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NASA

Technical Memorandum **85120**

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NOVEMBER 1983

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ABSTRACT

The hydromagnetic flow configurations associated with the cosmic ray modulation in 1977-1980 were determined using solar wind plasma and magnetic field data from Voyagers 1 and 2 and Helios 1. The modulation was related to two types of large-scale systems of flows: one containing a number of transients such as shocks, post-shock flows and magnetic clouds, the other consisting primarily of a series of quasi-stationary flows following interaction regions containing a stream interface and often bounded by a forward-reverse shock pair. Each of the three major episodes of cosmic ray modulation was characterized by the passage of a system of transient flows. Plateaus in the cosmic ray intensity-time profile were associated with the passage of systems of corotating streams.

1. Introduction

Contemporary models of the 11-year modulation of galactic cosmic rays view it as a quasi-stationary process. One class of models considers that the basic process is scattering of energetic particles by random, small-scale disturbances in the interplanetary magnetic field (see the reviews by Fisk, 1980; Rao, 1972; and Quenby, 1983). Another class of models considers that the basic motions are drifts in the ordered large-scale magnetic field (see Jokipii et al., 1977; Jokipii and Thomas, 1981). Barouch and Burlaga (1976) stressed that cosmic rays also interact with intermediate scale configurations associated with interplanetary flow systems and argued that cosmic ray propagation models should include the full spectrum of interplanetary magnetic field fluctuations, including the low frequency stream-related component where the power is largest. A model of cosmic ray interactions with a corotating stream was prsented by Thomas and Gall (1982). The Pioneer 10 cosmic ray experiments (McDonald et al. (1981a,b); Webber and Lockwood (1981); McKibben et al., 1982, and Van Allen, 1980) have shown that the modulation effects at ~ 100 Mev can occur on a relatively short time scale and propagate radially away from the sun at a speed of the order of the solar wind speed between 1 AU and 20 AU. This important observation indicates that a non-stationary model of cosmic ray modulation is required, and it raises anew the question of the nature of the modulating agents.

The 11-year modulation of galactic cosmic rays has been known for nearly 30 years (Forbush, 1954, 1958; Meyer and Simpson, 1955; Fenton et al., 1958; Neher and Anderson, 1958; and Lockwood, 1958). Morrison (1956) noted that the decline in cosmic ray intensity from sunspot minimum in 1944 to sunspot maximum in 1947 was not a slow regular effect, but rather took place in two sharp falls, each followed by a slow partial return towards the mean. During 1954 to 1958 in the following solar cycle, a series of large and sudden drops from which only partial recovery occurred, was observed by Lockwood (1960). A similar effect in the current solar cycle has been observed at lower energies by McDonald et al. (1981a) and Webber and Lockwood (1981).

The cause of the 11-year modulation has been discussed by many authors. Morrison (1956) pictured the step-like decreases as "a screening of the earth

by the scattering effect of a turbulent magnetic cloud in which it is immersed". This type of "cloud" was postulated prior to discovery of the solar wind. It was assumed that these systems took weeks to become established, and it is thus different from a small, short-lived, flare-associated cloud which he proposed as the source of Forbush decreases. The radial extent of the scattering region was imagined to be large--"tens of AU". He suggested that it was diffuse and more or less uniform, although it might be filled with channels especially within a couple of AU from Earth. Finally, he suggested that the large scattering region was formed by the "continual emission of smaller clouds from various parts of the sun". Singer (1958) also suggested that the 11-year modulation is produced by the magnetic screening of "clouds of magnetized plasma" ("high-speed jets", "puffs of gas") emitted from the sun during active periods, and he suggested that hydromagnetic turbulence is the essential factor. Whereas Morrison regarded the modulation mechanism as the result of sweeping-away the cosmic rays by the convected irregularities, Singer proposed that it is due to diffusive deceleration by an inverse Fermi effect.

Lockwood (1960) suggested that the step-like nature of the cosmic ray intensity decreases was the result of "certain Forbush decreases". In this early paper, the step-like decrease was presumed to be caused by a single cloud which was very large far from the sun as a result of expansion. Later, Lockwood (1971) stressed the importance of "long duration Forbush decreases" (lasting weeks or months) for the 11-year variation, and the modulation was viewed as the result of a series of overlapping Forbush decreases. Lockwood described the modulating region as possibly a thick, hollow, turbulent shell. Barouch and Burlaga (1975) found a correlation between cosmic ray intensity decreases and regions of enhanced interplanetary magnetic field strength, which has been confirmed by Duggal et al. (1983). Barouch and Burlaga (1975) showed that these long-lasting Forbush decreases are observed in association with several successive magnetic field enhancements. They discussed one case in which a succession of several shock-associated magnetic enhancements over a period of one month was associated with a long-lasting Forbush decrease. They also demonstrated that a long-lasting Forbush decrease can be produced by a succession of magnetic field strength enhancements which are not associated with shocks, but in those cases the cosmic ray intensity did return to nearly

its initial value. Burlaga and King (1979), in a study of magnetic field enhancements from 1963-1975, found that "the modulation was greatest ...when most of the enhancements were associated with shocks, and it was least... when most enhancements were associated with interfaces." They concluded that the nature of the enhancements in magnetic field strength is more important than the total number of enhancements in modulating cosmic rays. In other words, the transient shock-associated flow and field configurations are more important in the 11-year modulation than are field and flow variations associated with steady corotating flows.

Hatton (1980), using a technique originated by Nagashima and Morishita (1979), found that it was possible to reproduce the observed cosmic ray intensity profile by assuming that the 11-year variation is caused by propagating disturbances associated with flares of importance ≥ 1. The simulated cosmic ray profiles which he derived are based on lists of flares rather than interplanetary data. His assumption that the disturbances are caused only by flares may be too restrictive, for it is known that interplanetary flows with shocks and enhanced field strengths can also be associated with coronal mass ejections (Burlaga et al., 1982), and these are not necessarily associated with flares. The difficulty of associating shocks with flares was also discussed by Hundhausen (1972). The important point is that the modulation might be associated with non-stationary interplanetary flows which in turn are associated with solar activity.

McDonald et al. (1981b) showed that in the current solar cycle the cosmic ray intensity decreased in three "steps", and they observed that the decreases propagated radially away from the sun at approximately the mean speed of the solar wind (see Figure 1). This observation strongly supports the hypothesis that the 11-year variations may be related to the processes which produce Forbush decreases, being the result of magnetic field and flow configurations that propagate away from the sun. They specifically suggested that shocks are key factors in the modulation.

Newkirk et al. (1981) argued that the 11-year variation is caused by "magnetic inclusions" in interplanetary space, reminiscent of the concept of Morrison (1956) in which clouds rather than shocks are the essential feature.

They suggested that magnetic inclusions are the interplanetary manifestation of coronal mass ejections. The 11-year modulation would then be a consequence of a solar cycle variation of coronal transients. If this view were correct, then the observed step-like changes in cosmic ray intensity should be accompanied by similar abrupt changes in the number of coronal transients. Coronal mass ejections are not always accompanied by shocks. The relative importance of the cumulative effect of many small transients versus the effect of a few large disturbances (such as flare-associated shocks) remains to be determined.

2. Objective and Approach

The object of this paper is to investigate the hypothesis that cosmic ray modulation is caused by systems of transient, shock-associated field and plasma flow configurations in the heliosphere, which we shall refer to as "transient-systems". Since much of the modulation took place in three steps between 1977 and 1980, we concentrate on those three periods and on some of the adjacent periods during which the cosmic ray intensity was at a plateau. These intervals are discussed in turn in the following three sections.

We shall discuss energetic particle data, plasma data and magnetic field data from Helios 1, Voyager 1 and Voyager 2. On Helios, the energetic particle data are from the NASA/Goddard experiment of McDonald and Webber; the plasma data are from the MPI experiment of Rosenbauer, and the magnetic field data are from the University of Rome/Goddard experiment of Mariani and Ness. On Voyager, energetic particle data are from the Caltech/Godddard/University of New Hampshire C.R.S. experiment with R. Vogt as the Principal Investigator; the plasma data are from the experiment of Bridge, and the magnetic field data are from the experiment of Ness.

