NASA

Technical Memorandum 84956

COROTATING PRESSURE WAVES WITHOUT STREAMS IN THE SOLAR WIND

L. F. Burlaga

JANUARY 1983

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

COROTATING PRESSURE WAVES WITHOUT STREAMS IN THE SOLAR WIND

by

L. F. Burlaga
NASA/Goddard Space Flight Center
Laboratory for Extraterrestrial Physics
Greenbelt, MD 20771

SUBMITTED TO: Journal of Geophysical Research

ABSTRACT

Voyager 1 and 2 magnetic field and plasma data are presented which demonstrate the existence of large scale, corotating, non-linear pressure waves between 2 AU and 4 AU that are not accompanied by fast streams. The pressure waves are presumed to be generated by corotating streams near the sun. For two of the three pressure waves that are discussed, the absence of a stream is probably a real, physical effect, viz. a consequence of deceleration of the stream by the associated compression wave. For the third pressure wave, the apparent absence of a stream may be a geometrical effect; it is likely that the stream was at latitudes just above those of the spacecraft, while the associated shocks and compression wave extended over a broader range of latitudes so that they could be observed by the spacecraft. It is suggested that the development of large-scale non-linear pressure waves at the expense of the kinetic energy of streams produces a qualitative change in the solar wind in the outer heliosphere. Within a few AU the quasi-stationary solar wind structure is determined by corotating streams whose structure is determined by the boundary conditions near the sun. Beyond several AU there is a zone in which the solar wind structure is determined by non-linear pressure waves without streams, in which memory of the source conditions has largely been erased. Far from the sun ($\gtrsim$ 25 AU) these pressure waves should interact extensively with one another producing a zone which is more homogeneous on a large-scale yet more disordered on a smaller scale, where a statistical description may be more appropriate than deterministic models. This new view of heliospheric structure should provide a better foundation on which to interpret retrospectively prior observations and to analyze future data with respect to basic physical processes.

1. Introduction

Solar wind observations made in the outer heliosphere by Pioneers 10 and 11 and by Voyagers 1 and 2 showed that corotating streams may exist out to 10 AU or more. However, the statistical distribution of speeds (measured over a solar rotation, for example) is narrower at larger distances (Collard and Wolfe, 1974; Collard et al., 1982). This is interpreted as the result of a decrease in bulk speed at leading edge of any given corotating stream and an increase in the speed of the ambient flow ahead of the stream, both resulting from the interaction (collision) between the stream and the ambient flow (Hundhausen and Gosling, 1976). Burlaga et al. (1980) identified a corotating stream in the Imp 8 data at 1 AU and in the Helios 1 and 2 data inside of 1 AU, which was not observed by Voyagers 1 and 2 at 1.6 AU even though the latter were very close to the Imp 8-sun line. The stream interface seen by the Imp 8 and Helios 1 and 2 was observed at Voyagers 1 and 2 with the proper corotation time, so it is not likely that the absence of a stream at 1.6 AU was a latitude effect (The latitudinal separation between Voyager 1 and Imp 8 was only 1.5°). Burlaga et al. suggested that the disappearance of the stream was a dynamical effect rather than a geometrical one, associated with the relatively low momentum flux of this stream. They argued that the compression wave generated by the stream interaction propagated back through the stream and decelerated it to near-ambient speeds, effectively eliminating the signature of the stream. Application of a 2-D version of a MFD model of (Pizzo, 1982) to this flow system, with Imp 8 data as input conditions and the projection to Voyagers 1 and 2 as output (Burlaga et al., 1983a), confirmed that for this particular flow the interaction could effectively annihilate the stream, leaving only a remnant of the original stream at 1.6 AU.

It is well-known that at 1 AU a corotating stream is accompanied by a high field strength B, high density N and high proton temperature T_p in the region where the speed V is increasing. The "total" pressure $P_T = NkT_p + B^2/(8\pi)$ is thus higher in this region than elsewhere. Burlaga and Ogilvie (1970) called the high pressure region ahead of a corotating or transient stream the "interaction region", and they discussed the dynamical

importance of such regions. Siscoe (1972) analyzed high pressure regions ahead of corotating streams and referred to them as interaction fronts. The high pressure region is a "compression wave", generated by the transfer of kinetic energy of the flow into internal energy and magnetic energy. The existence of such a compression wave was initially suggested by Sarabhai (1963), who also proposed the existence of a rarefaction wave in the region of decreasing bulk speed. The rarefaction wave is usually much less evident at 1 AU than the compression wave. It should be noted that at $\gtrsim$ 1 AU the so-called compression wave is actually expanding at a speed of the order of the magnetoacoustic speed in the direction transverse to $\underset{\sim}{B}$ (e.g., see Burlaga, 1975 and Hundhausen and Gosling, 1976). The name refers to the fact that it originates in a collision in which converging characteristics generate a high-pressure wave.

It is now known that at sufficiently large distances from the sun the compression region may be bounded in the front by a forward shock and in the rear by a reverse shock. The occurrence of such shocks was suggested and modeled by Parker (1963), Dessler and Fejer (1963), Sonett and Colburn (1965), Simon and Axford (1966), Schubert and Cummings (1967), Formisano and Chao (1972), Hundhausen (1973a, b) Dryer and Steinolfson (1976), Dryer et al. (1978) and Pizzo (1980). Observations of shock pairs beyond 1 AU are discussed by Smith and Wolfe (1977), Hundhausen and Gosling (1976), Gosling et al. (1976), Smith (1979), Smith and Wolfe (1977) and Burlaga et al. (1980). A corotating reverse shock wave was observed at 1 AU by Burlaga (1970), but it was not accompanied by a forward shock. Whang and Chien (1981) showed theoretically that a reverse shock can form without a forward shock.

In this paper we use the word "corotating pressure wave" to denote both the high-pressure compression wave and the low-pressure rarefaction wave seen in the $P_T(t)$ profile. It is a wave in the sense that it is a corotating pattern and also in the sense that it is a dynamical system governed primarily by pressure gradients and inertia. The compression and rarefaction regions do not propagate radially as a whole relative to the solar wind. It will be shown that corotating pressure waves can be observed even in the absence of streams, i.e., in the absence of flows with

speeds $\gtrsim$ 450 km/s lasting a few days or more. We shall discuss two ways in which a corotating pressure wave might be observed without a stream. The first is a physical process in which a stream produces a pressure wave near the sun but is subsequently decelerated very substantially by the reaction of the compression wave and by the kinematic tendency of the fast plasma to advance into the interaction region. This process will be discussed in terms of two examples in Section 3. The second way in which a corotating pressure wave might be observed without a stream is a geometrical effect. The stream might be bounded sharply in latitude (Schwenn et al., 1978) so that it is not detected by a spacecraft above or below the stream, but the pressure wave might extend meridionally beyond the edge of the stream just as a bow shock extends over a much larger dimension than the obstacle which produces it. An example of such a configuration is discussed in Section 4.

The data that we use are hour averages from the GSFC magnetometers and the MIT plasma analyzers on Voyagers 1 and 2; the Principal Investigators are N. F. Ness and H. Bridge, respectively. We shall consider three events, observed between 2.2 AU and 4.6 AU. The spacecraft trajectories in this interval are shown in Figure 1. Note that Voyager 1 (V1) and Voyager 2 (V2) are close together in the inertial heliographic (IHG) plane projection X_{IHG}-Y_{IHG}. The latitudinal separation $\Delta\theta_{SC}$ diminishes from 3.2° on January 27, 1978 to 1.0° on March 27, 1978.

2. General Features of Three Corotating Pressure Waves without Streams

Three pressure waves and the associated speed profiles are shown in Figure 2. These were observed by Voyager 1 in the period January 27-31, October 6-15, and November 12-20 in 1978 at radial distances of 2.2 AU, 4.3 AU and 4.6 AU, respectively. The electron temperature measurements were not available, so we follow the tradition of ignoring it in the pressure P_T. Of course, the electrons are expected to make a significant contribution to the pressure, but this should not qualitatively alter the shape of the pressure profile, which is the principal concern in this paper. For example, using the polytropic law and radial, variation for electron temperature given by Sittler and Scudder (1980), we found only a small reduction in the amplitude of the pressure wave relative to that computed with $T_e = 0$.

Each of the pressure waves shows both a compression and a rarefaction relative to the ambient flow ahead. The amplitudes of these two components are large (note that pressure is plotted on a log scale). Specifically, the ratio of the maximum pressure to the minimum pressure ranges from 70 to 150 (see Table 1). Thus, the three pressure waves selected for this study are major perturbations in the ambient flow. They are non-linear waves. Comparing the pressure profiles on the left of Figure 2 with the corresponding speed profiles on the right, one sees that there are no streams associated with the pressure waves. In contrast to the familiar case in which streams are regarded as a primary phenomenon with pressure waves as an associated feature, here we observed pressure waves as a primary phenomenon which appears to be independent of any local stream.

It will be shown in the following sections that the pressure waves in Figure 2 are probably corotating configurations. Let us assume this and estimate their spatial dimensions as seen by an observer looking down on the ecliptic plane. In Figure 3 the relative sizes of the high and low pressure regions are shown correctly to scale by the intersections of the spirals with the radial lines. These spirals are drawn extending to the sun without regard to dynamical changes, so the width is probably exaggerated near the sun. Nevertheless, the figure serves to illustrate

the point that the pressure waves are large-scale features, with a radial cross-section of ∿ 2 AU when the wave arrives at ∿ 4 AU and extending over a wide range in both longitude and radius. We are discussing large-scale, non-linear waves whose size is comparable to that of corotating streams.

The width of the compression wave, ∿2 AU when the middle of the wave is at ∿ 3 AU, can be understood very roughly in terms of the tendency to expand normal to $\underset{\sim}{B}$ at a rate of the order of the magnetoacoustic speed. Assuming that the width of the pressure wave is zero at the sun, and assuming an expansion speed of the order of twice the magnetoacoustic speed ($2 V_m$ ∿ 2 x √2 x 50 km/s ∿ 150 km/s). The width of the interaction region, after the time that it takes for the flow to move from the sun to 3 AU (viz. ∿ 10 days) is ∿ 1 AU. This is consistent with the result shown in Figure 3. Figures 2 and 3 show that by the time the front of the pressure wave reaches 4 AU, the compression wave is nearly 2/3 the size of the total pressure wave.

