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UNDERSTANDING THE HELIOSPHERE AND ITS ENERGETIC PARTICLES

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L. F. Burlaga

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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

1. Introduction

Variability is a basic property of galactic cosmic rays which are observed in the heliosphere. Temporal changes are observed on all time scales that have been studied and at all distances that have been explored. These variations are of several different classes depending on the time scale considered, ranging from quasi-periodic changes with a scale of 11-years, to intermittent depressions on a scale of a month, and to nearly discontinuous changes on a scale of days. Five classes of cosmic ray variations, identified long ago from ground based observations, are shown in Figure 1. Reviews of the early results have been written by Sandstrom (1965), Dorman (1963), Webber (1962), Lockwood (1971), and Rao (1972). A Forbush decrease is recognized as a rapid decrease in cosmic ray intensity, followed by a more gradual recovery lasting several days. Corotating Forbush decreases are similar to Forbush decreases, but they differ in that 1) the intensity drops more slowly, the time of decrease being nearly as long as the recovery time, and 2) corotating Forbush decreases are quasi-stationary patterns which tend to recur (Rao, 1972) and which are observed to corotate between two spacecraft separated in longitude (Barouch and Burlaga, 1975), whereas Forbush decreases are non-stationary phenomena. The 27-day variations are essentially corotating Forbush decreases which recur at 27 day intervals, as seen at Earth. Long-lasting Forbush decreases resemble Forbush decreases in that the decrease occurs relatively rapidly, but the depression may last for weeks or even months (Lockwood, 1971). Cosmic ray storms (Sandstrom, 1965) appear to consist of a succession of closely spaced Forbush decreases, and may be regarded as a type of long-lasting Forbush decreases. The 11-year variation is a well-known quasi-periodic pattern which is anti-correlated with solar activity.

Observations of cosmic rays have been made from 0.3 AU to beyond

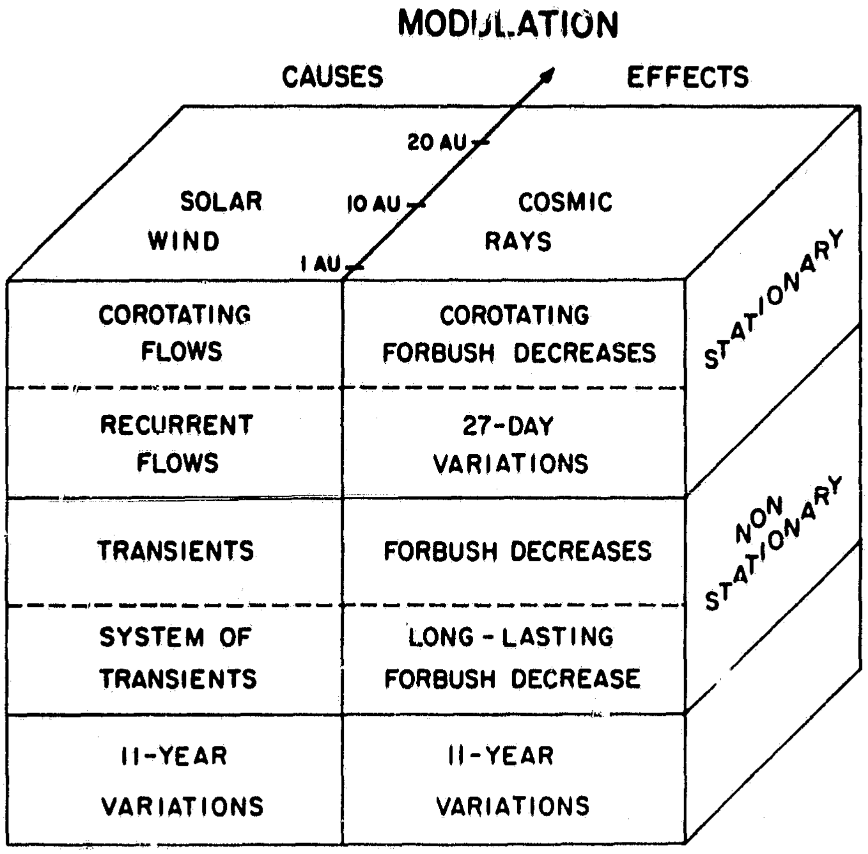

Figure 1: Classes of cosmic ray variations and corresponding classes of interplanetary flows.

25 AU. The Helios 1 and 2 spacecraft have made many passes between 0.3 AU and 1 AU since 1974. A nearly continuous record of cosmic rays for more than one solar cycle has been obtained from interplanetary spacecraft near earth. Pioneer 10 is moving beyond 25 AU, while Voyagers 1 and 2 and Pioneer 11 are making observations beyond 10 AU. Thus we now have an extensive network of interplanetary observatories. One objective of this review is to describe the cosmic ray variations observed by these spacecraft corresponding to the classes of variations listed in Figure 1.

It is generally assumed that the galactic cosmic ray intensity outside the heliosphere is essentially constant, so that the observed variations in cosmic ray intensity are due to the interplanetary magnetic field and the supersonic solar wind which carries the magnetic field. The problem is to determine the basic configurations of the interplanetary flows and fields, to understand the radial and temporal evolution of these configurations, and to relate these configurations to the cosmic ray variations. Various classes of flow patterns that have been observed in the solar wind are listed in Figure 1, and their relation to the classes of cosmic ray variations is indicated. This review aims to describe these relations in a general way, with emphasis on results from spacecraft observations. Some quantitative theoretical models of solar wind flows will also be discussed, but much progress in understanding to date has been made by means of inductive reasoning, intuition and insight. Scattering mechanisms and cosmic ray propagation models are not discussed; the large literature on this topic is reviewed by Quenby (1983), Jones (1983), Fisk (1979, 1980) and Rao (1972).