It is essential to make a distinction between transient shock-associated flows and quasi-stationary corotating flows. Shock-associated flows at 1 AU are non-stationary flows (although not all non-stationary flows are shock-associated). Their existence was inferred more than 30 years ago as the cause of large geomagnetic storms. Shock-associated flows were identified in this study using plots of one-hour averages of magnetic field strength B, bulk speed V, density N, and temperature T, where the shocks are seen as a simultaneous increases in B, V, N and T. Where possible, shock identifications were confirmed by inspecting high time-resolution plots. Figure 2 gives two examples of shock-associated flows at 1 AU. The shock is followed by a region of disturbed magnetic fields, and this is often followed by a high speed flow. The profiles of B, V, N and T are highly varied and one rarely sees the same profile twice. Furthermore, there is seldom a thin single clearly-defined boundary between the ejecta and the sheath. Nevertheless, the presence of transient ejecta can usually be identified by the following characteristics: moderately high speeds, high magnetic field

strengths, generally low temperatures and densities but irregular and filamentary temperature and density profiles. The shock fronts are broader than the ejecta, so on occasion one sees a shock without observing the ejecta. For our purposes, we shall assume that the presence of a shock alone is indicative of the presence of an interplanetary transient.

Corotating streams are quasi-stationary flows which originate in coronal holes (see Hundhausen, 1977). Corotating streams have been associated with unipolar magnetic regions on the sun (Morrison, 1956), and this has been confirmed by space observations (Hundhausen, 1977). Corotating streams may change slowly with time (Burlaga et al., 1978; Rhodes et al., 1981) but the time scale is generally much longer than that of the shock-associated interplanetary transients discussed above. An example of a corotating flow is shown in Figure 3. It is identified in a 27-day plot of hour-averages of B, V, N and T on the basis of the following characteristics: 1) A thin "interface" across which the temperature increases, the density drops, the speed increases, the flow direction changes, and at which the magnetic field strength reaches a maximum (see Burlaga, 1974, and Gosling et al., 1978); 2) the temperature in such a stream is high and relatively uniform, roughly proportional to the speed; 3) the density is low and inversely related to the speed; and 4) the field strength is high in the region of increasing V and somewhat lower than average in the region of decreasing V. Stream interfaces appear to be a necessary and sufficient condition for a corotating stream. We shall follow Burlaga and King (1979) in using the presence of a stream interface as an indication of the presence of a corotating stream. A peak in the B(t) profiles at the time of an interface at the front of a stream is an additional signature of a corotating stream that will be seen in the plots to be presented.

Transient shock-associated streams and stationary corotating streams are two extremes of a spectrum of interplanetary flows. There are also transient flows without shocks (e.g., some of the magnetic clouds discussed by Klein and Burlaga, 1982) and there are undoubtly short-lived, coronal-hole associated streams that cannot be regarded as stationary or even quasi-stationary. The effects of such flows on cosmic rays is a special topic which we shall not pursue here, although it may have some significance for the cosmic ray

modulation problem. Our concern in this paper is the basic issue of the effects transient versus quasi-stationary flows have on cosmic rays, and we emphasize the extremes of these two types of flows.

Our approach is to examine the interplanetary plasma and magnetic field observations to identify the interplanetary transients and corotating streams that are present, and to compare these results with the intensity profiles of cosmic ray protons with energies $\gtrsim$ 100 MeV. If the modulation was caused by systems of interplanetary transients, then we should find a predominance of shocks at the time of a permanent decrease in the cosmic ray flux; we should find a relative absence of shocks, and possibly a predominance of interfaces at times of constant or increasing cosmic ray intensity. We shall focus on the periods near the three "steps" in the cosmic ray profiles shown in Figure 1.

3. April to August, 1980

During this period, Helios 1 moved between 0.3 AU and 1 AU while Voyager 1 moved from ~ 7.7 AU to ~ 8.8 AU, as shown in Figure 4. The alignment of the two spacecraft was particularly favorable in May, and the radial propagation time from Helios to Voyager was ~ 30 days. After June, the longitudinal latitudinal separations were large enough that one must consider the possibility of spatial and temporal variations in comparing Helios and Voyager observations.

Helios observations for the period April 1 to June 20, 1980 are shown in Figure 5. The integral counting rate of protons $\geq$ 200 MeV measured by the GSFC experiment shows a broad but temporary depression in late April and early May and a long-lasting decrease in cosmic ray intensity in late May and early June. Thus, we see two kinds of cosmic ray decreases, and we shall attempt to identify the causes.

The nature of the magnetic field and flow configurations was determined as discussed above with magnetic field and plasma data from Helios 1. The identification of shocks and interfaces is shown in the middle of Figure 5; non-corotating shocks are shown in the panel labeled 'shocks', and interfaces are shown in the panel below it. A discontinuity which is possibly a corotating forward shock is shown as a solid dot in the 'interface' panel. The data coverage was not complete, so there may have been shocks and interfaces which were not detected. However, the gaps are uncorrelated with these discontinuities, so the relative proportion of transient shocks and interfaces (which is our principal concern) is not strongly affected by such gaps.

The broad, temporary decrease during late April and early May in Figure 5 was associated with a dominance of corotating flows, as indicated by the occurrence of 4 interfaces versus only one transient shock. Thus, the temporary decrease in cosmic ray intensity was caused by the passage of three or four corotating streams. In this case the enhancements in B/B_p (where B_p is the strength of the field predicted by Parker's model) are relatively small, whereas the enhancements in V (the streams) are large, suggesting that

the speed is a significant factor as suggested by Iucci et al., 1979, while enhancements in the strength of B are perhaps of secondary importance. There remains the possibility that the cosmic rays were scattered by small-scale irregularities convected by the streams. However, these large corotating streams had no long-lasting effect on the cosmic ray intensity, so they and the small-scale magnetic fluctuations within the streams are evidently not an effective long-term modulation agent.

A long-lasting decrease in cosmic ray intensity was observed by Helios 1 in late May. There were no corotating streams in this interval. Two shock-associated flows were observed (on May 27 and May 29), and these were preceded by fluctuations in B/B_p and V that were probably transient (Figure 5). To determine the mechanism responsible for the decrease will require an analysis of high resolution data. The shocks are clearly an important factor, as suggested by McDonald et al. (1981a,b), but apparently other transients can be important as well.

Let us now consider the corresponding Voyager 1 cosmic ray intensity and the plasma flow and field data, obtained near 8 AU in a period which includes the one discussed above, viz., April 11 to September 6, 1980. Note that the transit time for solar wind propagation from 1 AU to 8 AU is approximately 30 days. The large corotating streams observed by Helios 1 (labeled A and B in Figure 5) were seen by Voyager after an appropriate time delay and with some modification, as discussed by Burlaga et al. (1983); they are shown in Figure 6, again labeled A and B. The magnetic field strength and the integral counting rate of nuclei with energies > 75 MeV/nucleon are also plotted in Figure 6.

The long-lasting modulation occurred primarily at the end of June in association with an usually large magnetic field strength enhancement, 2 shocks and a stream. We cannot identify a system of interplanetary transients which we can say is the cause of the modulation in June, but the observation of 2 forward shocks and the lack of evidence for reverse shocks and a stream interface indicates that this is not a simple corotating flow. To understand this flow configuration one must understand the evolution of flows as they moved from within 1 AU to beyond 7 AU.

Near the sun, say $\lesssim$ 1 AU, corotating streams and interplanetary transient flows are often distinct and isolated. Beyond a few AU fast flows overtake slower flows, interplanetary transients, corotating flows and shocks from different sources, thereby producing a change in the structure of the interplanetary medium which may be irreversible. Burlaga et al. (1983) call this general process 'entrainment'. It includes the process of interacting corotating streams, but it is important to understand that it can also take place with transient flows and even with shocks. The theory of such interactions is not adequately developed. Burlaga et al. (1983) have shown that the large corotating streams marked B in the Helios 1 data in Figure 5 may have overtaken several interplanetary transients ahead of it (such as those seen by Helios 1 in late May and early June) as it moved out to the position of Voyager 1. The fields and plasmas from these transients would have been swept-up into a narrow shell. Their individual pressure waves would have coalesced to form a single new pressure wave, a "merged interaction region" (MIR), which would be detected by Voyager 1. Thus, the large increase in $\bar{B}/\bar{B}_p$ at the end of June in Figure 6 may be the result of entrainment of several transients. In this way the long-term decrease in cosmic ray flux that occurred at the end of June may indirectly be due to a transient-system, as we discussed earlier, but the individual transients cannot be identified at 8 AU because of their entrainment by a fast corotating stream.