From observations made at 1 AU it is well-known that the density and magnetic field strength are both enhanced in the compression wave in front of streams, but the rarefaction wave is much less evident in the B(t) profile and the low density observed in the body of the stream is largely due to the low density at the origin of the streams (coronal holes). However, as the compression and rarefaction waves grow with increasing distance from the sun at the expense of kinetic energy of the stream, one expects to see a stronger correlation between B and N, because the field is frozen to the plasma and because details of the source function tend to be lost in highly non-linear waves. Log-log plots of B vs N for the three pressure waves that we have been discussing are shown in Figure 4. Both Voyager 1 and Voyager 2 observations were used. These plots, which include both the compression and expansion waves, show a strong correlation between B and N. The results of the least square fits are given in Table 1. Such a strong correlation between B and N is not observed in streams at 1 AU. It represents an important phenomenon associated with the non-linear corotating pressure waves: they impose a new organization of the magnetic field and plasma parameters, which is governed more by interplanetary dynamical processes than by the source conditions.

3. Corotating Pressure Waves and Remnant Streams

In this section we discuss two pressure waves without streams, and we argue that the streams which produced the waves were eroded almost completely. Figure 5 shows magnetic field and plasma parameters measured by Voyagers 1 and 2 from ~ January 27 to ~ February 1. Note that the time scale at the top refers to the Voyager 2 observations (thin curves) and the time scale at the bottom refers to the Voyager 1 observations (heavy curves). The profiles for the data sets were shifted so that the stream interfaces coincide at the vertical dashed line B. The stream interface is identified by the criteria of Burlaga (1974): 1) a large abrupt drop in density N, 2) a large abrupt increase in proton temperature T_p, 3) a maximum in B(t), and 4) a transition from westward flow ($V_\lambda < 0$) to eastward flow ($V_\lambda > 0$) (see also Belcher and Davis, 1971). This signature is unambiguous in the event in Figure 5, and all available evidence in the literature suggests that it is uniquely related to the front boundary of a corotating stream. The observation of a stream interface in the pressure wave is our principal justification for calling it a corotating pressure wave.

Discontinuities A and C in Figure 5 probably represent a forward-reverse shock pair. At discontinuity A, the parameters B, N, T and V increase, consistent with the signature of a forward shock. The shock was observed somewhat farther from the interface at Voyager 1 than at Voyager 2. This is consistent with the fact that Voyager 1 was a little farther from the sun, so that the shock had time to move farther from the interface. Discontinuity C was observed by Voyager 2 as a drop in B, N, and T and an increase in V, consistent with the convection of a reverse shock past the spacecraft. Note that the reverse shock is farther from the interface than the forward shock. This is consistent with the fact that the reverse shock is moving into a region of low density and pressure while the forward shock is moving into a region of high density and relatively high pressure, for a shock wave in a low pressure region is stronger and moves faster than in a high pressure region (e.g., see Burlaga and Scudder, 1975). Discontinuity D in Figure 5 marks the end of the pressure wave. It

is identified by the abrupt rise in N and T_p, which is commonly observed at the end of streams, especially close to the sun (Rosenbauer et al., 1977).

The profiles measured by Voyager 1 are generally similar to those measured by Voyager 2. This suggests that both spacecraft were observing essentially the same flow. Further evidence in support of this conclusion is shown in Figure 6, which gives the azimuthal angle λ and the elevation angle δ of the magnetic field direction. The λ angle gives the sector polarity, and one sees that both spacecraft observed the same polarity throughout most of the pressure wave, as they should if both are observing the same flow system. However, there are some interesting differences in detail that are worth noting. First, V1 and V2 observed different polarities just prior to the arrival of the pressure wave, suggesting that they were straddling the heliospheric current sheet. Likewise different polarities were observed for half a day following the forward shock, possibly for the same reason. The changes in polarity might be due to motions of the current sheet induced by the shock. Following the interface, the polarity observed by V2 was uniform for the most part and close to the spiral direction, whereas the azimuthal direction observed by V1 was more variable. This might indicate that V1 was closer to the heliospheric current sheet, and thus farther from the center (maximum) of the wave than V2. This conjecture is supported by the observations in Figure 5, which indicate that behind the interface V2 observed higher B, N and T than V1 in the compression wave and lower B, N and T in the rarefaction wave. Similarly, the bulk speed observed by V2 was slightly higher than that of V1 suggesting that V2 was closer to the body of the stream which generated the pressure wave. Collectively, these results suggest that we are observing flow that was near the edge of a stream. Nevertheless, the existence of a clear interface indicates that both spacecraft had crossed into a stream flow region, and the absence of high speeds might be attributed to the deceleration of the flow at those latitudes by the compression wave. We cannot exclude the possibility that the wave was still driven by a fast flow at higher latitudes.

Let us now turn to another event, a corotating pressure observed by Voyager 2 at 4.3 AU between October 5 and October 14, 1978. The basic

magnetic field and plasma parameters are shown in Figure 7 in the same format as Figure 5. The data from V2 have been shifted relative to those from V1 so that the interfaces coincide at the dashed line B. Note that unlike the previous event, there are no systematic differences in the profiles. In this case, there is again an abrupt increase in T_p and change in the flow direction across the interface. The magnetic field is high at the interface, but there is no clear, narrow maximum such as is usually observed close to 1 AU. The pressure profile in Figure 2 shows the same result, which may be explained as follows. At this large distance the momentum of the stream was no longer high enough to maintain the collision and support a corresponding pressure wave. A narrow compression wave (which was presumably produced closer to the sun) expanded, distributing the magnetic energy over a larger volume and thereby reducing the maximum field strength relative to the ambient flow.

The density falls behind the interface, but in this case the decline is gradual rather than abrupt as seen closer to the sun. The reason for this is not clear, but one possiblity is that a mixing process occurs at the interface as a result of the velocity shear there. At the front of the compression wave (line A in Figure 7) B, N, T_p and V increase within a few hours, consistent with the passage of a forward shock, but there was a data gap so that the shock itself was not observed. At the rear of the compression wave (line C) Voyagers 1 and 2 observed a reverse shock. Again the reverse shock is much farther from the interface than the forward shock, probably for the same reason given above in our discussion of the January, 1978, event. The pressure wave ends at the line D in Figure 7, which is actually a forward shock from another flow.

The results just described all indicate that the October event is a corotating pressure wave, but there is no significant stream associated with it. We suggest that in this case, as in the January, 1978 event, the stream was eroded as a result of the tendency of fast plasma to advance into the sunward propagating part of the compression wave which decelerates it by virtue of the large adverse pressure gradient.

We conclude this section by summarizing the conceptual model that was introduced as an explanation of the two events described. As illustrated in the top-left panel of Figure 8, we assume that near the sun there is a mesa-like speed profile, corresponding to a stream issuing from a sharply bounded coronal hole, as suggested by the Helios observations (Burlaga, 1979). The pressure profile is not known, but we assume a constant pressure and thus no pressure wave. Initially the velocity gradient is entirely a shear, but as the stream moves away from the sun a component of velocity appears normal to the interface, owing to the corotation caused by the rotation of the sun. A collision ensues, and the momentum of the flow produces a pressure wave as shown in the second panel of Figure 8. This pressure wave grows as magnetic and thermal energy increase at the expense of kinetic energy of the flow, and eventually a shock pair forms. The reverse shock propagates into the stream as the fast material in the stream advances toward it, eroding the velocity profile, as shown in the third panel of Figure 8. The process just described is well-known (for references, see the reviews by Burlaga, 1979 and Gosling, 1981). The subsequent evolution is governed by the fact that the stream loses its momentum owing to the deceleration by the compression wave and a rarefaction produced by the expansion wave. The compression wave is no longer driven by a stream; it expands freely as an independent entity, further decelerating the remaining stream, and eventually a pressure wave is observed without a stream.

The process just described is probably a general one for corotating flows. In fact it is generally accepted that stream profiles are eroded with time. However, the essential process is not simply the smoothing of the velocity profile by conversion of kinetic energy into heat, but rather the conversion of a large-scale inhomogeneous flow into an internal wave field. Thus, the corotating streams which dominate the medium near the sun give rise to large, non-linear corotating pressure waves far from the sun. This process produces a qualitative change in the medium at large distances. The internal wave field looses memory of the source conditions and evolves in response to pressure gradients rather than gradients in speed. This conversion from streams near the sun to corotating pressure waves between $\sim$ 5 to 10 AU is illustrated schematically in Figure 9.

How does a corotating pressure wave evolve at large distances? One possibility is that it simply produces a secondary flow, as magnetic energy is converted back into kinetic energy. More likely, however, the neighboring pressure waves will interact producing heating and mixing, thereby further reducing the large-scale inhomogeneity of the solar wind. If the width of the compression wave continues to grow at a rate of $\sim$ 1 AU per 3 AU (see section 2) its width at $\sim$ 25 AU will be 7 AU , which is the distance that the solar wind moves in one solar rotation. Beyond $\sim$ 25 AU the compression waves from one rotation will rather thoroughly interact with those of the next, as well as with others from the same rotation. Thus, beyond $\sim$ 25 AU the mutual interactions of internal waves will have been very extensive, effectively obliterating the last vestiges of the signatures of the streams and their coronal origins (see Figure 9). At that point a statistical description of the solar wind will become more appropriate.

The dynamics of the outer heliosphere during "quiet times" as described above is qualitatively different from the traditional view, with significant implications for the global structure of the heliosphere and for the motion of cosmic rays through it which remain to be explored. It is important to understand that we have been discussing quasi-stationary flow systems. The situation at active times when there are many transients in the solar wind as well as corotating systems is more complicated (see e.g., Burlaga et al., 1982, 1983b) and it is probably such systems of transients that cause the modulation of cosmic rays (Burlaga et al., 1982; Mc Donald et al., 1982; and see also Barouch and Burlaga, 1975).

4. Corotating Pressure Waves without Streams as Edge Flows

Here we discuss another way in which corotating pressure waves might be observed without observing streams, which is illustrated in Figure 10. Suppose that a corotating stream is sharply bounded in latitude and lies just above the ecliptic plane. The cross-section of the stream tube is arbitrarily shown as elliptical, but the detailed shape is not important. A compression wave will develop in front of the stream, the maximum pressure occurring near the center of the stream, well above the latitude of a spacecraft in the ecliptic. A forward shock will develop at the front of the compression wave as a kind of bow shock. Just as a bow shock in front of an obstacle has a much larger extent than the obstacle, this corotating shock will extend beyond the boundaries of the stream, and in particular it will extend meridionally past the ecliptic plane where it can be observed even though the stream is not detected. The compression wave will also extend beyond the boundaries of the stream, for it expands at a speed of the order of the magnetoacoustic speed meridionally as well as radially. Thus, in this way one might observe a pressure wave without a stream, yet it would be incorrect to say that the stream has been dynamically eroded. The apparent absence of a stream is simply a geometrical effect; the stream may be present, but it is not seen. A dynamical model of such a 3-D configuration has been presented by Pizzo (1980, 1982).

