig. 7 Schematic meridional projection of the average interplanetary magnetic field based on the analysis by Coleman and Rosenberg. The multiple arrows at 7°S, 0°, and 7°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.

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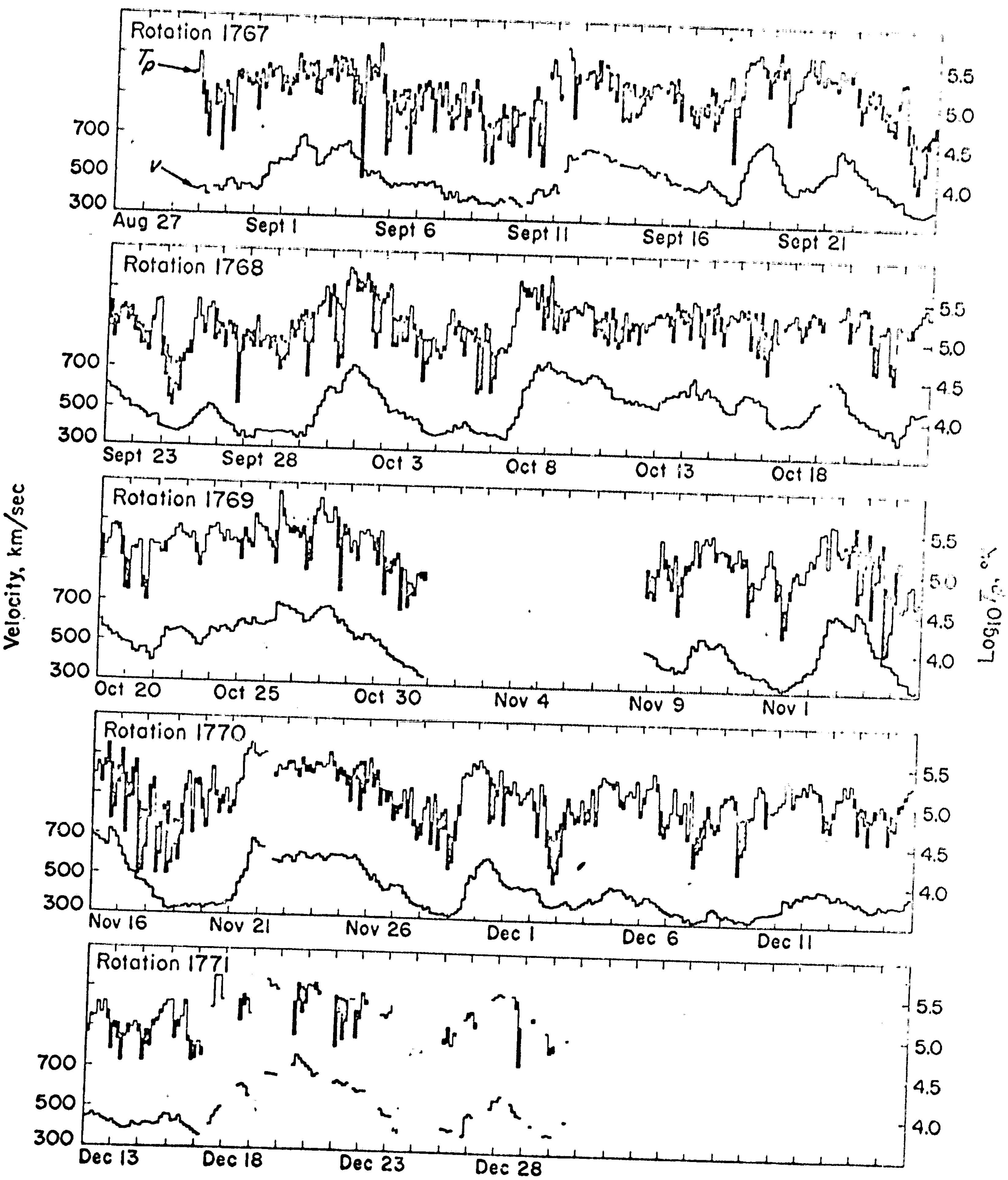

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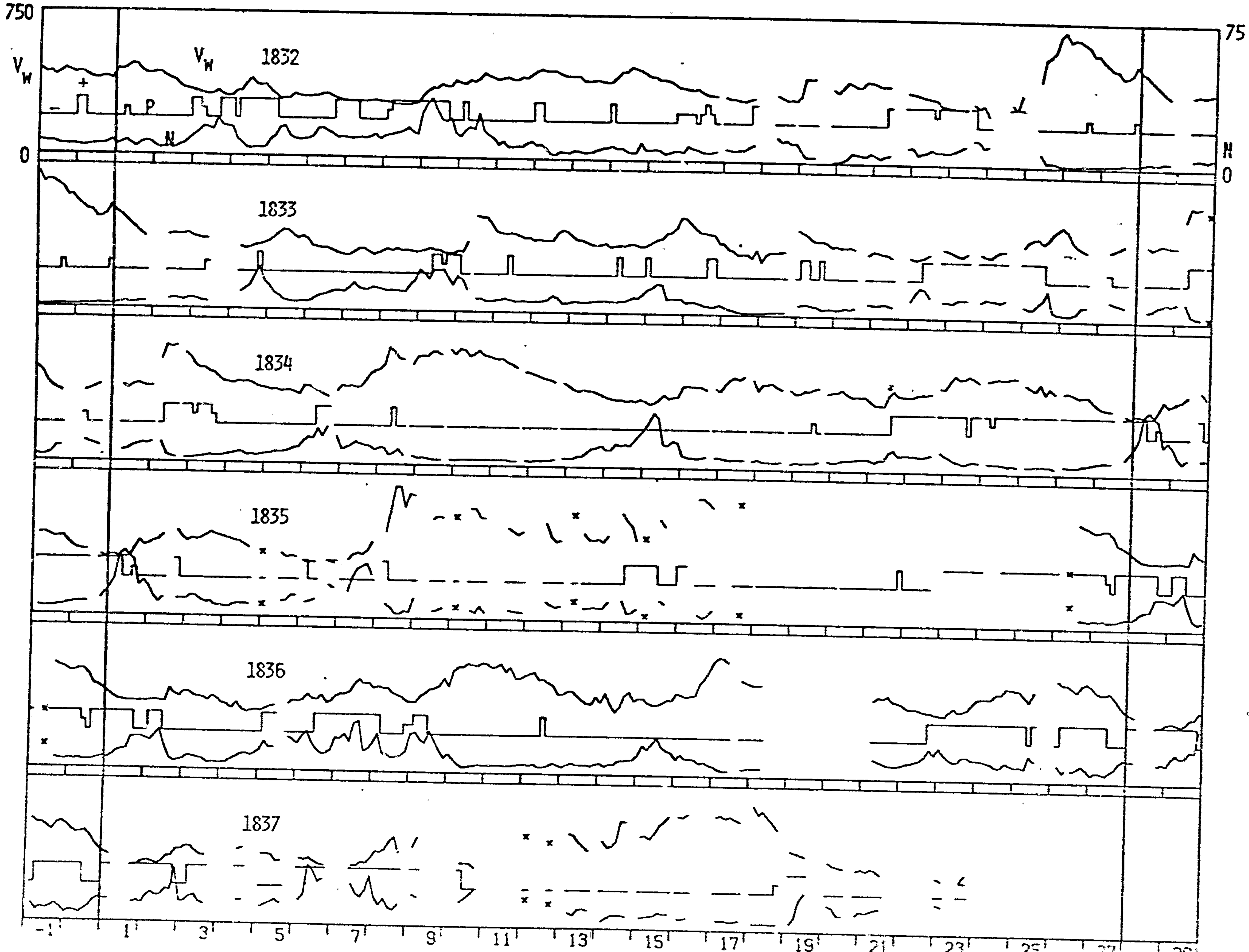