The temporary cosmic ray intensity decreases observed by Voyager 1 may have been produced by corotating structures. Stream A in Figure 6, observed by Voyager in early June, can be traced to the corotating, interface-associated streams observed in early May by Helios 1 (marked A in Figure 5). In this case, two pressure waves and streams observed at Helios merged as the faster flow entrained the slower one in transit to 8 AU. The signature of this "compound stream" (Burlaga and Ogilvie, 1973) at Voyager is the observation of 2 forward shocks and 2 reverse shocks one shock pair for each of the 2 corotating streams observed by Helios. This compound stream seen by Voyager 1 at the beginning of June should be considered to be a corotating or quasi-stationary flow, and the observation of temporary decrease in cosmic ray intensity associated with it (Figure 6), is consistent with the conclusion that we drew from the Helios data.

4. January 1 to July 1, 1979

During this time interval, the Voyager integral rates are significantly affected by large increases in Jovian electrons in the near-encounter period, and it is necessary to use actual flux measurements of higher energy protons. The flux of 150-250 MeV protons measured by the Voyager 2 cosmic ray experiment on Voyager 2 decreased relatively abruptly and durably in late February and March 1979, as shown in Figure 7. Prior to and following this interval significant variations in the cosmic ray flux (large in January and February and small in April and May), but there was no long-lasting decrease in cosmic ray flux during these intervals. Apparently, effective modulation agents passed the spacecraft in March but not in January and February or in April and May. The magnetic field strength B/B_p and the bulk speed V, measured by the GSFC magnetometer and plasma analyzer on Voyager 2, are shown at the bottom of Figure 7. In late April and May, a series of interfaces and corotating interaction regions (regions of high magnetic field strength bounded by shocks) is evident. These were related to small, temporary depresssions in the cosmic ray flux. The situation in January and February is more complicated, but three quasi-stationary interaction regions can be identified ahead of streams. Two shocks were seen in this interval, so that the flows in this interval may be classified as "mixed".

In the interval during which modulation occurred, late February and March, there were 5 shocks and no interfaces (Figure 7), the magnetic field strength profile was very irregular with many narrow peaks, and the field strength was higher than average. This is consistent with the passage of many transients carrying magnetic flux shed by the sun from active regions.

Summarizing, we have found that modulation of the 120-250 MeV protons observed by Voyager 2 during the first half of 1979 occurred primarily in late February and March, when the solar wind was dominated by a transient-system. During and following 3 months, the flow and field configurations were quasi-stationary as indicated by the presence of systems of corotating streams. During the preceding 2 months there were three large corotating streams, but some transients were also present.

5. September 1977 to July 1978

The modulation of cosmic rays in the current solar cycle began with an abrupt decrease in flux starting at the beginning of 1978 and ending in June 1978, with a plateau in April, as shown by data from the Voyager 2 cosmic ray experiment (Figure 8).

In the period September 1, 1977 to January 1, 1978 there were at least 8 interfaces and only 3 transient shocks, i.e., quasi-stationary flows were clearly dominant. During that time, there was no long-term decrease in the cosmic ray flux. In November and December there were large fluctuations in the cosmic ray flux associated with the quasi-stationary flows (indicated by 5 interfaces), showing that such flows can affect the cosmic ray flux temporarily, but there was no durable decrease in the flux. By contrast, in the interval January 1 to June 1978, when the cosmic ray flux did decrease for a long time there were 14 transient shocks and only 3 interfaces, i.e., modulation was associated with a dominance of transient configurations. In an interval during which the three interfaces were observed (April 1978) there was a relative plateau in the cosmic ray flux, showing again that quasi-stationary flows by themselves are not effective long-term modulating agents. The bottom panel shows the occurrence of magnetic clouds, which are transient loop-like configurations with strong fields (see Burlaga et al., 1981 and Klein and Burlaga, 1982), and one sees that they occur only in the interval in which the cosmic ray flux was decreasing. Thus, we conclude that the first step in the modulation of cosmic rays in the current solar cycle was associated with a dominance of transient flows and fields, while quasi-stationary flows and fields had only a short-term influence on the cosmic rays.

In the September 1977 to Janury 1, 1978 interval, which we have shown to be dominated by quasi-stationary flows, there were discrete magnetic field enhancements (presumably interaction regions) in front of isolated streams, and both were related to temporary depressions in the cosmic ray flux. In the January-June 1978 interval, which we said was dominated by transients, the magnetic field and velocity profiles were very complex, and the field strength was higher than average, suggestive of flows which carry additional magnetic

flux from the sun and which interact strongly with one another. Here too there were correlations among the field strength enhancements, the streams and short-term depressions in the cosmic ray flux, but they are of a different nature than those for quasi-stationary flows. Because of the correlation between B/B_p and V, it is difficult to determine from these results whether field strength or speed is the more important physical parameter. Nevertheless, the field strength and velocity profiles in Figure 1 are consistent with our earlier conclusion that modulation is associated with transient-systems, while corotating-systems have only a temporary effect on the cosmic rays.

6. Summary and Discussion

We have investigated the interplanetary magnetic field and plasma associated with galactic cosmic ray modulation in the years 1977-1980, the ascending part of solar cycle 21, using data from Voyager 1 and 2 and from Helios 1. We found that long-term modulation is caused by systems of transient magnetic field and flows. Systems of corotating configurations produce only temporary depressions in the cosmic ray flux.

To visualize the kind of large-scale morphology involved in the modulation process, we show a highly idealized situation in Figure 9, in which the heliosphere is viewed on a scale of 50 AU in the ecliptic plane. We assume that initially (Figure 9a) there are no transient flows in the system, implying no activity on the sun for about 200 days. Under this condition, the heliosphere is filled with slow flows and/or stationary corotating streams. Next, we assume that the sun becomes very active, ejecting shocks, magnetic clouds, and other transient magnetic field configurations which fill the shaded region in Figure 9b. This "active state" continues for about two solar rotations, and then the sun returns to its previous quiet, stationary state (Figure 9c). The system of transient flows and magnetic field configurations now form a giant expanding ring or shell surrounding the sun. This is an effective barrier to galactic cosmic rays. The cosmic ray flux decreases toward the inner part of the shell, and remains relatively low on the sunward side of the shell until the shell reaches the distant heliosphere. Eventually the shell will pass through the heliopause and ultimately will be swept away, forming part of the wake of the heliosphere.

The above picture is an oversimplification, of course, intended to show in the simplest way the essential ideas. The sun is never completely active or completely quiet. In general, the thickness of the shell might change as it moves away from the sun, e.g., it might decrease if the corotating flows behind it move faster than the transients. There may be several shells of various thicknesses. And the shells may sometimes be penetrated by corotating streams, especially closer to the sun. These complications may be combined in endless ways, so that a deterministic approach based on detailed flow and field configurations may not be the most efficient means of modeling the general situation. In addition, it must be remembered that a spherically symmetric model is an unjustified simplification.

Several further investigations are suggested by this work. There is need for a systematic survey of the cosmic ray variations over many years and their relation to interplanetary conditions. This can perhaps best be done initially with data from spacecraft close to the sun (e.g., Helios, Imp, ISEE-3), using the methods of this paper. Understanding of the physical mechanisms involved in the modulation process will require detailed analysis of individual flow systems and their effects on cosmic rays. This will involve high resolution data describing shocks, magnetic turbulence and static structures in merged interaction regions, Alfvénic fluctuations, etc. Statistical methods of describing flow systems must be devised, and they must be capable of distinguishing between systems of interplanetary transients and systems of corotating configurations. (See Goldstein et al., 1983 for results of this kind.) The radial evolution of systems of flows and flow systems must be better understood. (The radial evolution of two flow systems has recently been discussed by Burlaga and Goldstein, 1983). The spectrum of interplanetary disturbances is very broad, ranging from discontinuities and waves, through streams and interacting flows, to systems of flows and the large-scale spiral configuration. Theories have been developed to describe the interaction of energetic particles with the smallest and largest of those configurations. It is now necessary to attack the difficult problem of the interaction of cosmic rays with systems of streams such as shells of transients.

Acknowledgments

We thank H. Bridge and H. Rosenbauer, the Principal Investigators of the plasma experiments on Voyager and Helios, respectively, and R. Vogt, the Principal Investigator of the C. R. S. experiment, for allowing us to use their data. L. Klein provided valuable programming assistance.