Does the configuration described above occur? If so, how can one distinguish it from the case described in the previous section? Answers to these questions are given by the results in Figure 11, which gives plasma and magnetic field parameters for the third pressure wave without stream described in section 2. Again one sees a forward shock, followed by a compression wave with high B, N and T_p which is in turn followed by a rarefaction wave with low B, N and T_p. The essential difference between this case and the others is in the nature of the stream interface. Since the interface is by definition the boundary of a stream near the sun, an observer would cross it only once if the original stream were along the sun-observer line, but he would not cross it at all if the stream were at latitudes above him. Furthermore, if the original stream were along the

sun-observer line, an observer would see an east-west flow deflection as described earlier, whereas no such deflection would be seen if the stream were above him. Returning to Figure 11, one sees that between the compression and rarefaction wave there is no single interface like that in our previous examples or like that which is typically observed at 1 AU. There is a possible crossing of an interface by V1 but not V2 at the time given by the dashed line B, where the magnetic field strength has a broad maximum, N drops and T_p increases. There is no east-west deflection, suggesting that the surface corresponding to this interface is nearly parallel to the ecliptic plane. Several hours later there is an abrupt increase in N and a decrease in T_p at V1, suggesting that the spacecraft again crossed the interface, this time moving away from the stream. Finally a few hours later there is another drop in N and increase in T_p at V1, suggesting reentry into the stream region. Thus, the boundary of stream which produced the pressure was probably nearly parallel to the ecliptic, just above the latitude of Voyager 2 and very close to the latitude of V1. (Recall from Figure 1 that the latitudinal separation between V1 and V2 was only 1°!) Note that in the compression wave B, N and T_p are higher at V1 than at V2, and in the rarefaction wave they are lower at V1 that at V2, giving further support to the inference that the center of the pressure wave lies above the ecliptic. Conclusive evidence that V1 and V2 sampled different regions separated by a thin boundary is given in Figure 12 which shows the azimuthal direction λ and hence the sector polarity of the magnetic field (the other angle of $\underset{\sim}{B}$ is shown for completeness). Shortly following the third crossing of the interface, Voyagers 1 and 2 observed opposite polarities for 5 days, i.e., through most of the pressure wave. Thus, there was a sector boundary surface between V1 and V2. It is known that stream interfaces are close to sector boundaries (e.g., Gosling et al., 1978 and Klein and Burlaga, 1980) so that we may infer that the stream interface boundary, if present at all, must be nearly parallel to the sector boundary surface, close to the ecliptic plane and nearly between V1 and V2.

Thus, the configuration of the flow just described probably resembles that in Figure 10. It is possible that even in this case the stream was eroded, but V1 and V2 did not enter the body of the stream, so we cannot tell whether or not a stream was present.

5. Summary and Conclusions

We have demonstrated the existence of large-scale non-linear corotating pressure waves between 2 AU and 4 AU which are observed without an accompanying stream. It is suggested that these pressure waves represent compression/rarefaction waves generated by corotating streams closer to the sun. The absence of an accompanying stream can be explained in two ways, one geometrical and one physical. Streams can be sharply bounded in latitude and the pressure wave can extend beyond the stream in latitude as well as in the radial direction, so that it is possible to observe the pressure wave without passing through the stream if the stream lies above or below the spacecraft. Alternatively, a stream originating near the sun and directed at the observer might be decelerated by the pressure wave, so that a stream would not be seen at large distances. We have given examples of both situations. The geometrical effect requires a special relation between the positions of the stream and the spacecraft, so it should be observed relatively infrequently. It cannot explain the general diminution of streams with increasing distance from the sun that has been observed.

We suggested that the formation of pressure waves accompanying the erosion of streams is a general process, so that at large distances from the sun, say $\sim$ 10 AU, the interplanetary medium may be dominated by pressure waves rather than by streams as it is closer to the sun. In other words, there may be a qualitative change in the interplanetary medium, illustrated in Figure 9. Near the sun ($\lesssim$ few AU) the dominant structures are fast streams which carry strong identifiable signatures of their solar origin, whereas farther from the sun (several AU) the dominant structures are non-linear pressure waves in which coronal signature is less evident and the relations among the plasma and magnetic field parameters are largely determined by the dynamics of the wave. Still farther from the sun, the pressure waves will interact, like waves forming the surf on a beach. (Within $\sim$ 10 AU, the fast streams may overtake and entrain slow streams (Burlaga et al., 1983b); the wave-wave interaction is a different process.) Beyond $\sim$ 25 AU these wave-wave interactions will be very extensive, and the medium will be thoroughly mixed, leaving little

recognizable signature of the streams and coronal signals that generated them. In this way the solar wind at large distances should become more homogeneous on a large scale and more disordered on smaller scales, first as a result of the erosion of streams by the compression waves, and ultimately by very extensive, non-linear wave-wave interactions. The transition is basically an irreversible thermodynamic process, for the temperature will increase at the expense of kinetic energy.

Acknowledgments

We thank the Principal Investigators of the magnetic field and plasma experiments, Drs. N. F. Ness and H. R. Bridge, respectively, for permission to use their data, and L. W. Klein for preparing the data plots. Helpful comments on a draft of the manuscript were provided by Drs. N. F. Ness and A. J. Lazarus.

References

Barouch, E. and L. F. Burlaga, Causes of Forbush decreases and other cosmic ray variations, J. Geophys. Res., 80, 449, 1975.

Belcher, J. and L. Davis, Jr., Large-amplitude Alfvén waves in the interplanetary medium, 2, J. Geophys. Res., 76, 3534, 1971.

Burlaga, L. F., A reverse hydromagnetic shock in the solar wind, Cosmic Electrodynamics, 1, 233, 1970.

Burlaga, L. F., Interplanetary stream interfaces, J. Geophys. Res., 79, 3717, 1974.

Burlaga, L. F., Interplanetary streams and their interaction with the earth, Space Sci. Rev., 17, 327, 1975.

Burlaga, L. F., Magnetic fields, plasmas, and coronal holes: The inner solar system, Space Sci. Rev., 23, 201, 1979.

Burlaga, L. F. and K. W. Ogilvie, Magnetic and thermal pressures in the solar wind, Solar Phys., 15, 61, 1970.

Burlaga, L. F., and J. D. Scudder, Motion of shocks through interplanetary streams, J. Geophys. Res., 80, 4004, 1975.

Burlaga, L. F., V. Pizzo, and A. J. Lazarus, Stream evolution and shock formation, to be submitted to J. Geophys. Res., 1983a.

Burlaga, L., R. Lepping, R. Weber, T. Armstrong, C. Goodrich, J. Sullivan, D. Gurnett, P. Kellogg, E. Keppler, F. Mariani, F. Neubauer, H. Rosenbauer, and R. Schwenn, Interplanetary particles and fields, November 22 to December 6, 1977: Helios, Voyager and Imp observations between 0.6 and 1.6 AU, J. Geophys. Res., 85, 2227, 1980.

Burlaga, L. F., F. B. Mc Donald, R. Schwenn, and A. J. Lazarus, Interplanetary flow systems associated with cosmic ray modulation in 1977-1980, Bulletin of the American Physical Society, 27, 571, 1982.

Burlaga, L. F., K. W. Ogilvie, D. H. Fairfield, M. D. Montgomery, and S. J. Bame, Energy transfer at colliding streams in the solar wind, Astrophys. J., 164, 137, 1971.

Burlaga, L. F., R. Schwenn, and H. Rosenbauer, Dynamical evolution of interplanetary magnetic fields and flows between 0.3 AU and 8.5 AU: Entrainment, submitted to Geophys. Res. Lett., 1983b.

Collard, H. R. and J. H. Wolfe, Radial gradient of solar wind velocity from 1 to 5 AU, Solar Wind Three, Ed., C. T. Russell, p. 281, Inst. of Geophysics and Planetary Physics, U. of California, Los Angles, 1974.

Collard, H. R., J. D. Mihalov, and J. H. Wolfe, Radial variation of the solar wind speed between 1 and 15 AU, J. Geophys. Res., 87, 2203, 1982.

Dessler, A. J. and J. A. Fejer, Interpretation of Kp index and M-region geomagnetic storms, Planet. Space Sci., 11, 505, 1963.

Dryer, M. and R. S. Steinolfson, MHD solution of interplanetary disturbances generated by simulated velocity perturbations, J. Geophys. Res., 81, 5413, 1976.

Dryer, M., Z. K. Smith, E. J. Smith, J. D. Mihalov, J. H. Wolfe, R. S. Steinolfson, and S. T. Wu, Dynamic MHD modeling of solar wind corotating stream interaction regions observed by Pioneer 10 and 11, J. Geophys. Res., 83, 4347, 1978.

Formisano, V. and J. K. Chao, On the generation of shock pairs in the solar wind, Cosmic Plasma Physics, Ed., K. Schindler, p. 103, Plenum, New York, 1972.

Gosling, J. T., Solar wind stream evolution, Solar Wind Four, ed. H. Rosenbauer, Report Number MPAE-W-100-81-31, p. 107, 1981.

Gosling, J. T., J. R. Asbridge, S. J. Bame, and W. C. Feldman, Solar wind stream interfaces, J. Geophys. Res., 83, 1401, 1978.

Gosling, J. T., A. J. Hundhausen, and S. J. Bame, Solar wind evolution at large heliocentric distances: Experimental demonstration and the test of a model, J. Geophys. Res., 81, 2111, 1976.

Hundhausen, A. J., A non-linear model of high-speed solar wind streams, J. Geophys. Res., 78, 1528, 1973a.

Hundhausen, A. J., Evolution of large-scale solar wind structures beyond 1 AU, J. Geophys. Res., 78, 2035, 1973b.

Hundhausen, A. J. and Gosling, Solar wind structure at large heliocentric distances: An interpretation of Pioneer 10 observations, J. Geophys. Res., 81, 1436, 1976.

Klein, L. W. and L. F. Burlaga, Interplanetary sector boundaries: 1971-1973, J. Geophys. Res., 85, 2269, 1980.