We have only local measurements of the magnetic field and plasma at just a few widely separated points near the ecliptic plane in the vast three-dimensional heliosphere, so the interplanetary configurations cannot be determined unambiguously. The cosmic rays, on the other hand, provide indirect, integral measurements of the global configuration, since they sample a large volume of the heliosphere in a relatively short time before being detected. Thus, measurements of cosmic rays complement measurements of the magnetic field and plasma.

2. Corotating Flows, Corotating Forbush Decreases, and 27-day Variations

"Recurrent interplanetary streams", having a period of ~ 27 days as seen at Earth, are shown by the heavy curve in Figure 2, from Iucci (1979). The existence of such streams was originally postulated to explain the observation of recurrent geomagnetic storms and was demonstrated by Neugebauer et al. (1966). "Twenty-seven day variations" in the galactic cosmic ray intensity are shown by the lighter curves in Figure 2. The existence of such variations has also been known for many years (e.g., Meyer and Simpson, 1954; Monk and Compton, 1939) and a relation between these 27-day cosmic ray variations and recurrent streams was suggested in the early papers. Figure 2 shows that recurrent streams are indeed associated with 27-day variations, and it was suggested that the speed itself is a factor which causes the cosmic ray variations.

The 27-day variations in cosmic ray intensity are simply recurrences of a "corotating Forbush decrease". Similarly, a recurrent stream is simply the reappearance of a single long-lived stream, which is called a "corotating stream" because it appears to rotate with the sun as seen by an observer in an inertial frame. Thus the problem of understanding 27-day variations reduces to the problem of understanding corotating Forbush decreases. This in turn involves understanding the relation between corotating Forbush decreases and corotating streams, as well as an understanding of the corotating streams themselves.

A correlation between corotating Forbush decreases and corotating enhancements of the interplanetary magnetic field strength was observed by Barouch and Burlaga (1975). Barouch and Burlaga (1976) suggested that drifts associated with the gradients in $|\underset{\sim}{B}|$ might be a factor in producing corotating Forbush decreases. The correlation between increases in $|\underset{\sim}{B}|$ and reductions in cosmic ray intensity was confirmed by Duggal et al. (1983), who also showed a relation between reductions in $|\underset{\sim}{B}|$ and increases in cosmic ray flux.

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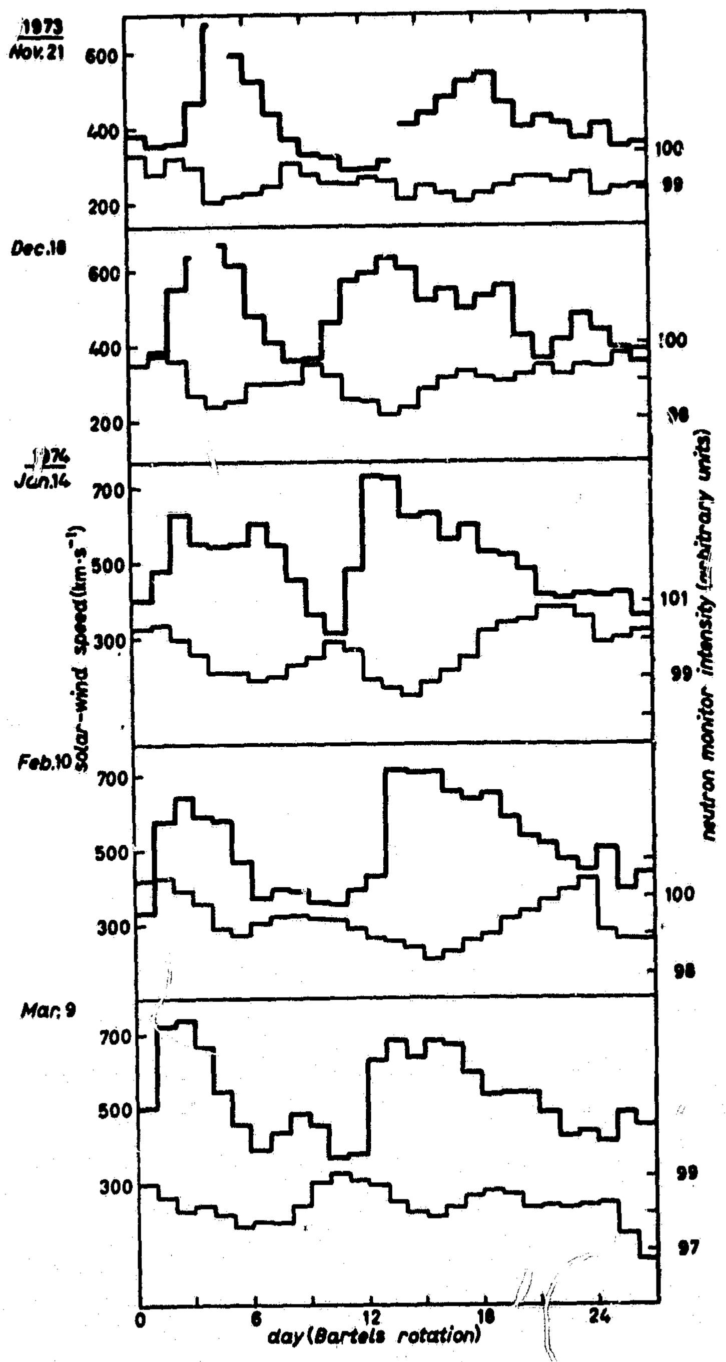

Figure 2: Recurrent solar wind streams (heavy lines) and recurrent Forbush decreases (light lines).