References

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

Barouch, E., and L. F. Burlaga, Three-dimensional interplanetary stream magnetism and energetic particle motion, J. Geophys. Res., 81, 2103, 1976.

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

Burlaga, L. F. and M. L. Goldstein, Radial evolution of large-scale magnetohydrodynamic fluctuations in the solar wind, (NASA TM 85116, submitted to Geophys. Res. Lett., 1983.

Burlaga, L. F., and J. King, Intense interplanetary magnetic fields observed by geocentric spacecraft during 1963-1975, J. Geophys. Res., 84, 6633, 1979.

Burlaga, L. F., and K. W. Ogilvie, Solar wind temperature and speed, J. Geophys. Res., 78, 2028, 1973.

Burlaga, L. F., L. Klein, N. R. Sheeley, Jr., D. J. Michels, R. A. Howard, M. J. Koomen, R. Schwenn, and H. Rosenbauer, A magnetic cloud and a coronal mass ejection, Geophys. Res. Lett., 9, 1317, 1982.

Burlaga, L. F., N. Ness, F. Mariani, B. Bavassano, U. Villante, H. Rosenbauer, R. Schwenn, and J. Harvey, Magnetic fields and flows betwen 1 AU and 0.3 AU during the primary mission of Helios 1, J. Geophys. Res., 83, 5167, 1978.

Burlaga, L., E. Sittler, F. Mariani, and R. Schwenn, Magnetic loop behind an interplanetary shock: Voyager, Helios and IMP-8 observations, J. Geophys. Res., 86, 6673, 1981.

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, Geophys. Res. Lett., 10, 413, 1983.

Duggal, S. P., M. A. Pomerantz, R. K. Schaefer, and C. H. Tsao, Cosmic ray modulations related to the interplanetary magnetic field intensity, J. Geophys. Res., 88, 2473, 1983.

Fenton, A. G., K. G. Fenton, and D. C. Rose, The variation of sea level cosmic ray intensity between 1954 and 1957, Can. J. Phys, 36, 824, 1958.

Fisk, L. A., Solar modulation of galactic cosmic rays, Proc. Conf. Ancient Sun, ed. J. A. Eddy and R. B. Merrill, p. 183, 1980.

Forbush, S. E., Jr., World-wide cosmic ray variations, 1937-1952, J. Geophys. Res., 59, 525, 1954.

Forbush, S. E., Jr., Cosmic-ray intensity variations during two solar cycles, J. Geophys. Res., 63, 651, 1958.

Goldstein, M. L., L. F. Burlaga and W. H. Matthaeus, Power spectral signatures of interplanetary corotating and transient flow systems, to be submitted to J. Geophys. Res., 1983.

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

Hatton, C. J., Solar flares and the cosmic ray intensity, Solar Physics, 66, 159, 1980.

Hundhausen, A. J., An interplanetary view of coronal holes, in cornonal holes and high speed streams, p. 225, ed. J. B. Zirker, Colorado Associated University Press, 1977.

Jokipii, J. R., and B. Thomas, Effects of drift on the transport of cosmic rays IV. Modulation by a wavy interplanetary current sheet, Ap. J., 243, 1115, 1981.

Jokipii, J. R., E. H. Levy, and W. B. Hubbard, Effects of particles drift on cosmic ray transport. 1, General properties, applications to solar modulation, Astrophys. J., 213, 861, 1977.

Klein, L. W., and L. F. Burlaga, Magnetic clouds at 1 AU, J. Geophys. Res., 87, 613, 1982.

Lockwood, J. A., Variations in cosmic-ray nucleonic intensity, Phys. Rev., 112, 1750, 1958.

Lockwood, J. A., On the long-term variation in the cosmic radiation, J. Geophys. Res., 65, 19, 1960.

Lockwood, J. A., Forbush decreases in the cosmic radiation, Space Sci. Rev., 12, 658, 1971.

McDonald, F. B., N. Lal, J. H. Trainor, and M. A. I. Van Hollebeke, and W. R. Webber, The solar modulation of galactic cosmic rays in the outer heliosphere, Ap. J. (Letters), 249, L71, 1981a.

McDonald, F. B., J. H. Trainor, J. D. Mihalov, J. H. Wolfe, and W. R. Webber, Radially propagating shock waves in the outer heliosphere: The evidence from Pioneer 10 energetic particle and plasma observations, Ap. J. (Letters), 246, L165, 1981b.

McKibben, R. B., K. R. Pile, and J. A. Simpson, The galactic cosmic ray radial intensity gradient and the large-scale modulation in the heliosphere, Astrophys. J., 254, L23, 1982.

Meyer, P., and J. A. Simpson, Changes in the low-energy particle cutoff and primary spectrum of cosmic radiation, Phys. Rev. 99, 1517, 1955.

Morrison, P., Solar origin of cosmic-ray time variations, Phys. Rev., 101, 1347, 1956.

Nagashima, K. and I. Morishita, Long term modulation of cosmic rays and inferable electromagnetic state in solar modulation region, Planet. Space Sci., 28, 177, 1980.

Neher, H. V., and H. R. Anderson, Cosmic-ray changes from 1954-1957, Phys. Rev., 109, 608L, 1958.

Newkirk, G., A. J. Hundhausen, and V. Pizzo, Solar cycle modulation of galactic cosmic rays: Speculation on the role of coronal transients, J. Geophys. Res., 86, 5387, 1981.

Quenby, J. J., The theory of cosmic ray modulation (to appear), 1983.

Rao, U., Solar modulation of galactic cosmic radiation, Space Sci. Rev., 12, 719, 1972.

Rhodes, E. J., Jr., and E. J. Smith, Multi-spacecraft observations of heliographic latitude-longitude structure in the solar wind, J. Geophys. Res., 86, 8877, 1981.

Singer, S. F., Cosmic ray time variations produced by deceleration in interplanetary space, Nuovo Cimento, Supplement, 8, series X, 334, 1958.

Thomas, B. and R. Gall, The effect of corotating interaction regions on the propagation of relativistic cosmic rays in the heliosphere, J. Geophys. Res., 87, 4542, 1982.

Van Allen, J. A., Galactic cosmic-ray intensity to heliocentric distance of 18 AU, Astrophys. J., 238, 763, 1982.

Webber, W. R., and J. A. Lockwood, A study of the long-term variation and radial gradient of cosmic rays out to 23 AU, J. Geophys. Res., 86, 11458, 1981.

Figure Captions

Figure 1 — Cosmic ray flux versus time from 1977 - 1981 as observed by Pioneer 10, Voyager 1 and Helios 1.

Figure 2 — Two transient, shock-associated flows. Here the magnetic field strength is designed F.

Figure 3 — A corotating stream. Note the high temperature and low density in the stream. A stream interface is indicated by the vertical line on June 26.

Figure 4 — Trajectories of Voyagers 1 and 2 and Helios 1.

Figure 5 — Top. Cosmic ray intensity observed by Helios 1 versus time. Middle. The times at which interfaces, transient shocks and a possible corotating shock (solid circle in the interface panel) were observed. Bottom. Magnetic field strength B relative to that predicted by Parker's model B_p, and the bulk speed V. A and B denote fast corotating streams.

Figure 6 — Voyager 1 observations of cosmic ray intensity versus time (top) and the magnetic field strength and bulk speed (bottom) for April to September, 1980.

Figure 7 — Cosmic ray flux observed by Voyager 2 and the associated flows, during January - July, 1979. The format is the same as that in Figure 5.

Figure 8 — Cosmic ray intensity and associated flows observed by Voyager 2 during September 1977 - August 1978. The format is the same as that in Figure 5.

Figure 9 — A highly idealized sketch to illustrate the development of a shell consisting of a system of interplanetary transients.