Mc Donald, F. B., L. F. Burlaga, J. H. Trainor, M. A. I. Van Hollebeke, and T. von Rosenvinge, Observation of the long term cosmic ray modulation between 1 and 25 AU, Bulletin of the American Physical Society, 27, 571, 1982.

Parker, E. N., Interplanetary Dynamical Processes, Interscience Publishers, New York, 1963.

Pizzo, V. J., A three-dimensional model of corotating streams in the solar wind, 2. Hydrodynamic streams, J. Geophys. Res., 85, 727, 1980.

Pizzo, V. J., A three-dimensional model of corotating streams in the solar wind, 3. Magnetohydrodynamic streams, J. Geophys. Res., 87, 4374, 1982.

Rosenbauer, H., R. Schwenn, E. Marsch, B. Meyer, H. Miggenreider, M. D. Montgomery, K. -H. Mühlhäuser, W. Pillip, W. Vogés, and S. Zink, A survey of initial results of the Helios plasma experiment, J. Geophys., 42, 561, 1977.

Sarabhai, V., Some consequences of nonuniformity of solar wind velocity, J. Geophys. Res., 68, 1555, 1963.

Schubert, G. and W. D. Cummings, The double shock wave structure in the solar wind, J. Geophys. Res., 72, 52775, 1967.

Schwenn, R., M. D. Montgomery, H. Rosenbauer, H. Miggenrieder, and K. H. Mühlhäuser, S. J. Bame, W. C. Feldman, and R. T. Hansen, Direct observation of the latitudinal extent of a high-speed stream in the solar wind, J. Geophys. Res., 83, 1011, 1978.

Simon, M. and W. I. Axford, Shock waves in the interplanetary medium, Planet. Space Sci., 14, 901, 1966.

Siscoe, G. L., Structure and orientation of solar wind interaction fronts: Pioneer 6, J. Geophys. Res., 77, 27, 1972.

Sittler, E. and J. Scudder, An empirical polytrope law for solar wind thermal electrons between 0.45 and 4.76 AU: Voyager 2 and Mariner 10, J. Geophys. Res., 85, 5131, 1980.

Smith, E. J., Interplanetary magnetic fields, Rev. Geophys. Space Phys., 17, 610, 1979.

Smith, E. J. and J. H. Wolfe, Pioneer 10, 11 observations of evolving solar wind streams and shocks beyond 1 AU, in Study of Traveling Interplanetary Phenomena, M. A. Shea et al. (Eds.), pp. 227-257, D. Reidel Publishing Co., Dordrecht-Holland, 1977.

Smith, E. J. and J. H. Wolfe, Fields and plasmas in the outer solar system, Space Sci. Rev., 23, 217, 1979.

Sonett, C. P. and D. S. Colburn, The SI^+ - SI^- pair and interplanetary forward-reverse shock ensembles, Planet. Space Sci., 13, 675, 1965.

Whang, Y. C. and T. H. Chien, Magnetohydrodynamic interaction of high-speed streams, J. Geophys. Res., 86, 3263, 1981.

Figure Captions

Figure 1 — Trajectories of Voyager 1 and 2. The left panel is the equatorial plane projection of the orbits in inertial heliographic coordinates. The right panel shows the latitude of the spacecraft relative to the solar equatorial plane.

Figure 2 — Pressure profiles (left) and speed profiles (right) for three flow systems, showing the existence of large-scale non-linear pressure waves which are not accompanied by streams.

Figure 3 — Configuration of the three pressure waves shown in Figure 2. The intersection with the radial line is drawn correctly to scale. The spirals extending to the sun are only illustrative, indicating that the pressure waves are corotating structures; they are not drawn to scale near the sun.

Figure 4 — Relation between B and N for the three pressure waves observed by Voyagers 1 and 2. The proportionality is largely due to the new organization imposed by the pressure wave, rather than a signature of source conditions.

Figure 5 — Magnetic field strength and plasma parameters for the pressure wave observed by Voyagers 1 and 2 in January, 1978.

Figure 6 The magnetic field directions for the pressure wave observed by Voyagers 1 and 2 in January, 1978. The angles are in heliographic coordinates, λ being the azimuthal direction ($\lambda = 0$ when the field is directed radially away from the sun) and δ the elevation angle ($\delta = 0$ when the field is on the spacecraft-sun line).

Figure 7 Mangetic field strength and plasma parameters for the pressure wave observed by Voyagers 1 and 2 in October, 1978.

Figure 8 A sketch illustrating how a corotating stream (left) and its associated pressure wave (right) evolve with distance from the sun. Near the sun the stream is prominent and the pressure wave is small, whereas far from the sun the stream is seen only as a small remnant and the pressure wave is a prominant feature.

Figure 9 A sketch illustrating the suggested quasi-stationary large-scale interplanetary configuration. Near the sun the solar wind is dominated by corotating fast flows, near 10 AU it is dominated by corotating pressure waves (shown schematically as annuluses rather than spirals) and beyond $\sim$ 25 AU the pressure waves interact with one another, destroying the ordered spiral configurations.

Figure 10 A sketch illustrating how it is possible to observe a shock and corotating pressure wave without seeing a stream which may be present at latitudes above the observer, who is assumed to be in or near the ecliptic plane.

Figure 11 Magnetic field strength and plasma parameters for the pressure wave observed by Voyagers 1 and 2 in November, 1978.

Figure 12 Magnetic field directions for the pressure wave observed by Voyagers 1 and 2 in November, 1978 (see the caption of Figure 6).

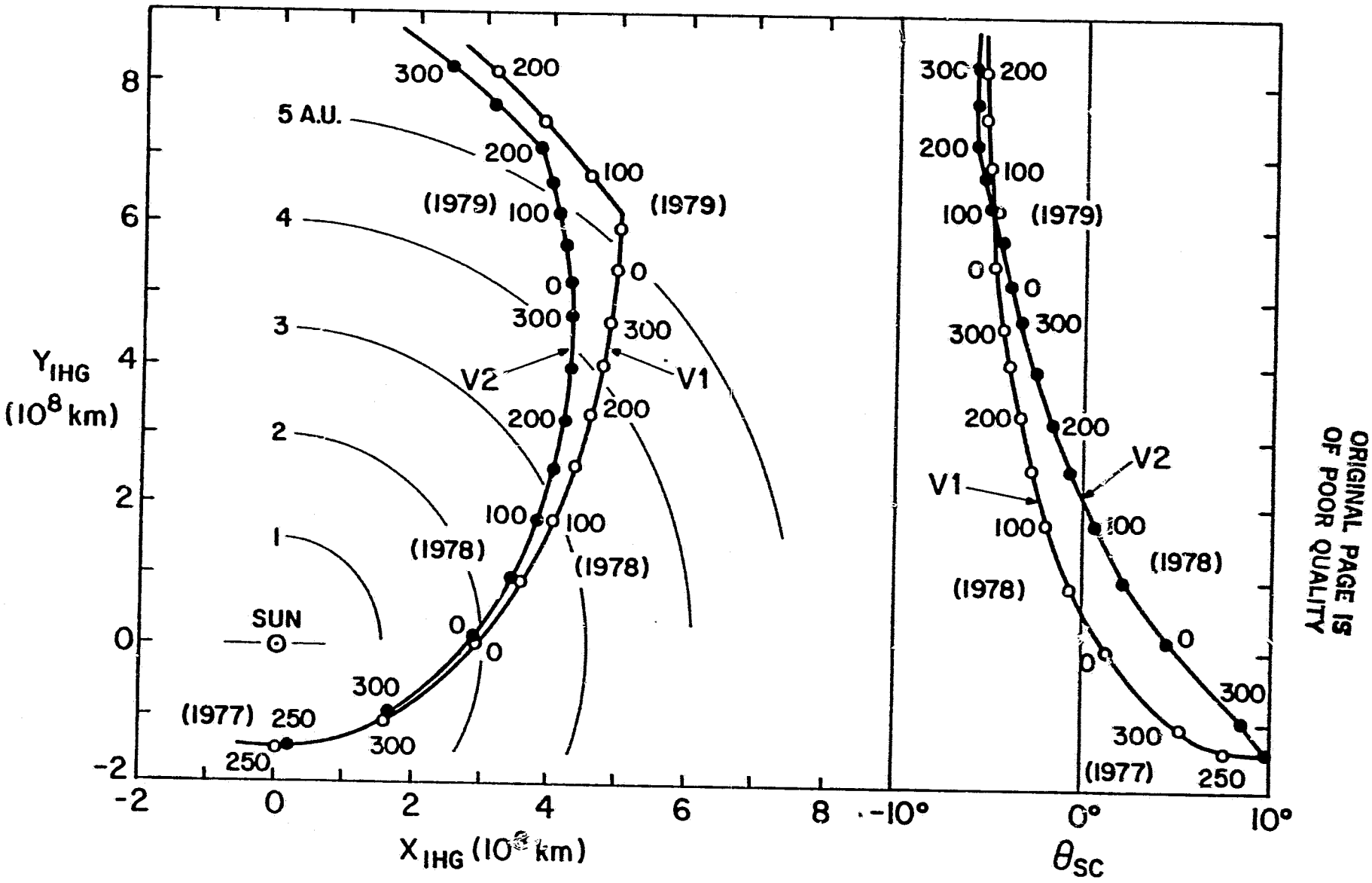

5 A.U.
4
3
2
1
SUN
V1
V2
(1977)
(1978)
(1979)
250
300
200
100
0
Y_{IHG} (10^8 km)
X_{IHG} (10^8 km)
θ_{SC}
-10°
0°
10°
ORIGINAL PAGE IS OF POOR QUALITY