In addition to the speed and magnetic field strength, a third factor which might be involved in corotating Forbush decreases is the presence of small-scale fluctuations in the magnetic field direction. The amplitudes of such fluctuations are largest where the speed is highest (Belcher and Davis, 1971; Behannon and Burlaga, 1981; and Barnes, 1979) so the cosmic ray intensity might be reduced by diffusion among these disturbances. The diffusion mechanism was proposed by Morrison (1954, 1956) and a quantitative diffusion model was presented by Morfill et al. (1979). A model based on tracing particle orbits was presented by Thomas and Gall (1982).

The relative importance of the speed, magnetic field strength and magnetic fluctuations has not been determined. One of the difficulties is that the enhancements in magnetic field strength are correlated with the velocity profile and with enhancements in the fluctuations of the magnetic field, so that a correlation between one of these factors and the cosmic ray intensity implies a correlation of the other factors with the cosmic ray intensity. The relation between B and V is caused by the dynamical evolution of a corotating stream, and it should change with distance from the sun. Thus an understanding of the magnetohydrodynamics of corotating streams, together with measurements as a function of distance from the sun, should contribute to a better understanding of recurrent Forbush decreases.

Some of the basic features of corotating streams are illustrated in Figure 3. A stream originates in a long-lived source (a coronal hole--see Hundhausen, 1977) with a limited azimuthal extent. Near the sun corotating streams have a thin boundary (Rosenbauer et al., 1977; Schwenn et al., 1978; Burlaga, 1979). An element of plasma tends to move at a nearly constant supersonic speed beyond several solar radii, but of course the speed profile is inhomogeneous in longitude. As a consequence of the sun's rotation, fast plasma overtakes slower plasma ahead of it, which was emitted from more westerly solar longitudes. As a result, material at the interface between fast and slow plasma is compressed. Since the magnetic field is frozen to the highly conducting plasma, it too is enhanced at the leading part of the speed profile. This is the

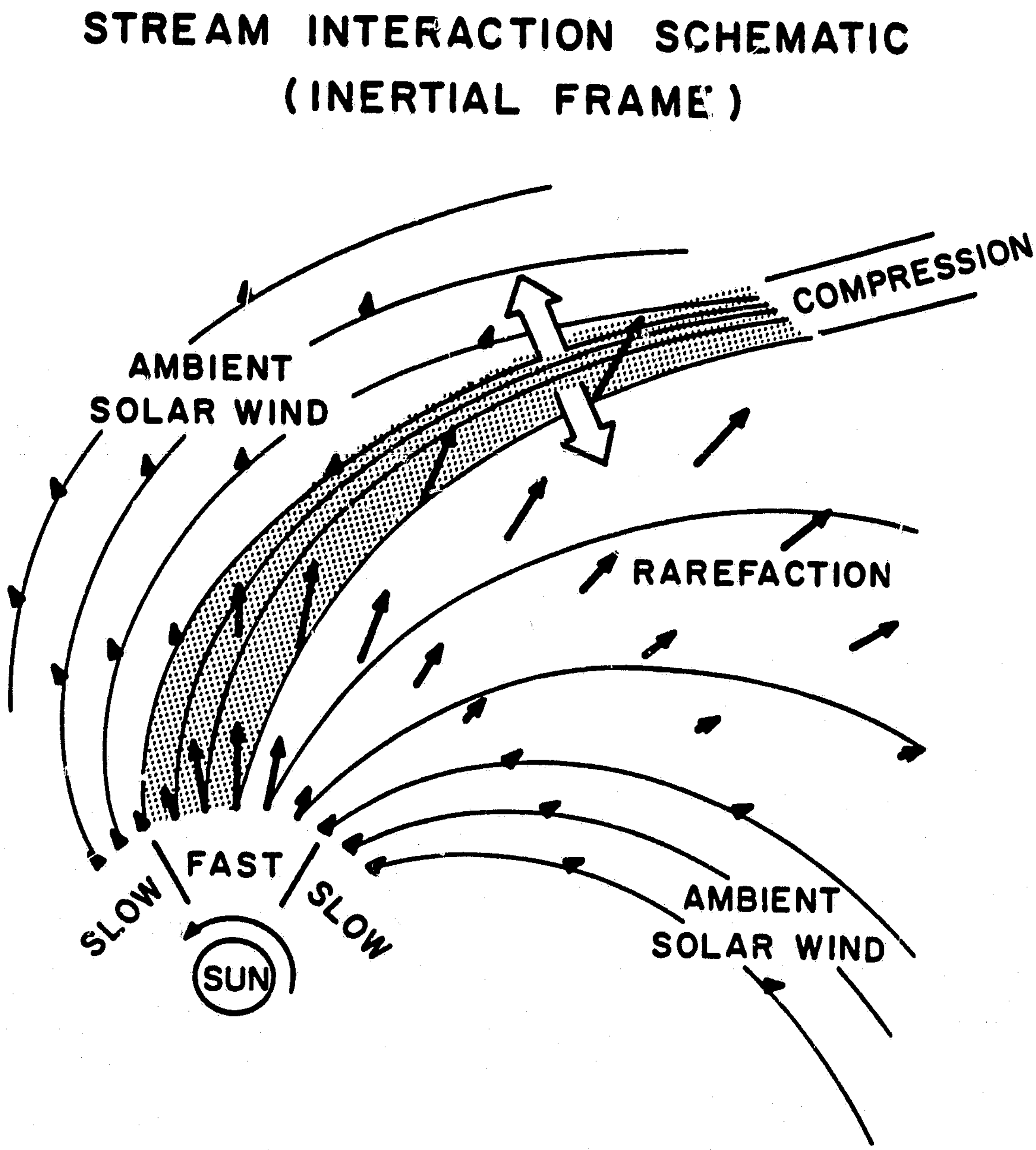

Figure 3: Corotating stream structure.