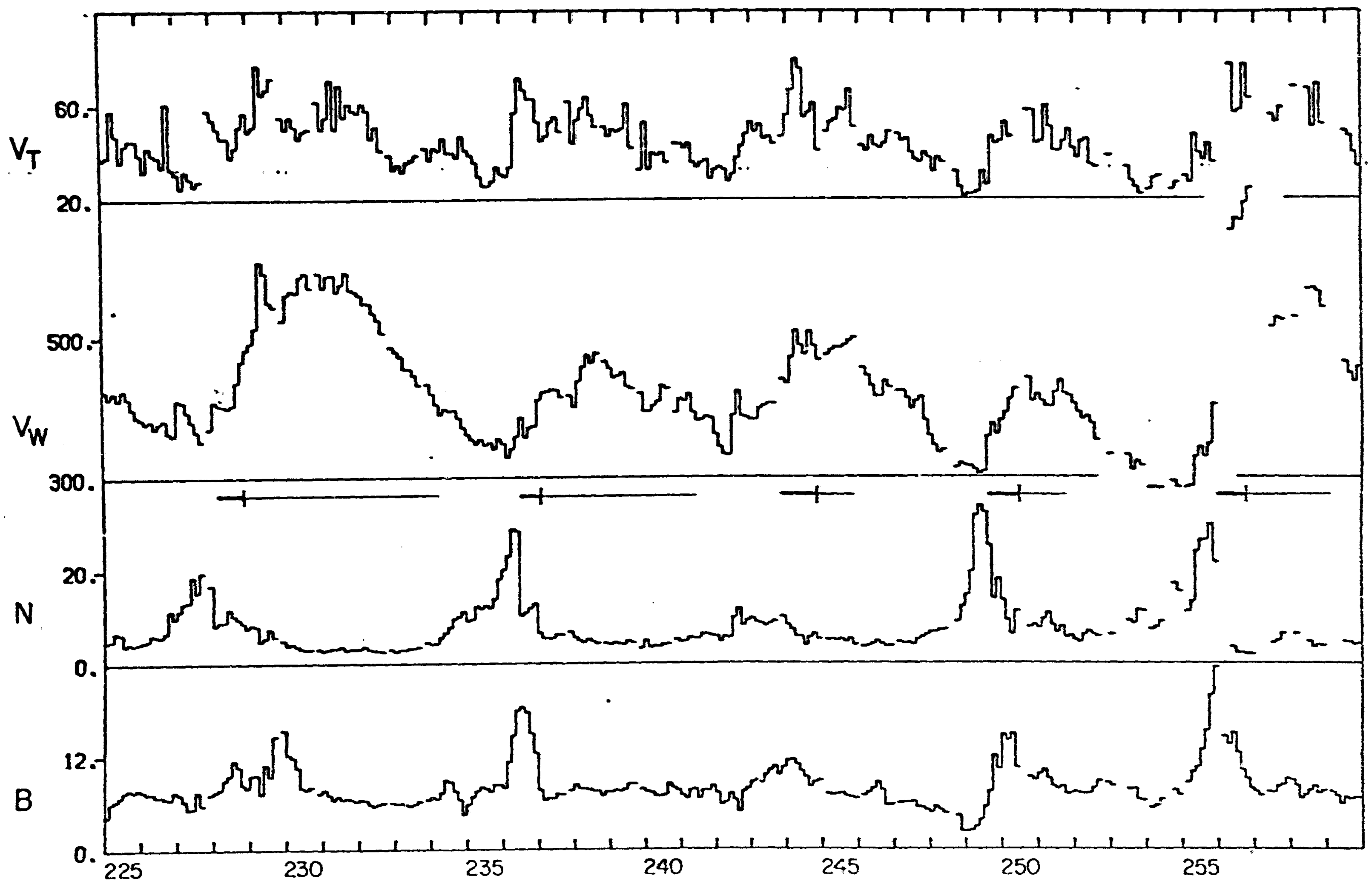


Figure 2. Three-hour averages of Mariner 5 wind velocity, density, and magnetic polarity for 6 solar rotations (see pg. 23).