Figure 1

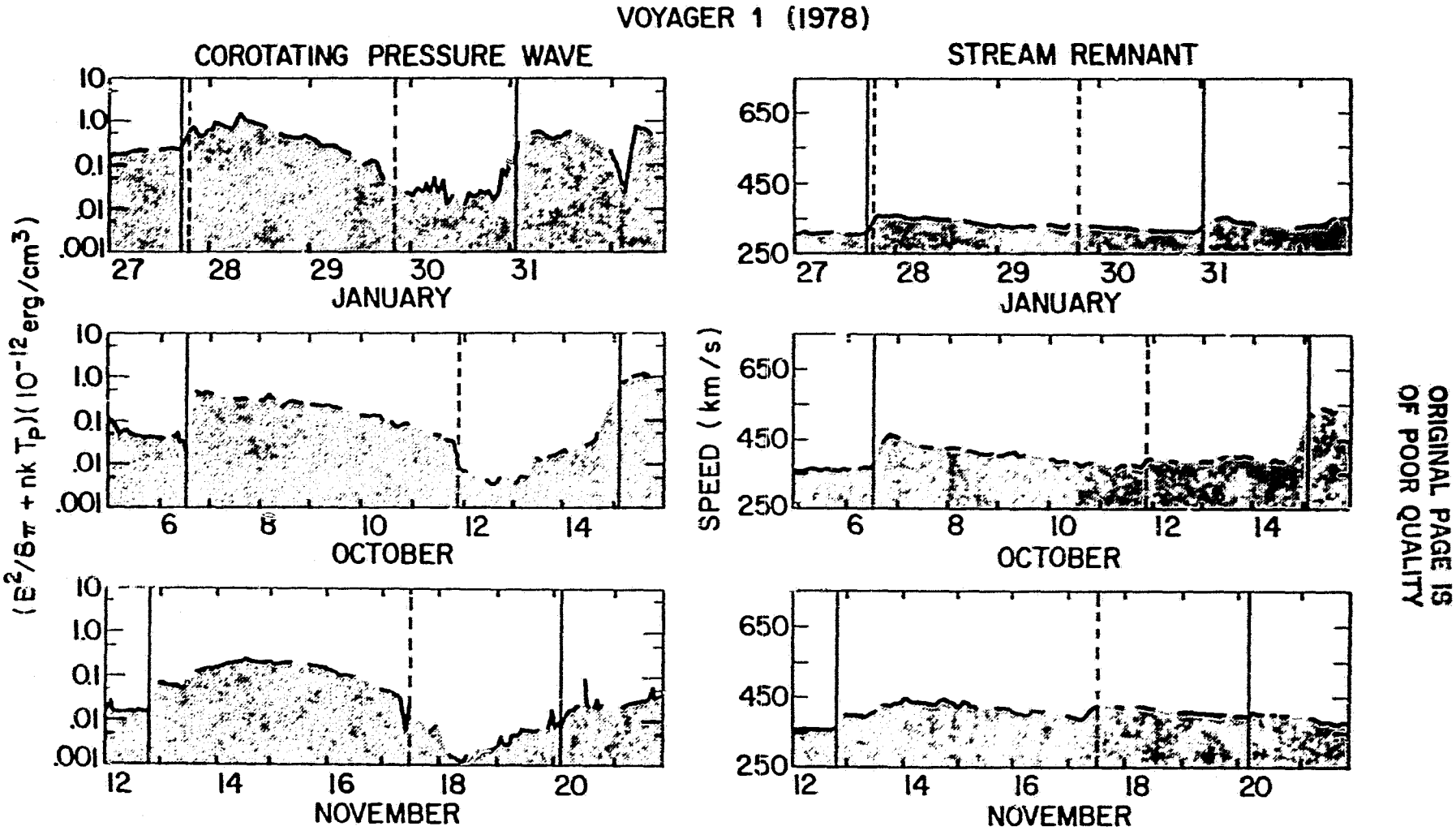
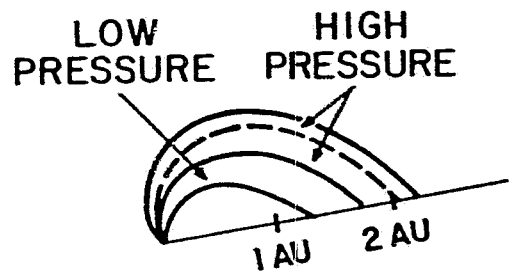
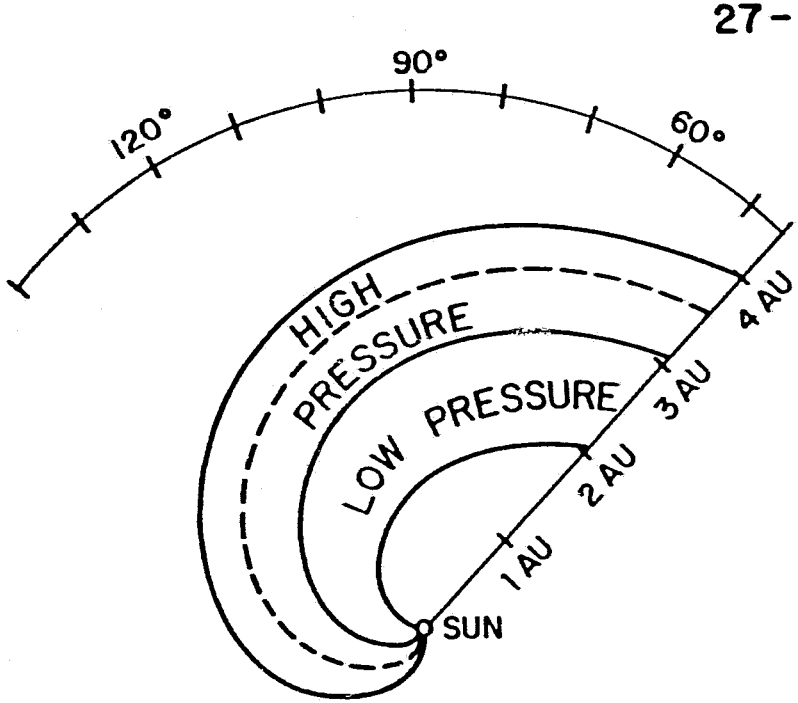