reason for the correlation between field strength and speed discussed above. The temperature is also increased in this process, and altogether the result is the formation of a pressure wave ahead of the stream (Burlaga and Ogilvie, 1970) at the expense of kinetic energy of the stream, essentially by a kinematic process related to the rotation of the sun (Burlaga and Barouch, 1976). This pressure wave tends to expand both toward and away from the sun, and corotating forward and reverse shock can form at the boundaries of this pressure wave beyond 1 AU. The existence of a corotating reverse shock at 1 AU has been demonstrated by Burlaga (1970). The presence of corotating shock pairs beyond 1 AU was established using Pioneer data by Hundhausen and Gosling (1976), Gosling et al. (1976), Smith and Wolfe (1976), and confirmed with Voyager data by Gazis (1983). For reviews of the early work, see Hundhausen (1972), Burlaga (1975), Gosling (1981) and Pizzo (1983).

Magnetohydrodynamic models of corotating streams have been extensively developed (e.g., Steinolfson et al., 1975; Dryer et al., 1978; Goldstein and Jokipii, 1977; Whang, 1980, 1981; and Pizzo, 1982). They are illustrated by results of a model of Pizzo (1980) shown in Figure 4, taken from a review by Burlaga (1979). At the left are assumed profiles at the inner boundary for the calculation (0.3 AU); these are based on actual observations of stream profiles made by the plasma experiment of Rosenbauer on Helios. Note that 1) the boundary of the stream is relatively thin, 2) the density N is low in the stream, and 3) the temperature T is high in the stream. The computed profiles at 1 AU are shown at the right of Figure 4. The boundary of the corotating stream is marked by an interface at which the flow direction changes, the density drops and the temperature increases. At the front of the stream, there is an enhancement in density, temperature and field strength owing to the compression discussed above, and collectively they produce an enhancement in the total (magnetic plus thermal) pressure P_T. One can see a reverse shock beginning to form behind the interface, and a forward shock would form ahead of the interface beyond 1 AU. In situ observations at 1 AU very closely resemble the theoretical profiles shown in Figure 4.

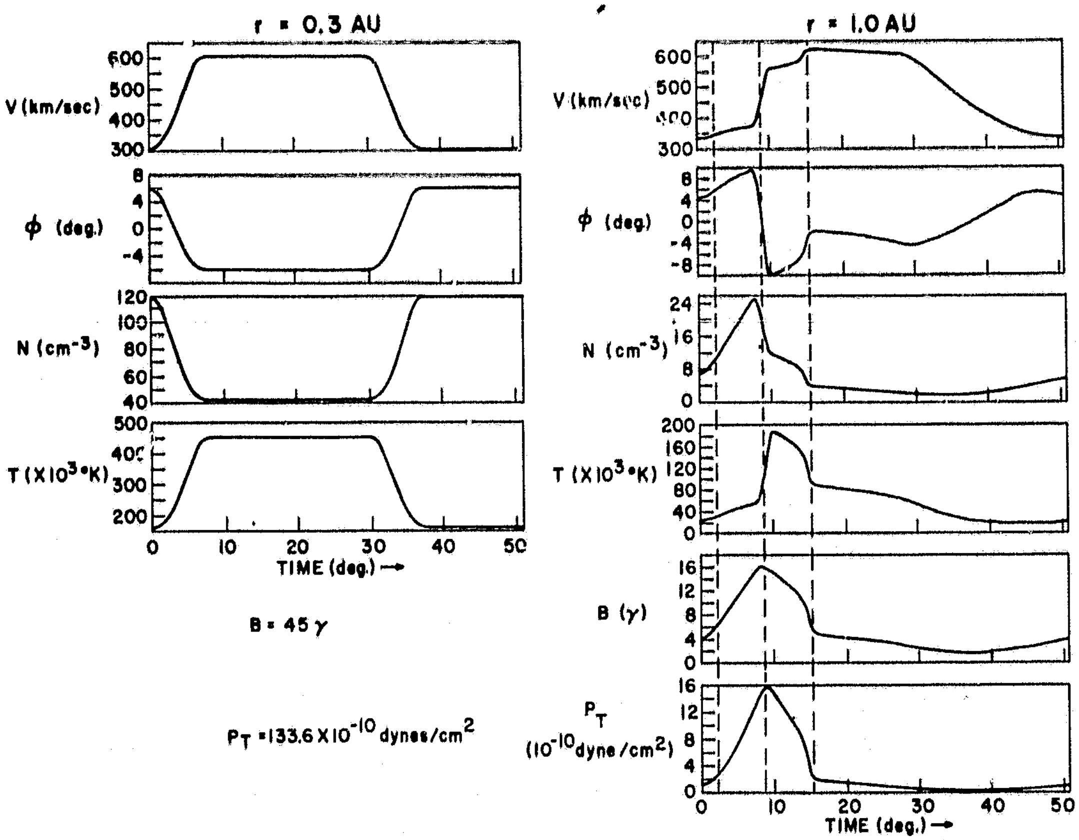

Figure 4: MHD model of a corotating stream. Input conditions (left) based on Helios observations at 0.3 AU, and predicted profiles (right) at 1 AU.