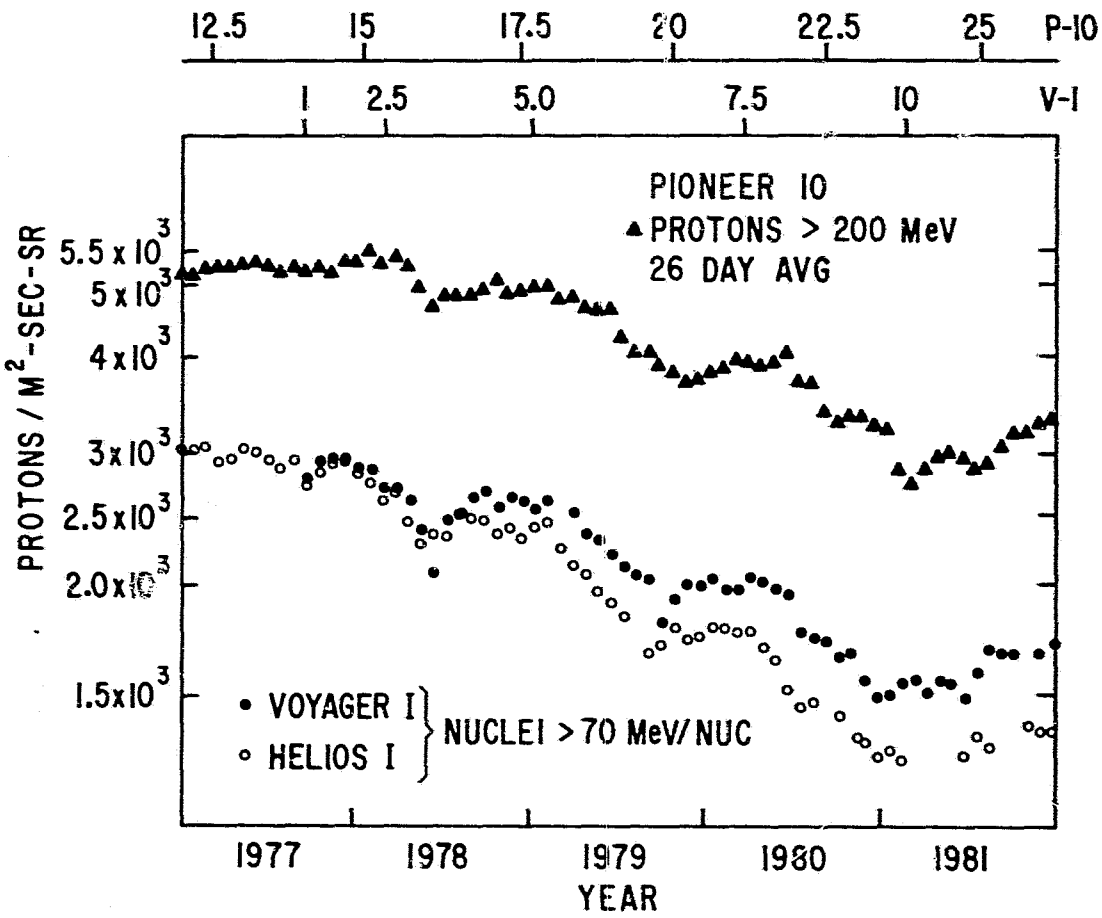

Figure 1

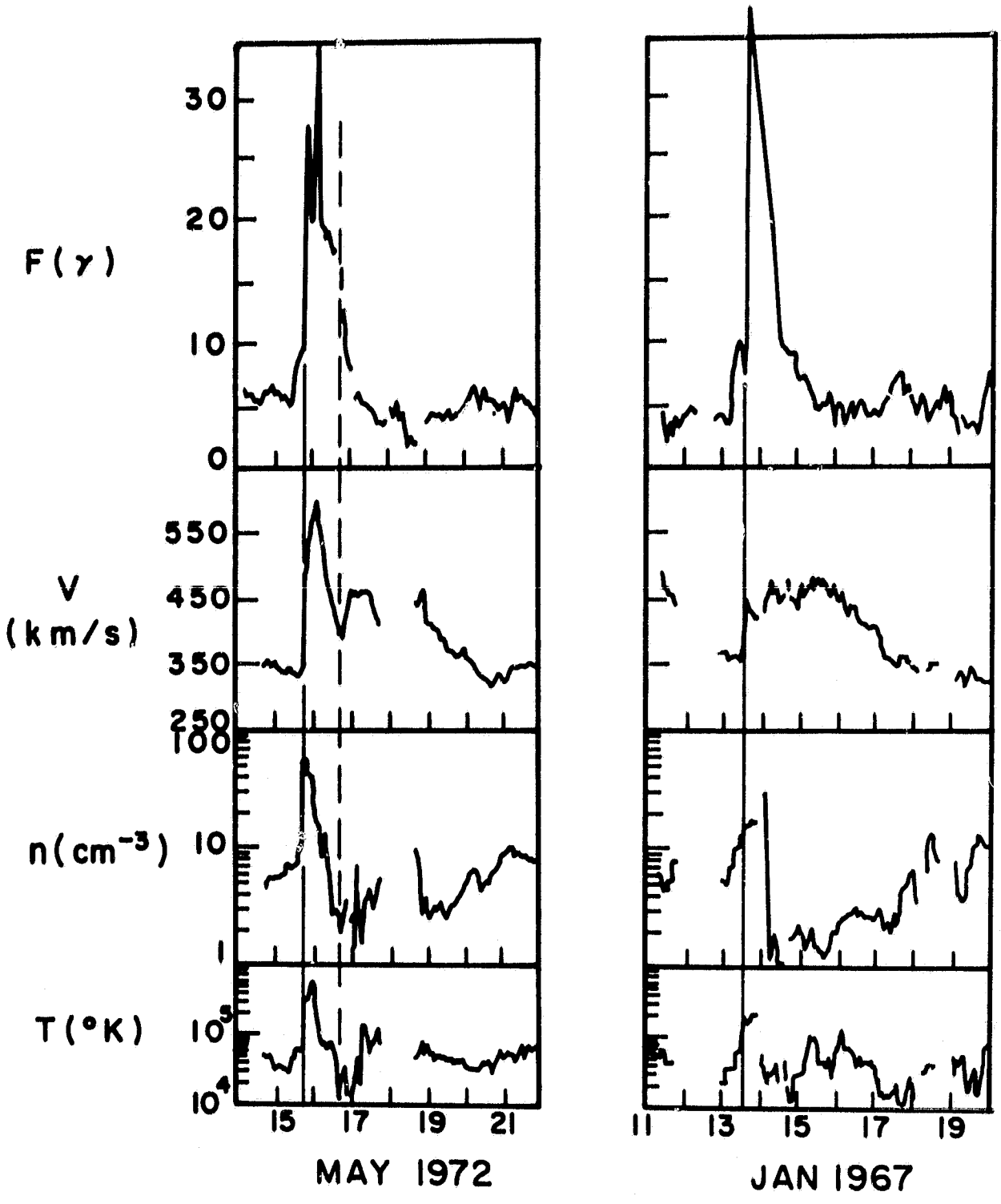

Figure 2