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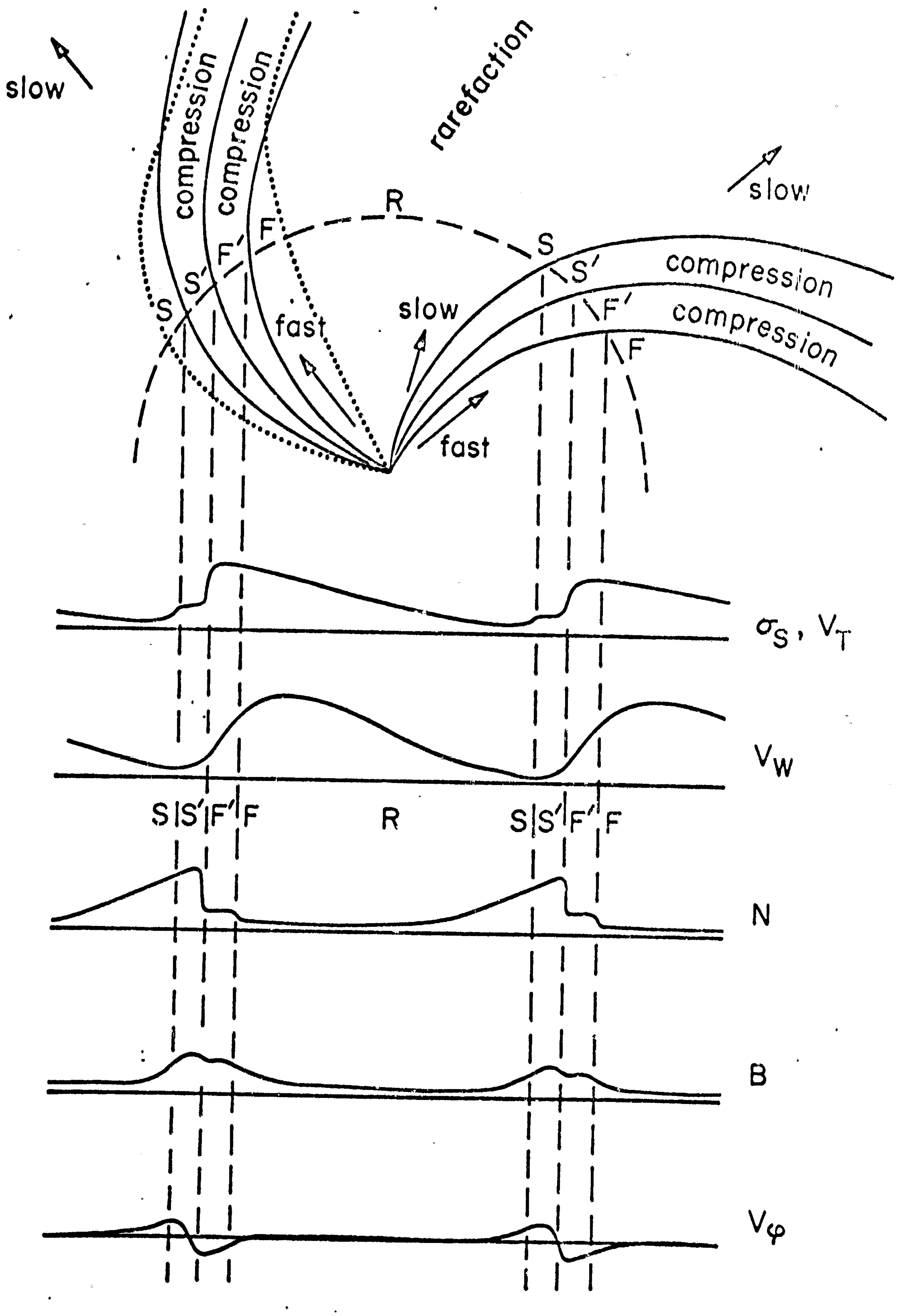
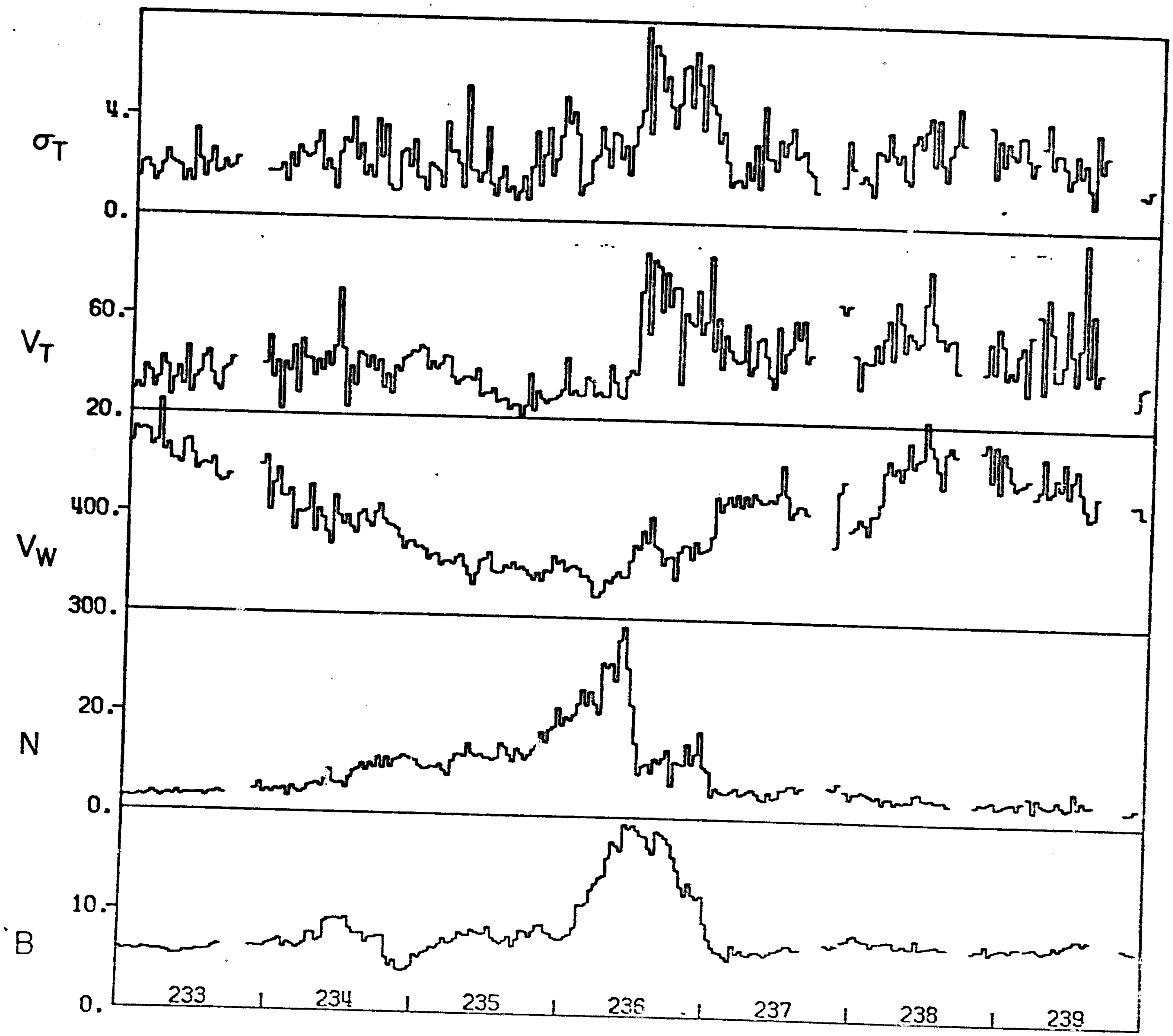