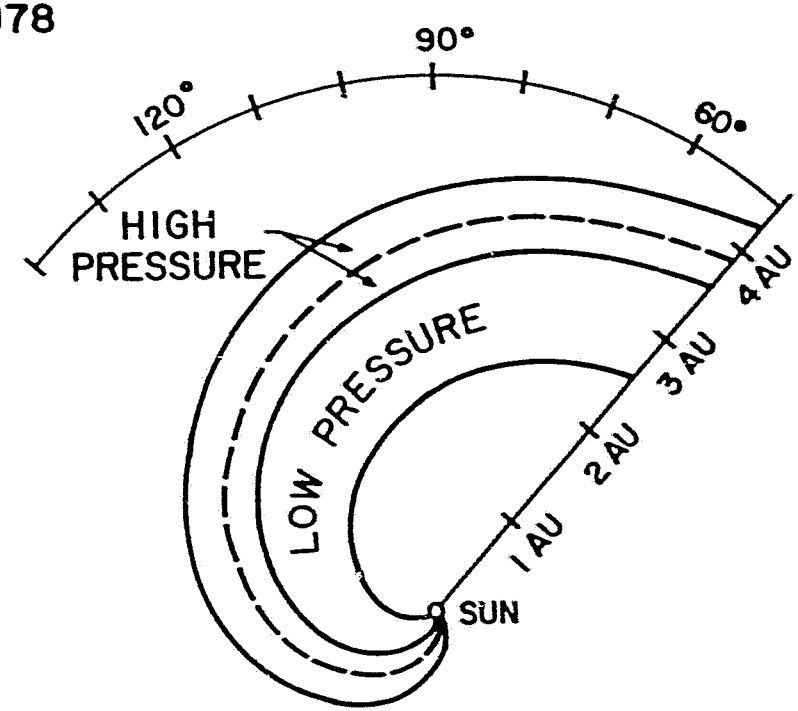
Figure 2



27-31, 1978



278-287, 1978



316-324, 1978

Figure 3

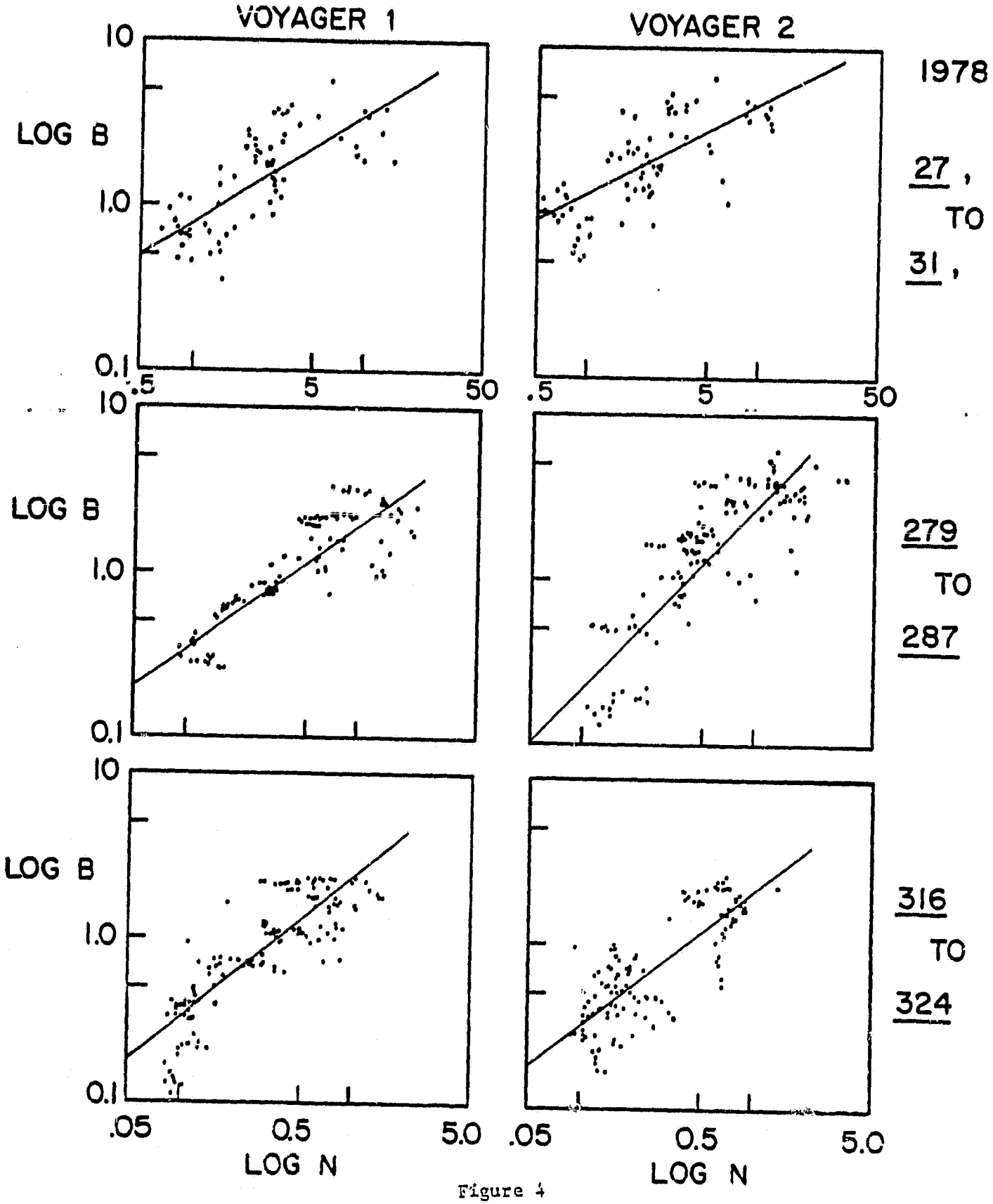


Figure 4

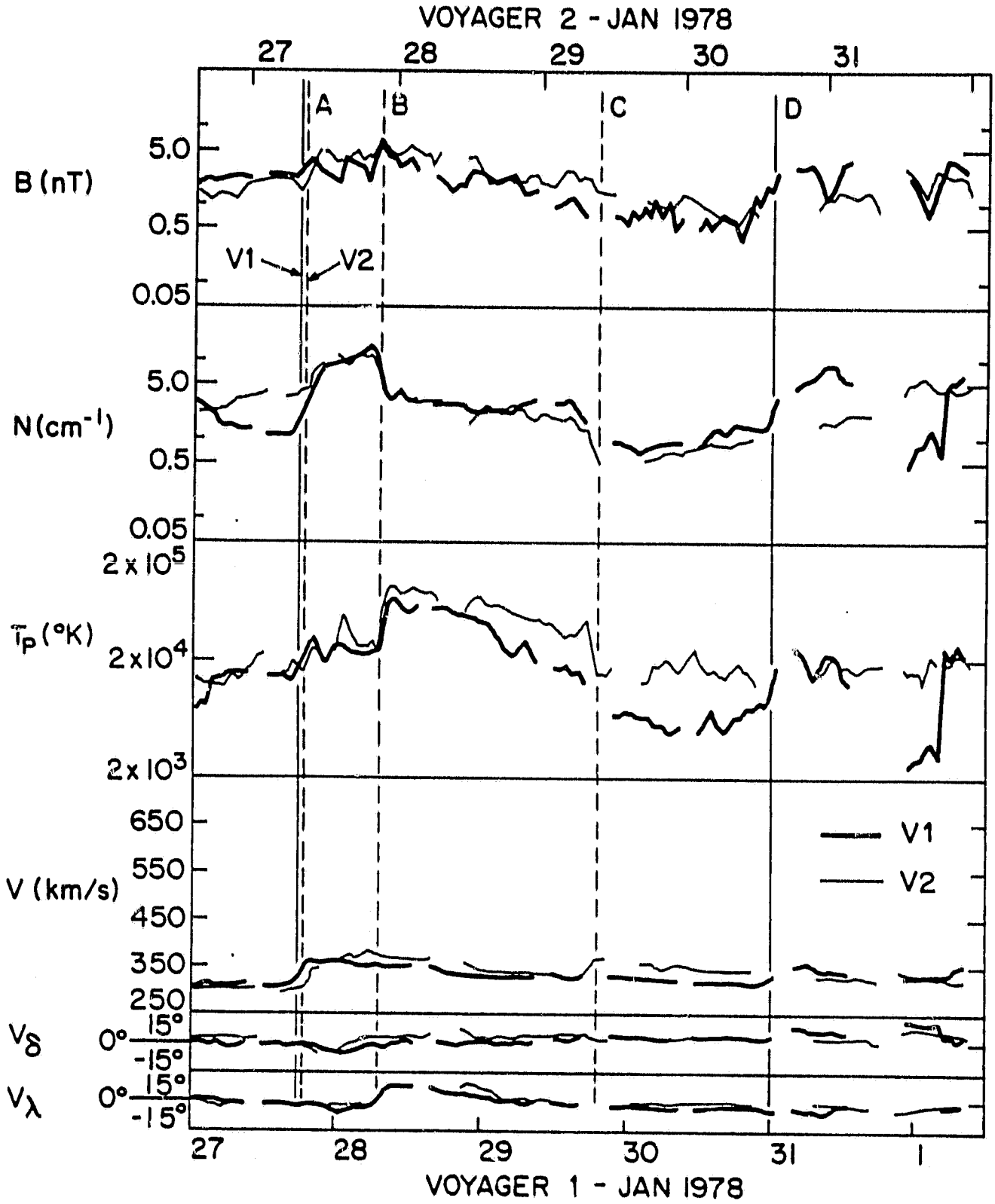