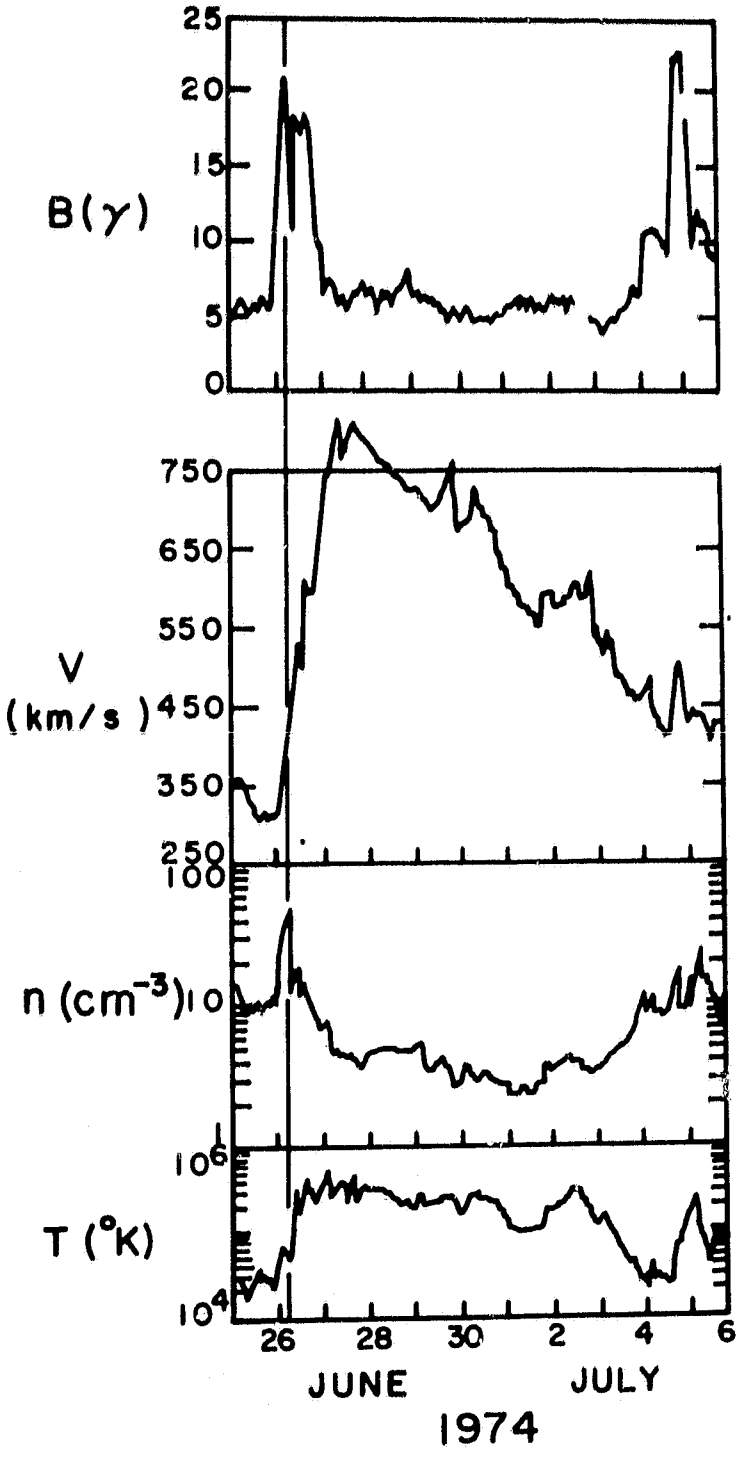

Figure 3

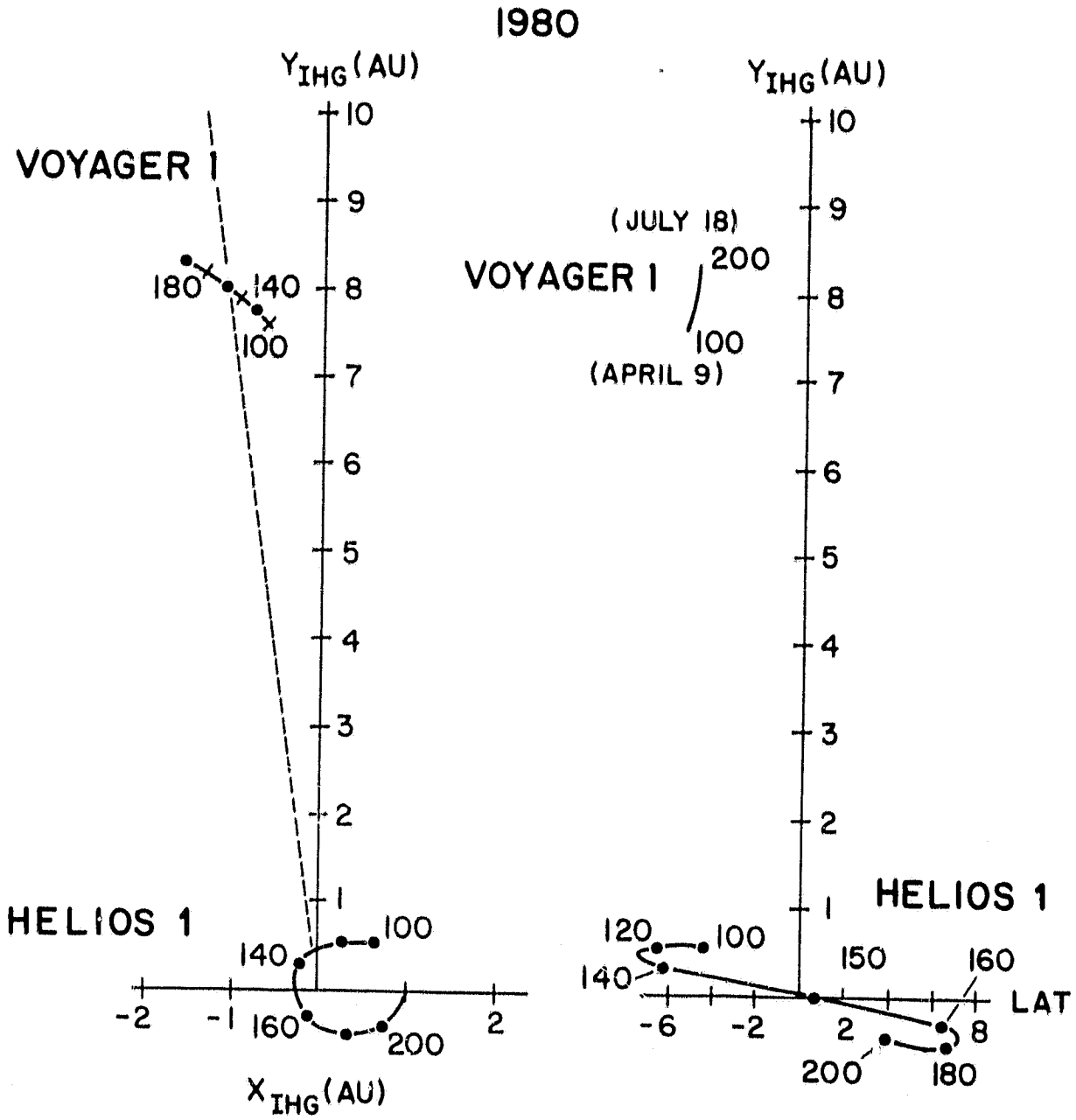

Figure 4

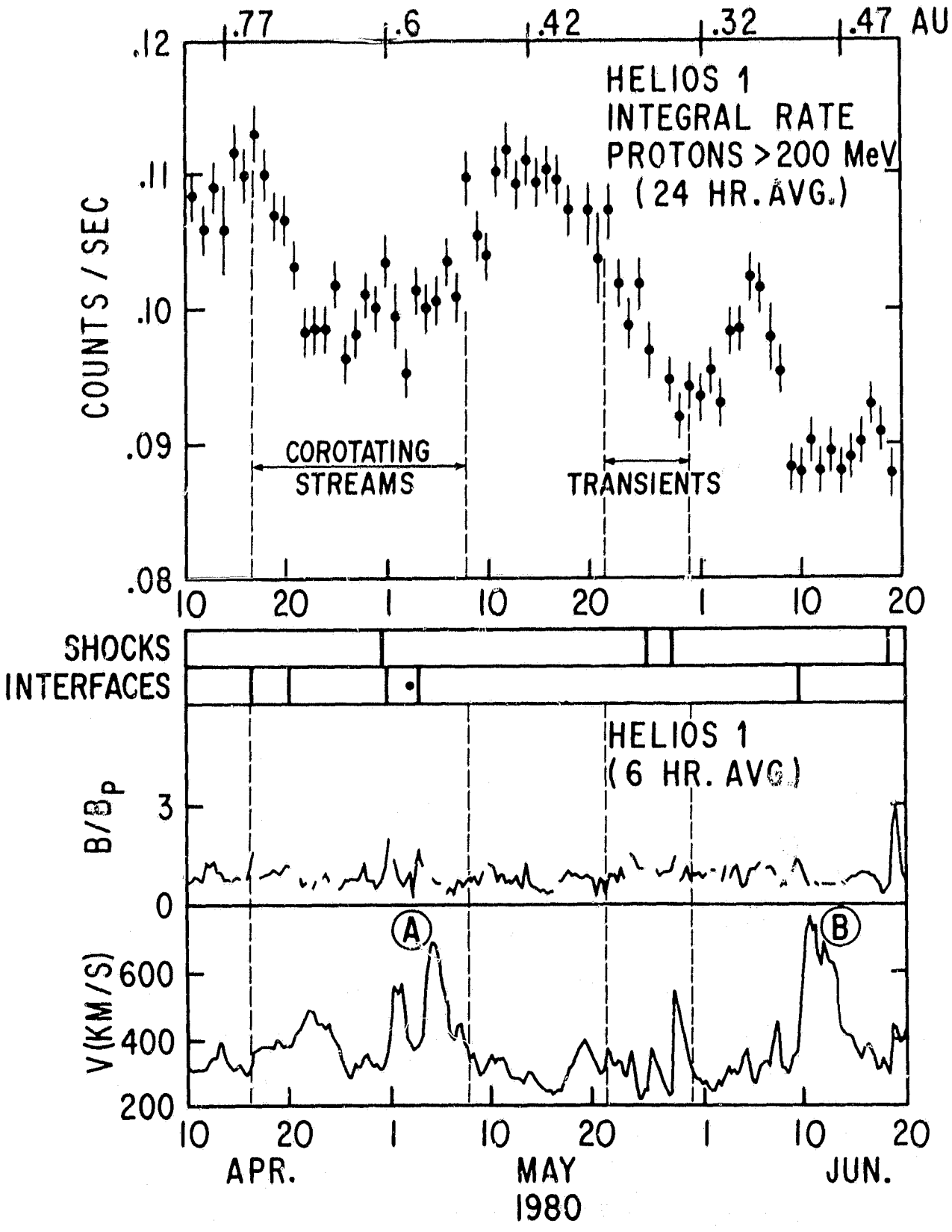