Figure 4. Top: two compression regions and one rarefaction region produced by the interaction of high and low velocity streams. Bottom: typical schematic curves showing, as functions of time, the changes in solar wind parameter as observed by a spacecraft. (see pg. 23)



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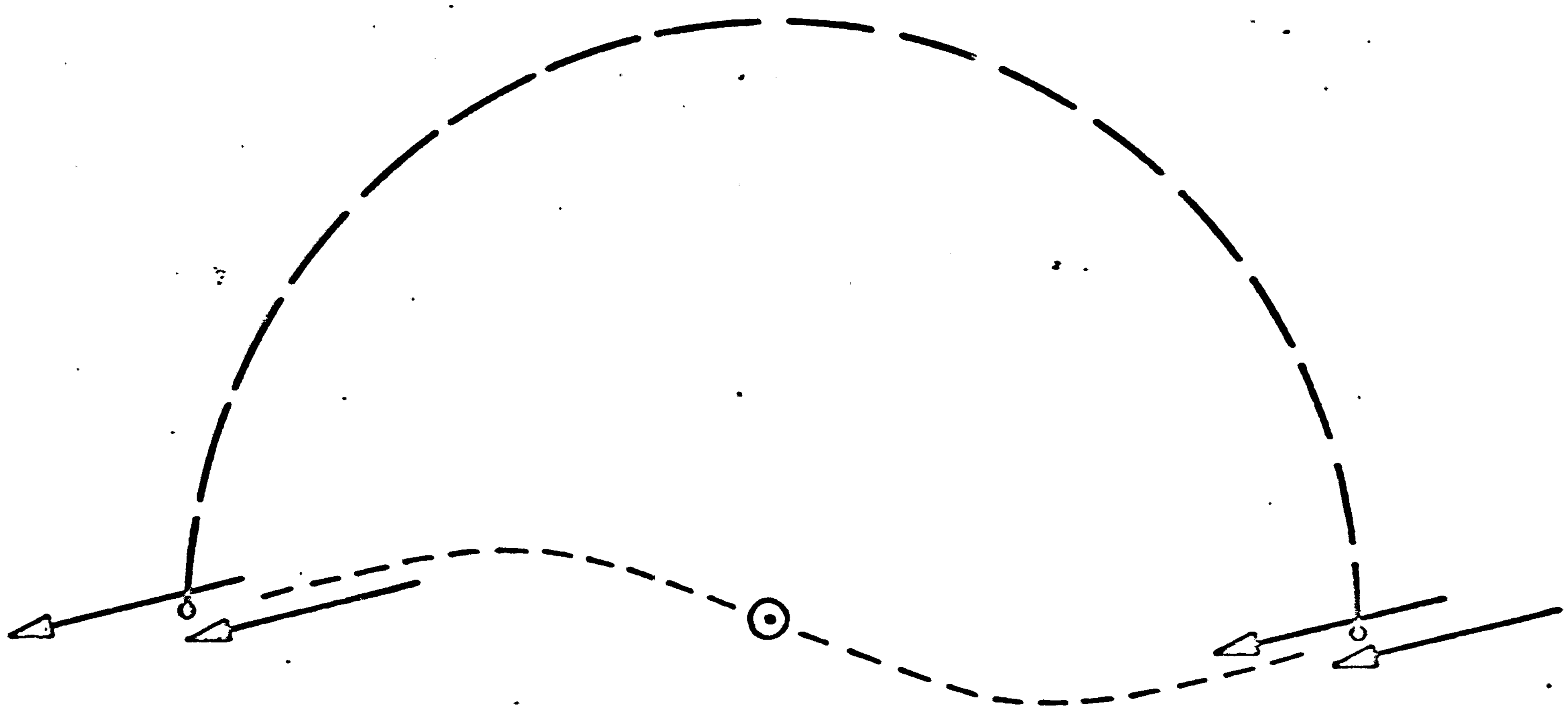