Models of the evolution of streams beyond 1 AU have been referred to above, and they are reviewed by Pizzo (1983) and Gosling 1981). Here we shall simply discuss the basic qualitative features of the radial evolution of corotating flows as shown in Figure 5. The amplitude of the pressure wave grows out to some distance, and it is bounded by a forward shock and a reverse shock. As the shocks move apart, the pressure wave expands. This accelerates material in an increasingly large region ahead of the stream, and it decelerates an increasingly large part of the stream itself. Thus, at large distances, the streams are eroded and the dominant features are the pressure waves. The diminution of the streams with heliospheric distance has been demonstrated by Mihalov and Wolfe (1979) and Collard et al. (1982) using Pioneer data and it was confirmed by Gazis (1983). The existence of large corotating pressure waves in the absence fast corotating streams beyond 1 AU has been demonstrated by Burlaga (1983) using Voyager data.

The models and observations of corotating streams show that the amplitude of the streams diminishes with distance from the sun while the enhancement of the magnetic field strength relative to the ambient value increases. Thus, in principle it is possible to determine whether the bulk speed or the magnetic field strength (or the fluctuations of the magnetic field which accompany enhancements in field strength) is more important in producing corotating Forbush decreases. The final answer is not yet known, but an example of the kind of results available is given in Figure 6, from Burlaga et al. (1982) which shows measurements made at ~ 8 AU by Voyager 1. Recurrent Forbush decreases were observed in April-May, 1980 and in June, 1980. As observed at 1 AU, the decreases in cosmic ray intensity are correlated with the bulk speed and with enhancements in the magnetic field strength. At 8 AU, however, the amplitudes of the streams are small, whereas the enhancements in magnetic field strength are large. Correlative studies, using these results together with measurements made at Helios and near earth, should determine the relative importance of B and V in modulating cosmic rays.

The large-scale structure of the heliosphere at times when stationary corotating systems are dominant is sketched in Figure 7, from Burlaga

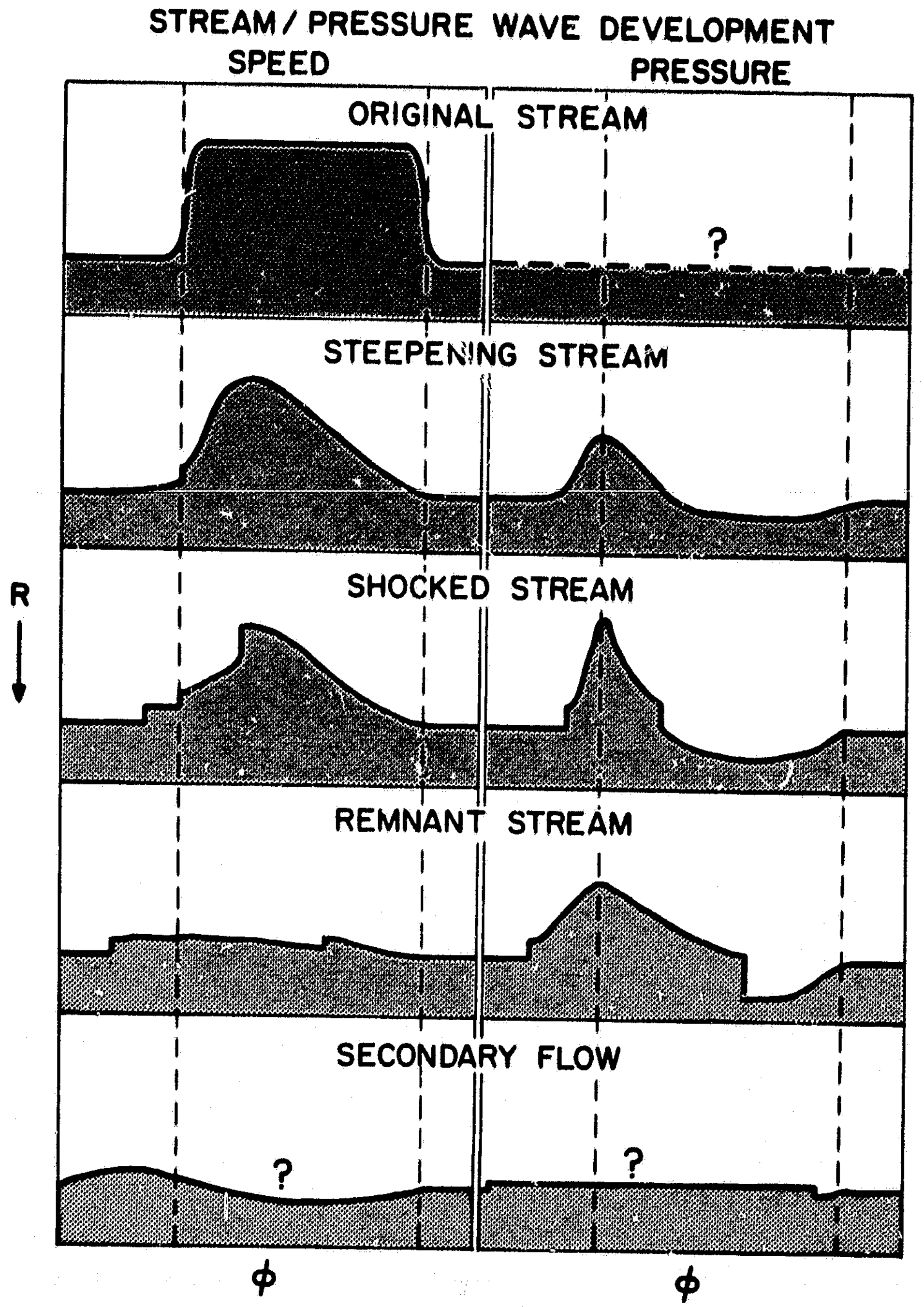

Figure 5: Sketch illustrating the erosion of a corotating stream with increasing distance from the sun, and the corresponding growth and decay of a pressure wave.