Figure 5

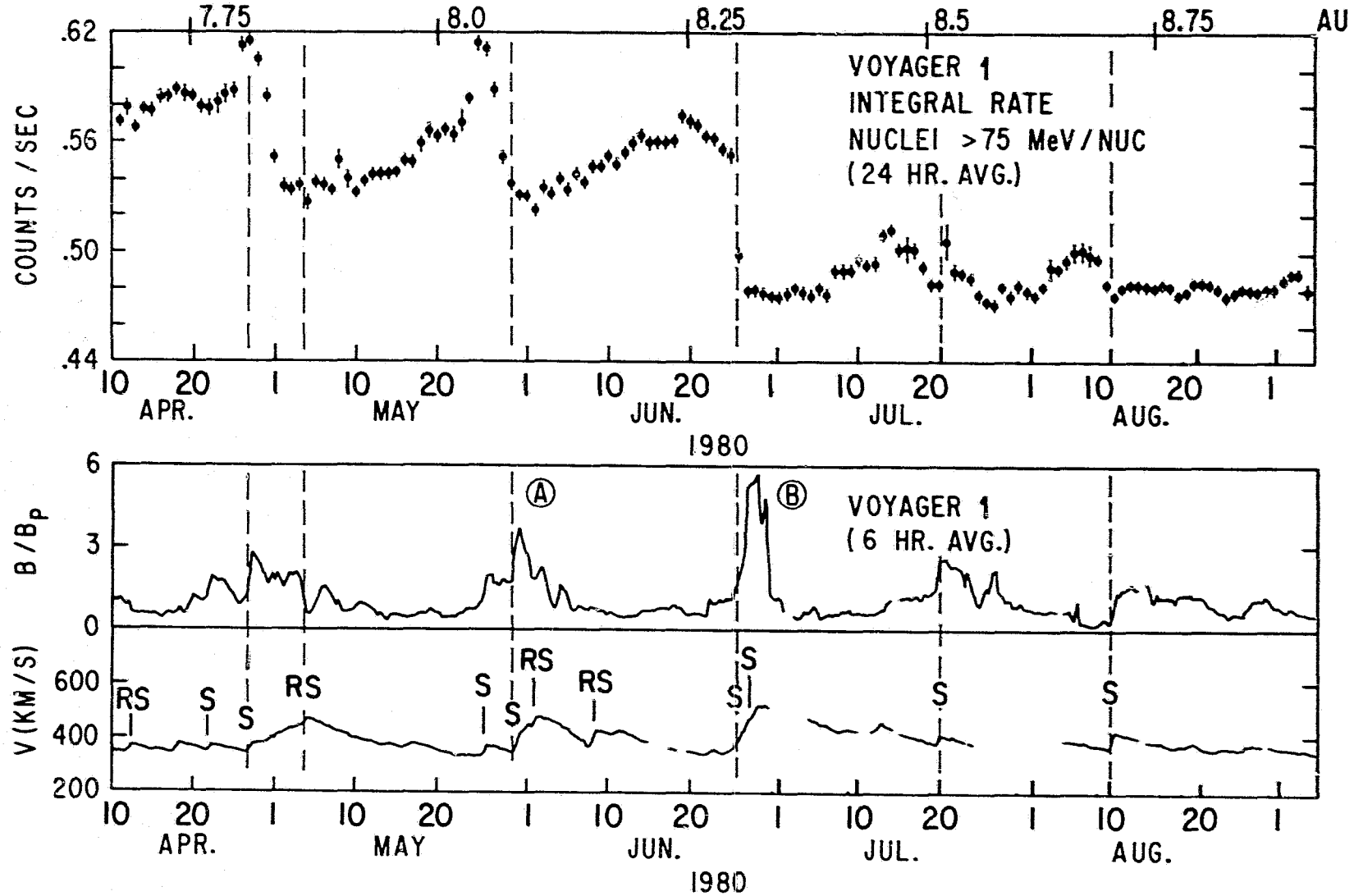

Figure 6

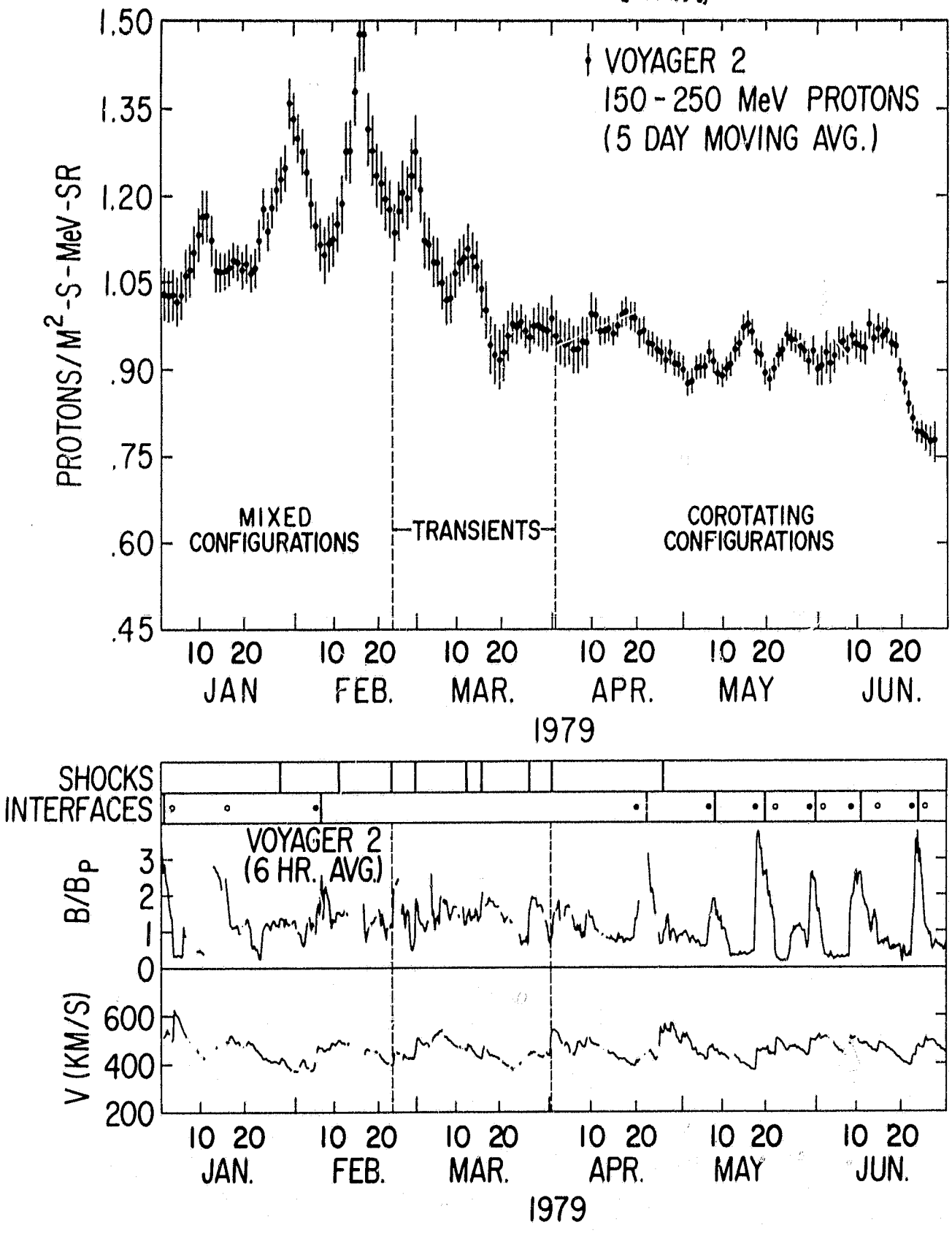