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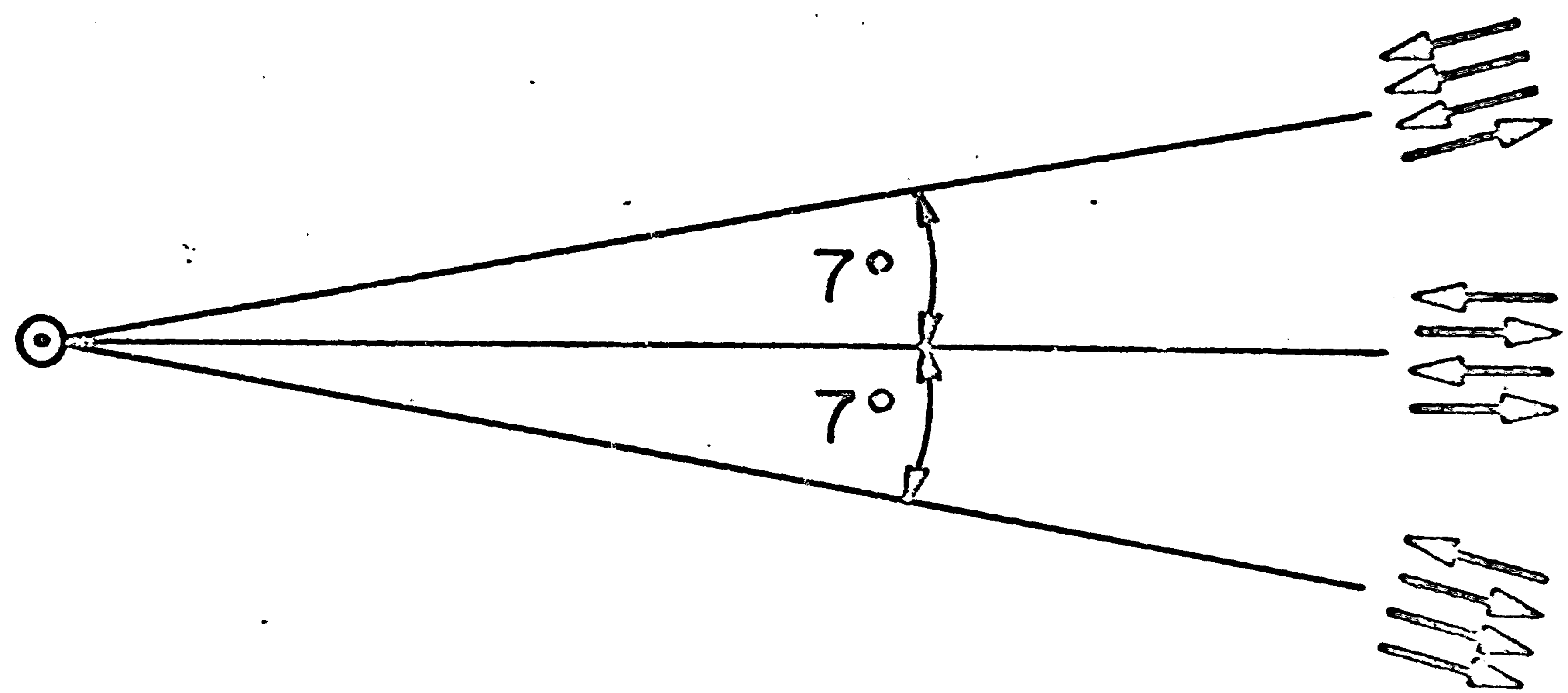

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