Figure 5

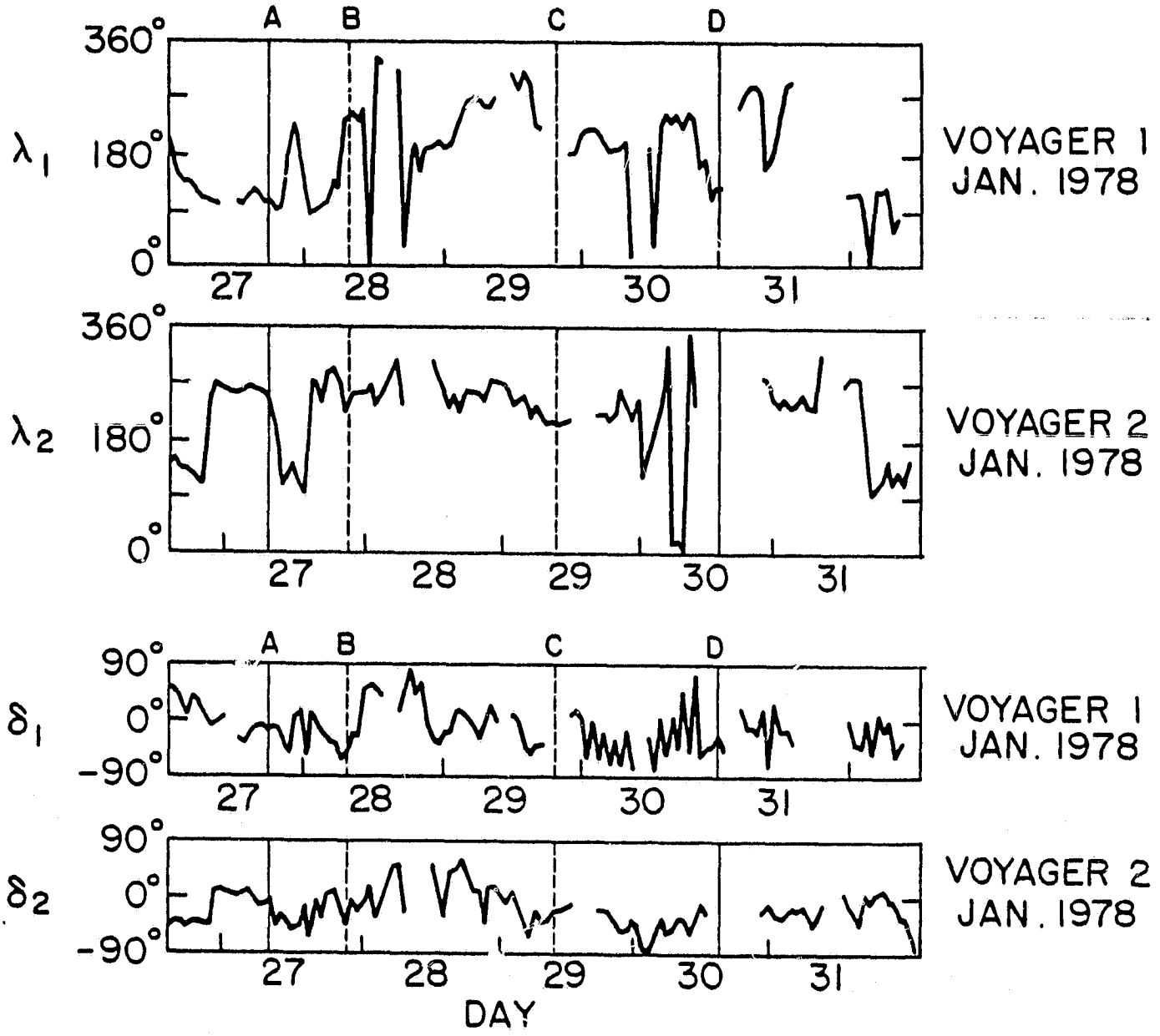


Figure 6

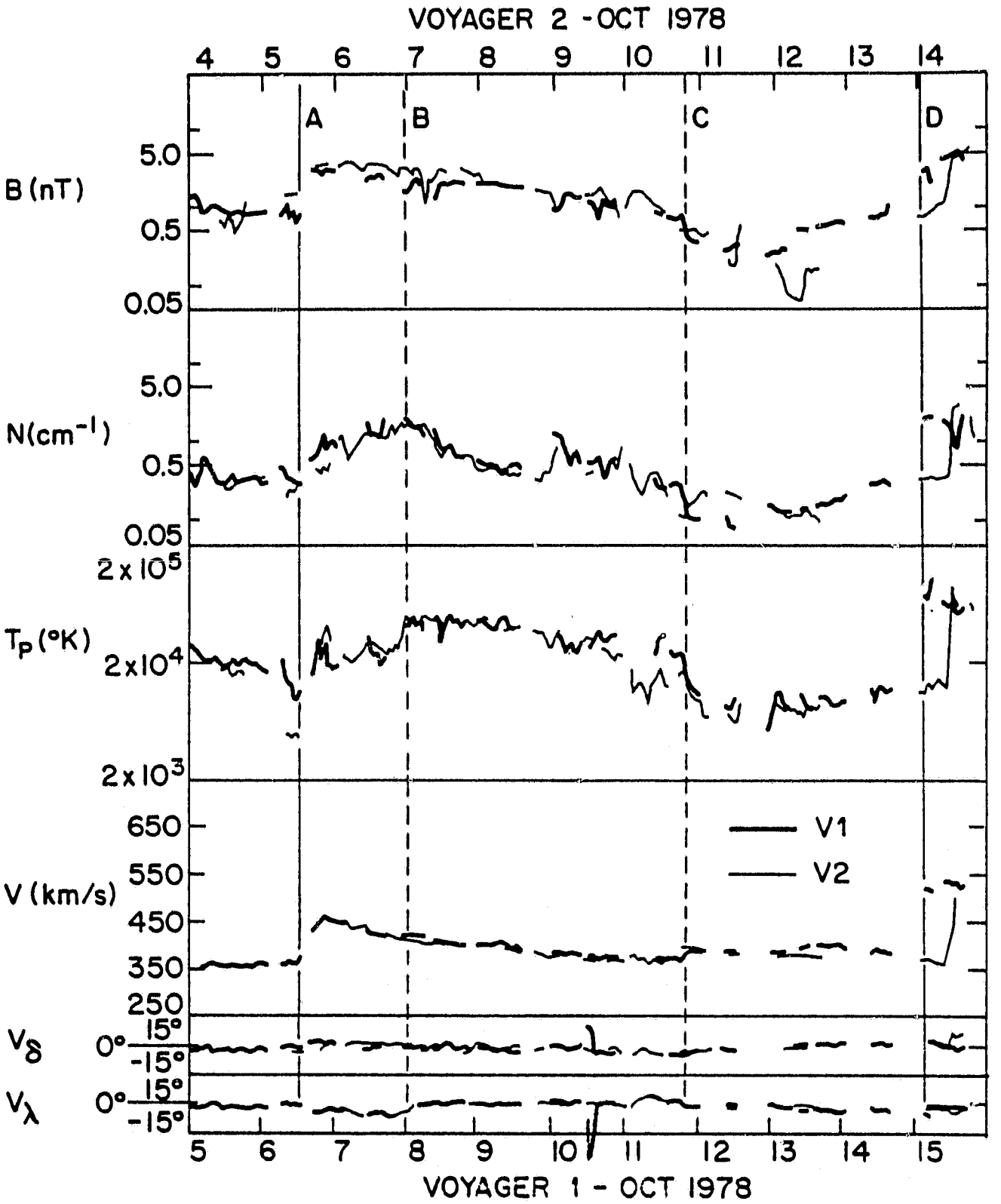


Figure 7

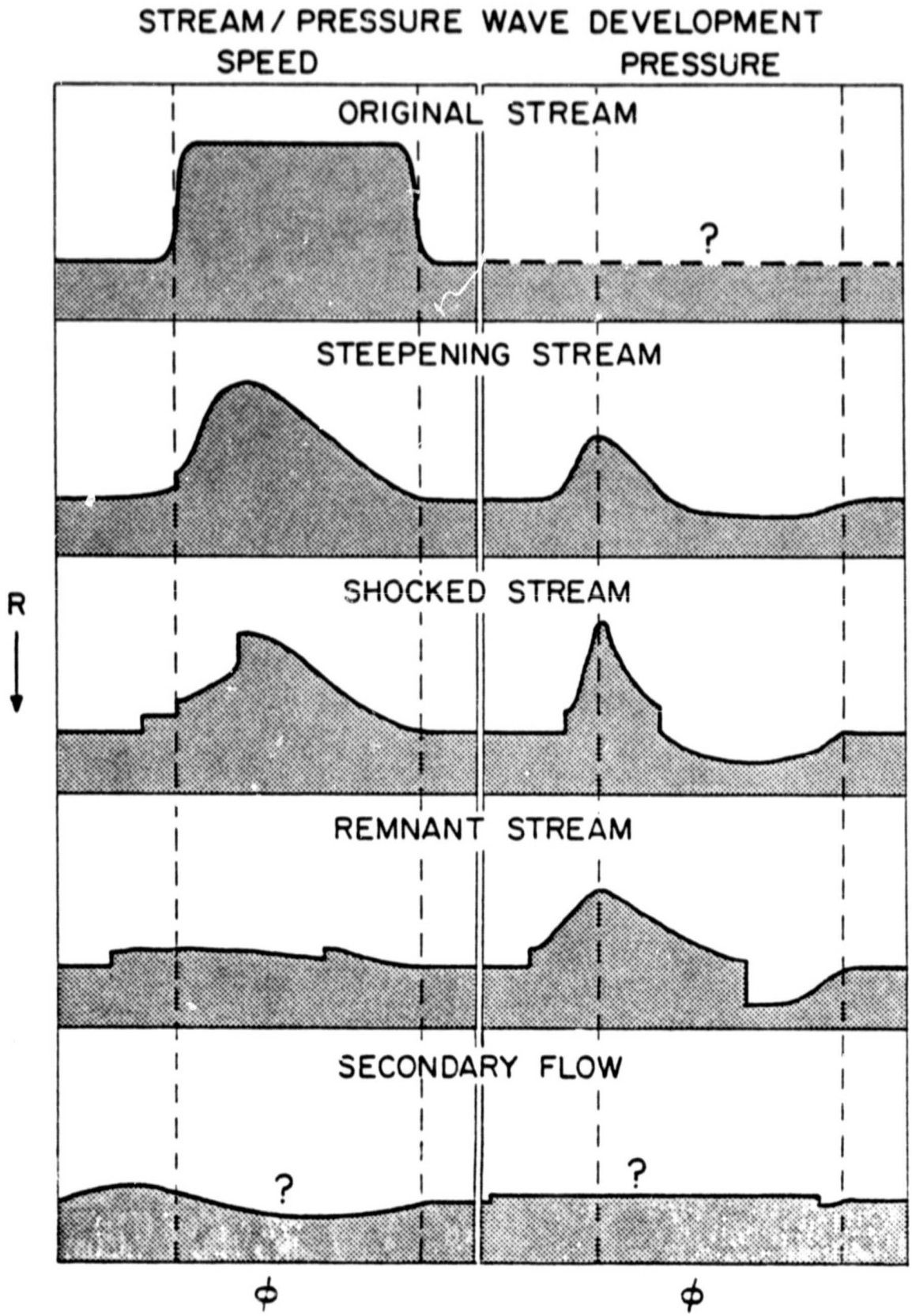


Figure 3