Figure 7

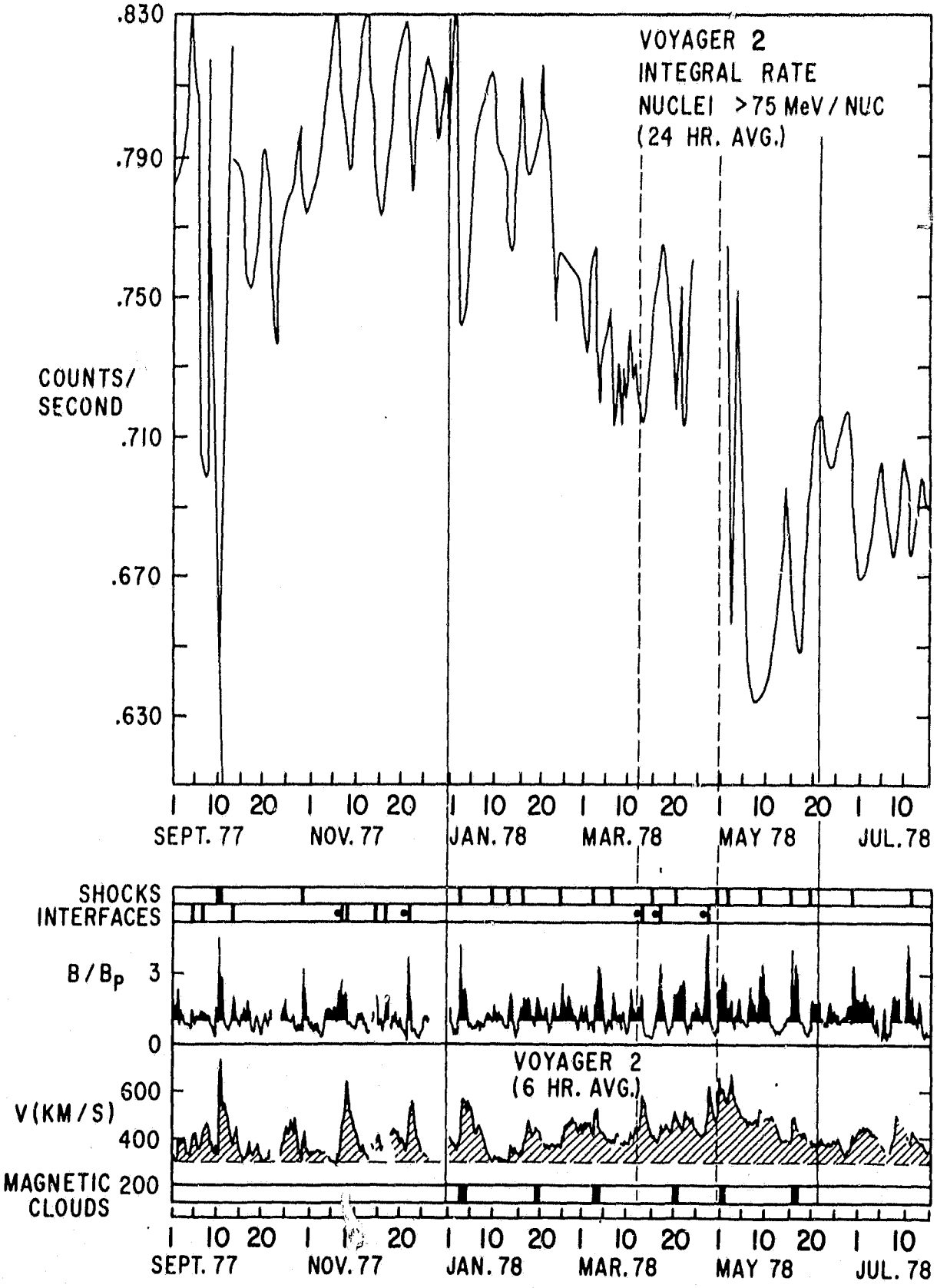

Figure 8

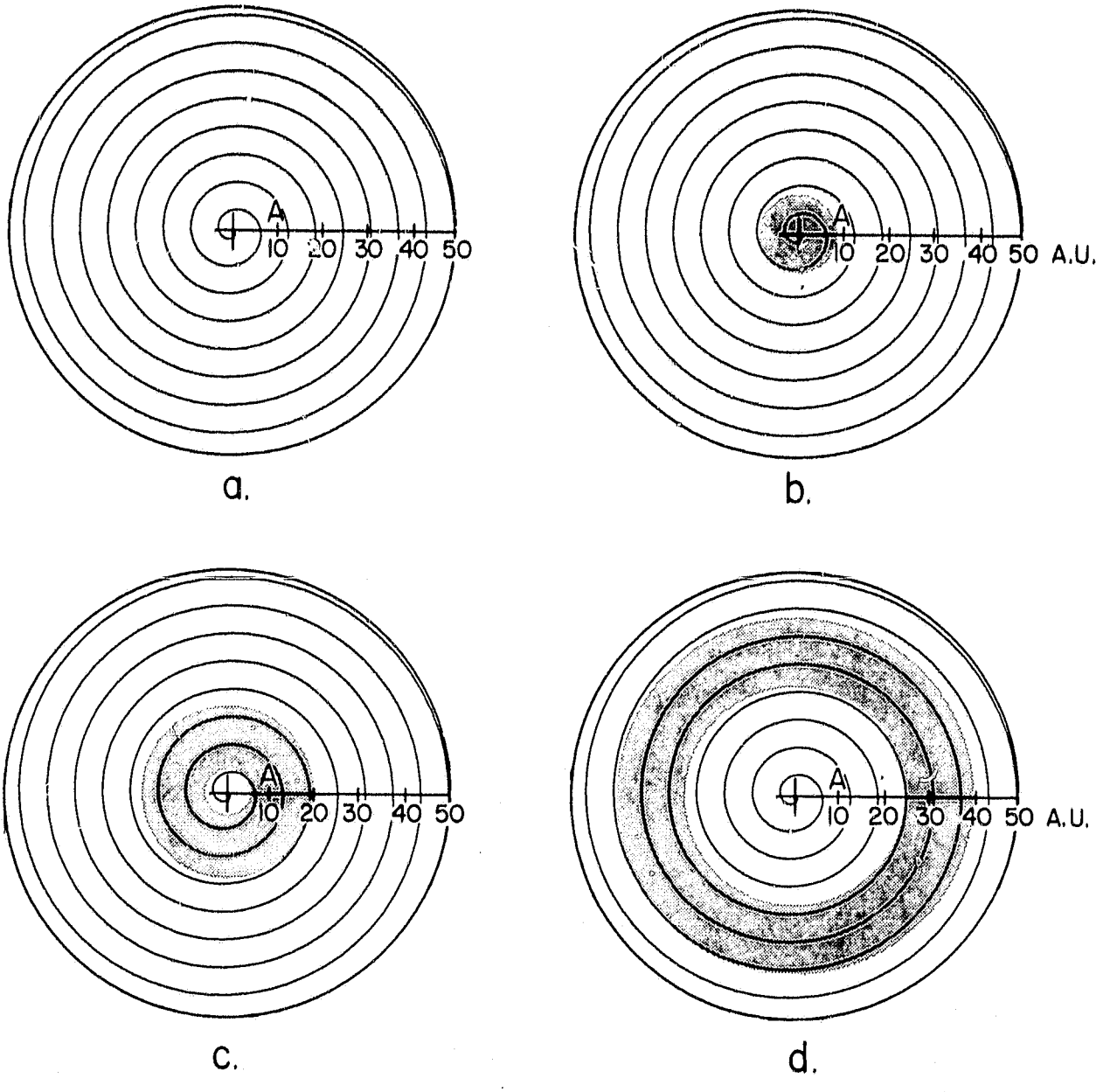

Figure 9