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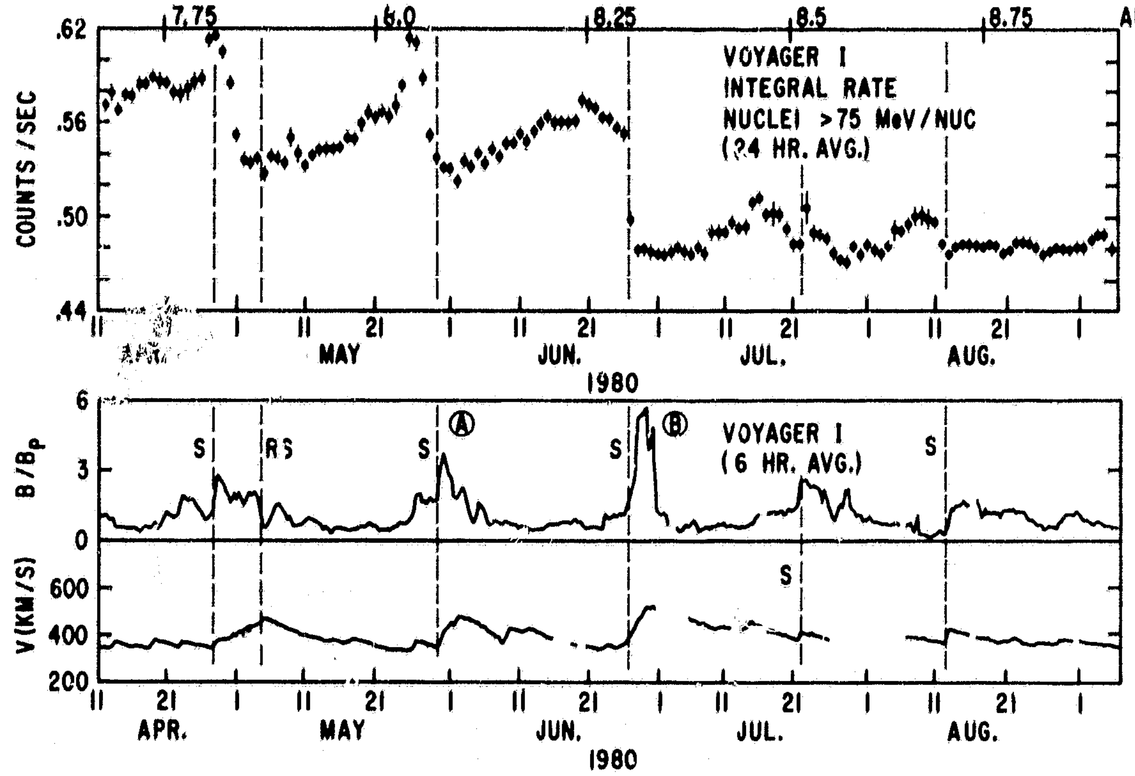

Figure 6: Observations of recurrent (corotating) Forbush decreases near 8AV and the corresponding corotating streams and magnetic field strength enhancements.

(1983) and Burlaga et al. (1983). Near the sun, corotating streams are dominant, and they carry a strong signature of their source (e.g., low density corresponding to coronal holes). Farther from the sun, non-linear pressure waves grow and the streams are eroded, so that corotating pressure waves should be the dominant feature rather than corotating streams. A significant restructuring of N, B, T occurs as a result of dynamical processes driven by the nonuniformity in V, and information about the source is gradually lost. The pressure waves expand, and beyond ~ 25 AU the pressure wave associated with one stream will have interacted extensively with the pressure wave from the following stream, so that the individual interaction regions lose their identity. There results a "wave interaction zone", in which one no longer expects to see simple corotating Forbush decreases like those inside of ~ 10 AU. We may thus anticipate qualitatively different cosmic ray variations at large distances from the sun.