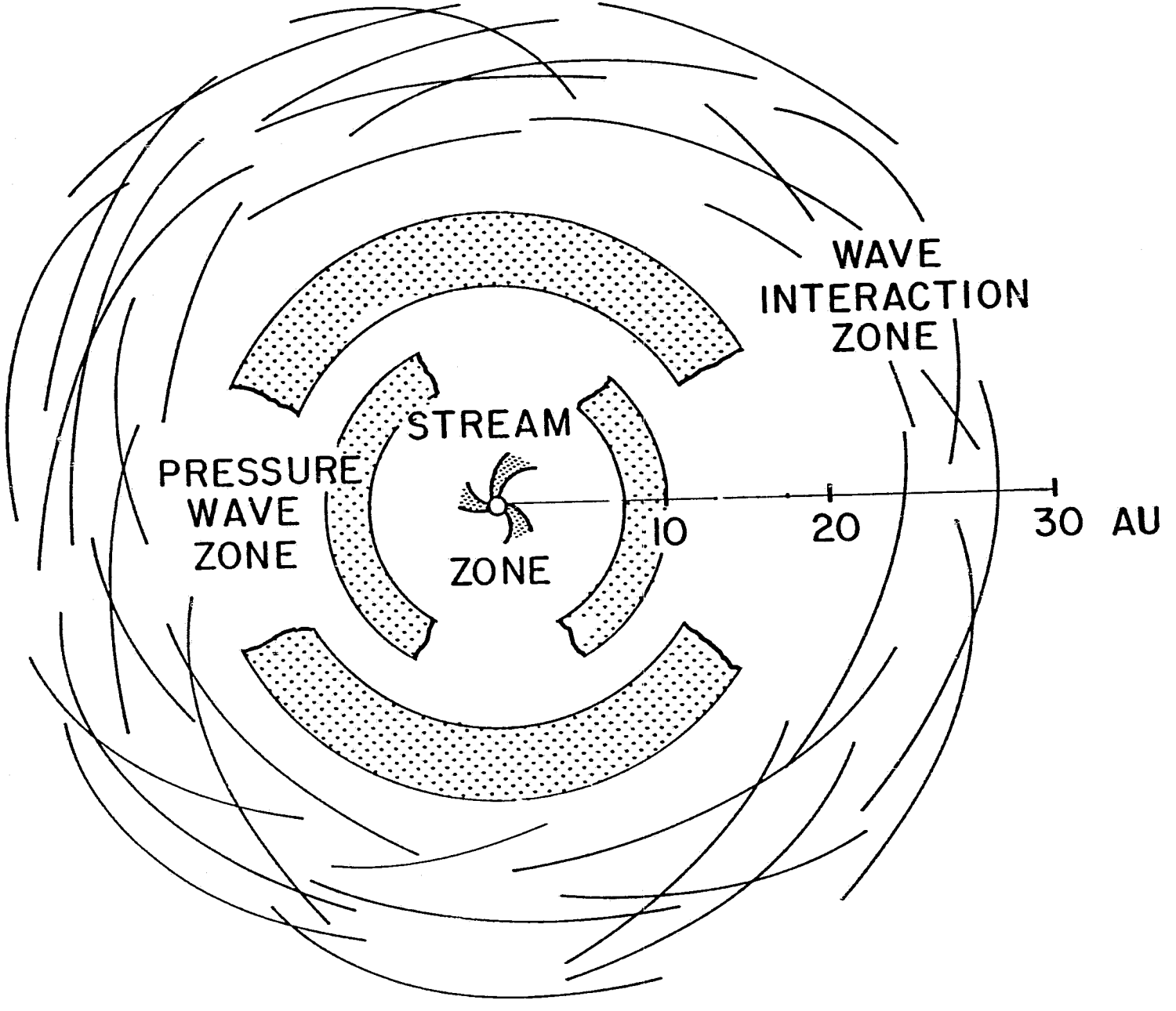


Figure 9

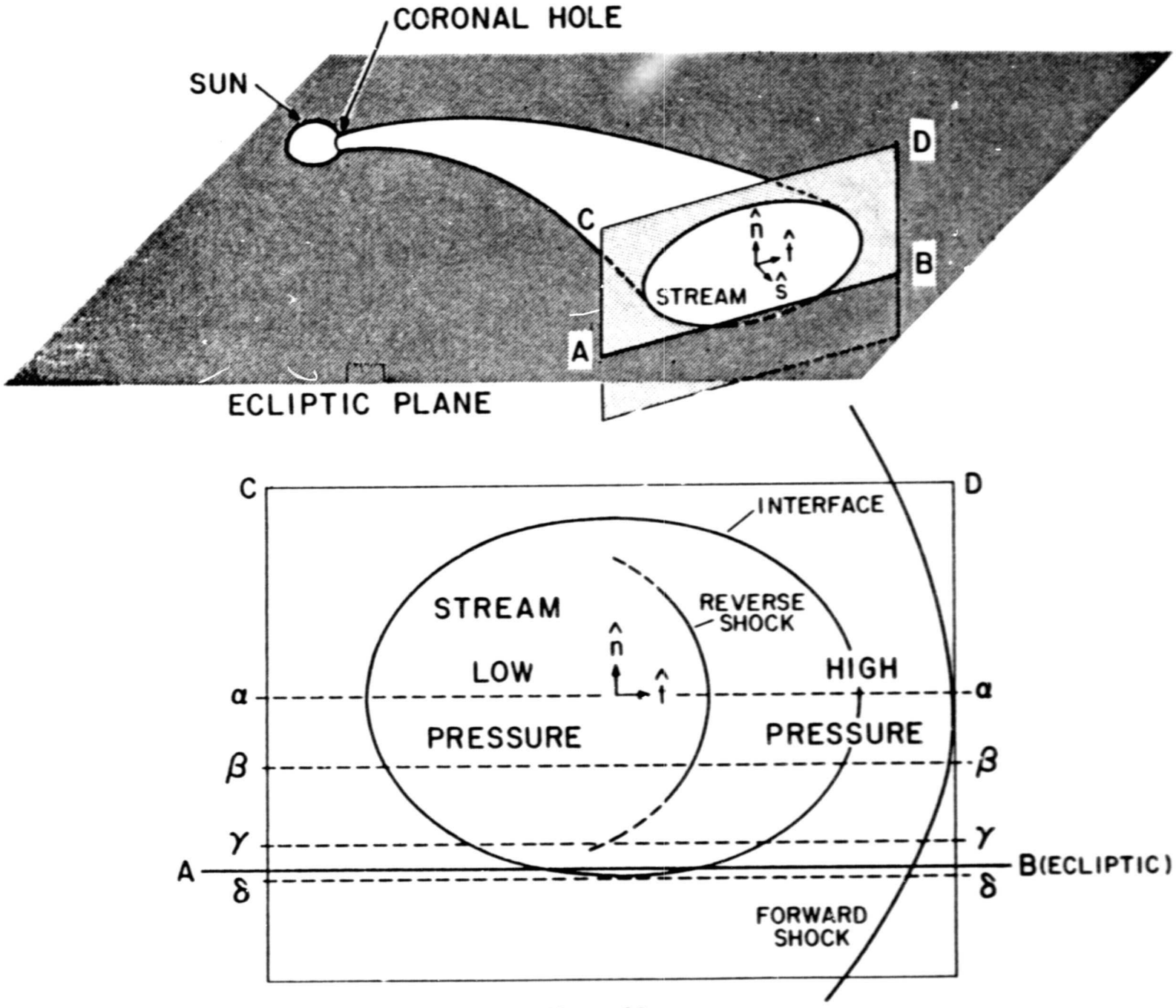


Figure 10

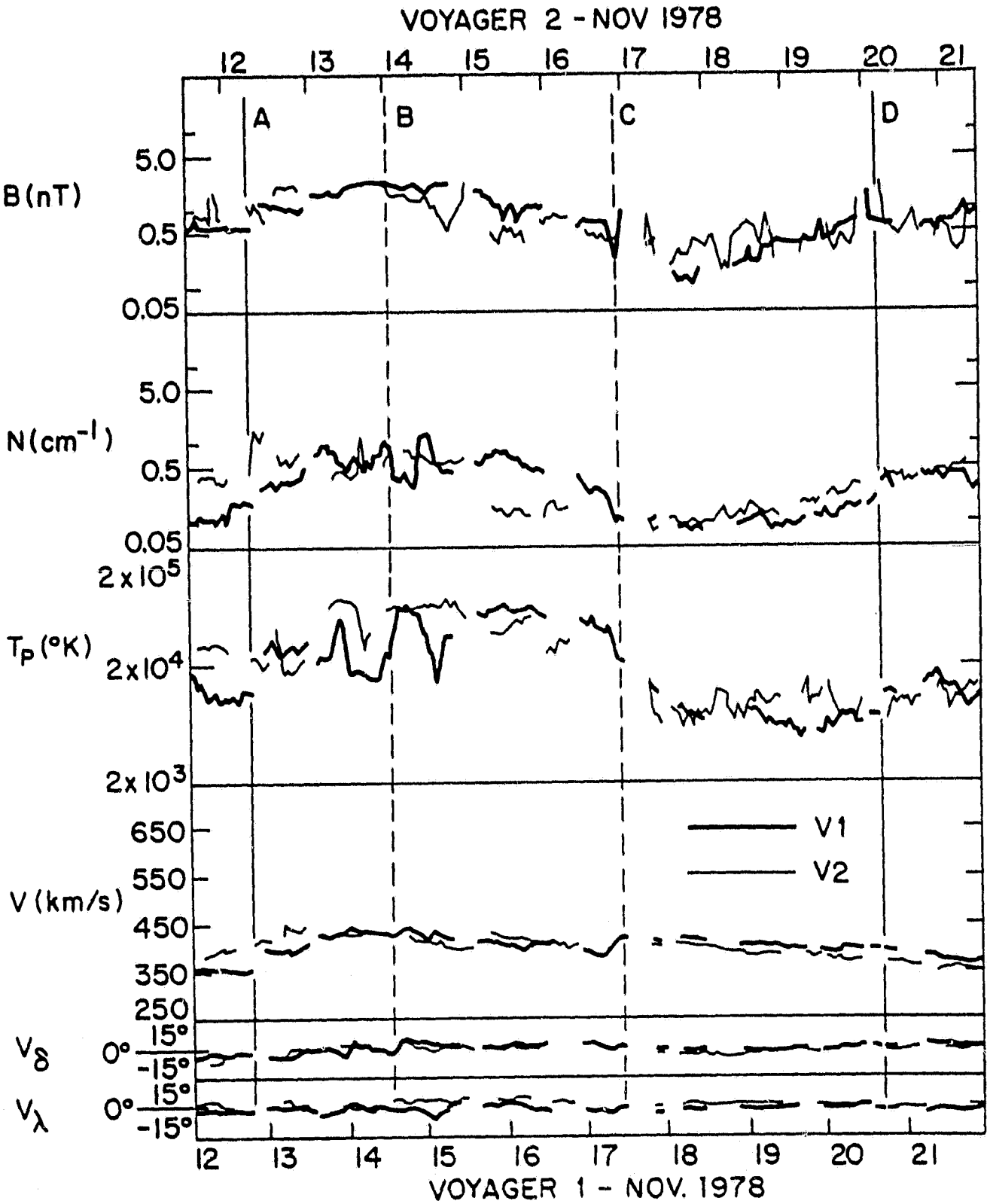


Figure 11

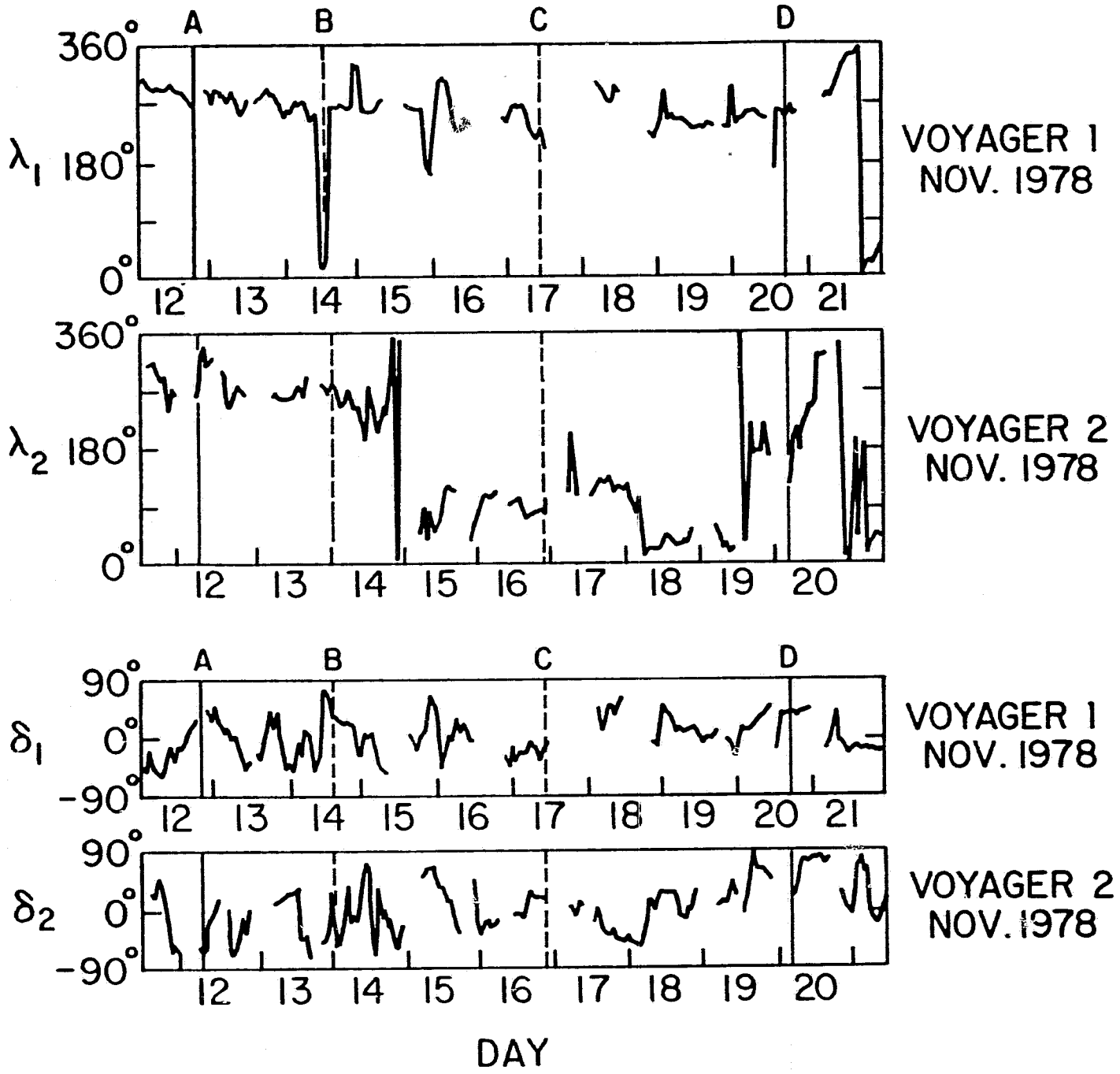


Figure 12