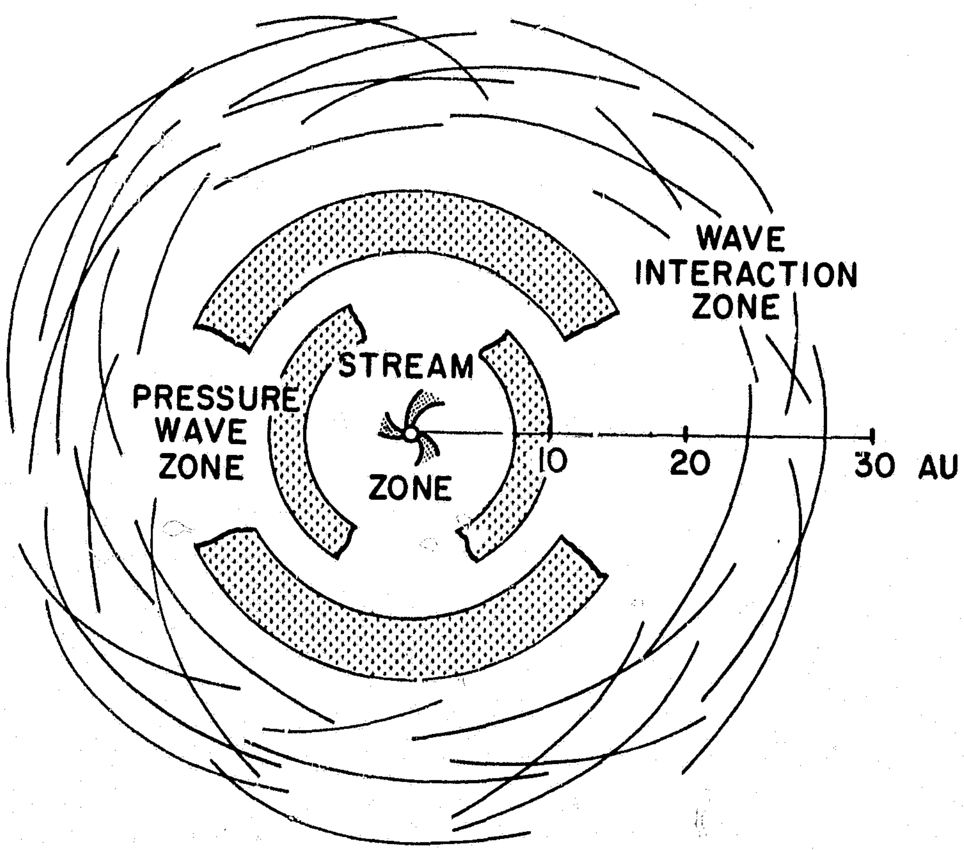

Figure 7: A schematic view of the solar wind structure under stationary conditions.

3. Transients and Forbush Decreases

In the preceding section we discussed quasi-stationary patterns, which persist for many days or even many solar rotations and are associated with long-lived sources on the sun. In this section we shall consider transient phenomena, whose effects are seen for only a few days, which do not corotate or recur, and which are associated with impulsive solar processes such as flares and prominances.

Forbush decreases are characterized by a rapid decrease in cosmic ray intensity followed by a gradual recovery lasting several days. An association between Forbush decreases and geomagnetic storms was identified in the earliest papers (see Sandstrom, 1965; and Dorman, 1963). Magnetic storms were attributed to plasma clouds (compact objects composed of fully ionized plasma propagating away from the sun) by Lindeman (1919) and by Chapman and Ferraro (1929). Alfvén (1954) showed that a beam of plasma moving away from the sun would carry along magnetic fields from the sun. Although he considered quasi-stationary streams in his calculation, the idea of a magnetic cloud is suggested by his sketch, reproduced in Figure 8. Thus, it was natural to attribute Forbush decrease to the interaction of cosmic rays with a "magnetized plasma cloud".

The nature of the interaction of cosmic rays with a magnetized plasma cloud depends on the configuration of the magnetic field in the cloud. Morrison (1954, 1956) suggested that the magnetic field in a cloud is turbulent. He argued that cosmic rays would propagate into a cloud by diffusion, and he explained Forbush decreases as a consequence of the fact that the time to fill a cloud by diffusion is smaller than the time for a cloud to propagate from the sun to 1 AU. Cocconi et al. (1958) and Gold (1959, 1962) suggested that the magnetic field in a cloud is ordered and rooted at the sun, forming a "magnetic tongue" (see Figure 8). They explained Forbush decreases as a consequence of scattering of cosmic rays by gradients in the magnetic field. Piddington (1958) suggested that a magnetic tongue could become detatched from the sun by the process of magnetic reconnection, forming a closed "bottle" or "bubble".

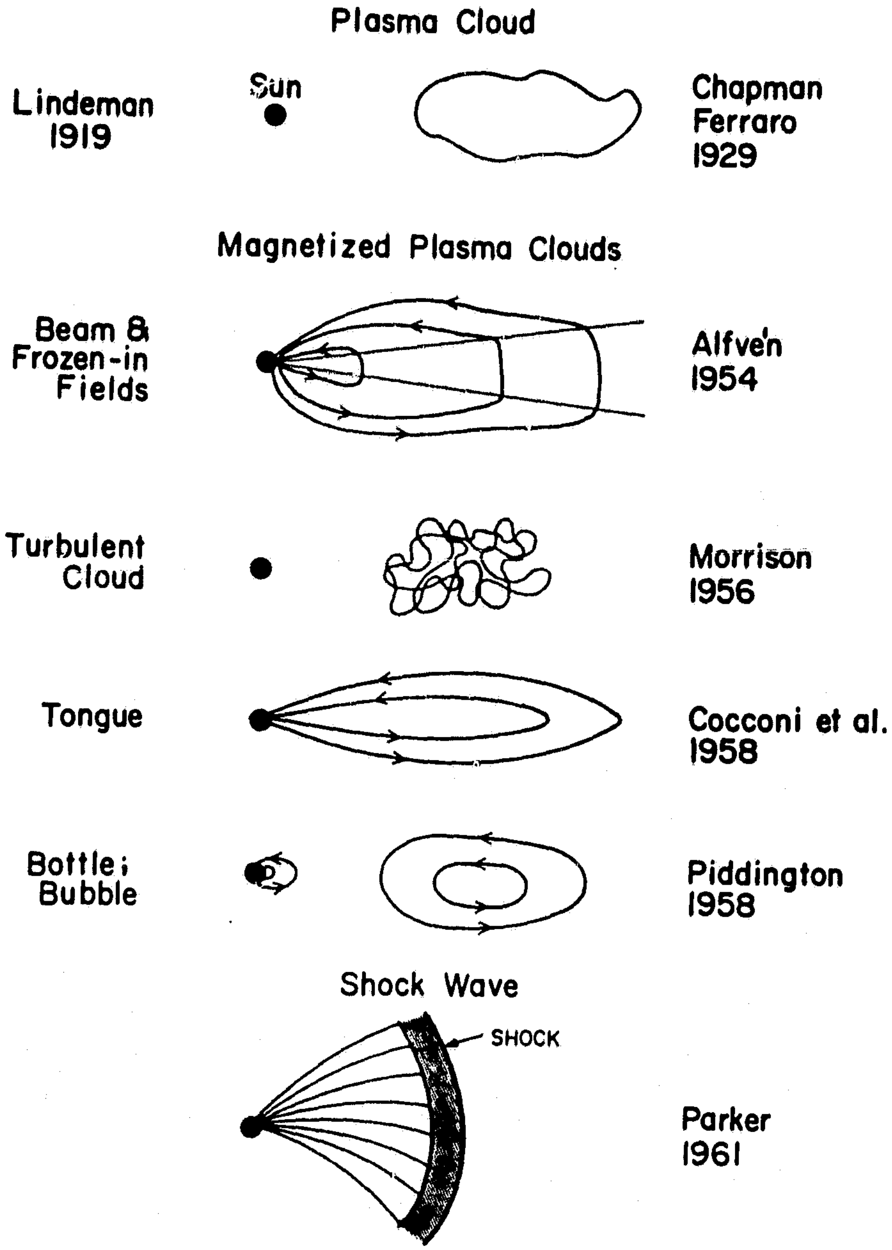

Figure 8: A summary of early views of plasma clouds and possible magnetic field configurations in the clouds. Parker's picture (bottom) does not require the presence of a plasma cloud.

The existence of shock waves in the solar wind was suggested by Gold (1955), and Parker (1961) showed that the ambient interplanetary magnetic field would be compressed and distorted by a shock, forming a shell of intense magnetic fields. He argued that Forbush decreases could be produced by the diffusion of cosmic rays through this shell (also see Parker, 1963). Note that in this model there is no plasma cloud carrying additional magnetic flux from the sun, but the effect of the shell of the compressed interplanetary field on cosmic rays is similar to that of Morrison's turbulent magnetized plasma cloud.

In situ observations have demonstrated the existence of hydromagnetic shocks and a "sheath" behind the shock consisting of compressed, distorted ambient magnetic fields, as suggested by Parker. There is also evidence for plasma clouds of more limited angular extent in which the magnetic field is higher than average. These plasma clouds often follow shocks, and it is thought that many (or even all) interplanetary shocks are driven by such plasma clouds (see Borrini et al., 1982 and the extensive references therein). Currently, the words "driver" or "ejecta" are used in the literature instead of plasma cloud to emphasize this relation to shocks. The present view, based on in situ observations, is a synthesis of the early ideas (see Hundhausen, 1972). We shall refer to the total configuration (consisting of a shock, a sheath, and a magnetized plasma cloud), as an "interplanetary transient". The magnetic field configurations in plasma clouds can have many different forms. Although there is much indirect evidence for tongues and bottles (e.g., see Hundhausen, 1972; Gosling et al., 1973; Bobrov, 1979; Pudovkin, 1977, 1979; Geranios, 1981; Bame et al., 1981; Sarris and Krimigis, 1982), convincing evidence based on direct observations of the magnetic field has been elusive.

Observations of a magnetized plasma cloud with a loop-like magnetic field configuration are shown in Figure 9, from Burlaga _et_ _al_. (1982). The cloud is indicated as the region between the two dashed lines on June 20. One sees that the magnetic field strength in the cloud is higher than average, as suggested by the early models. When the spacecraft entered the cloud, the magnetic field was pointing northward at a large angle with respect to the ecliptic. As the cloud moved past the spacecraft, the magnetic field vector was observed to rotate parallel to a plane to a southward direction at the rear (sunward) boundary of the loop. This pattern is consistent with the passage of a magnetic loop. Observations by just one spacecraft are not sufficient to determine the geometry of the loop. In particular, one cannot determine whether or not the loop is open or closed (see Burlaga and Behannon, 1982). Even multispacecraft observations (Burlaga _et_ _al_., 1981) are not always sufficient to answer this questions.

The magnetic cloud in Figure 9 was moving faster than the ambient solar wind, as may be seen from the speed profile. The density in the cloud was filamentary (see also Burlaga _et_ _al_., 1981), probably related to the fact that the magnetic pressure in a cloud is higher than the thermal pressure (Klein and Burlaga, 1982). The cloud was preceded by a shock across which the density, temperature, and magnetic field strength increased. Between the cloud and the shock was a sheath consisting of compressed and disordered magnetic fields, as suggested by Parker's model. Thus, Figure 9 illustrates an interplanetary transient which combines all the features of earlier models: a magnetized plasma cloud with an ordered loop-like configuration, a shock, and a sheath of compressed and turbulent magnetic fields.

Cosmic rays encountering such a configuration might be expected to diffuse in the sheath behind the shock and drift due to the gradients in field strength and direction both within and ahead of the cloud. Another factor of possible significance to the motion of cosmic rays is the indication that magnetic clouds might expand at approximately half the Alfvén speed as they move away from the sun (Burlaga and Behannon, 1982). This could be a consequence of the fact that the magnetic field

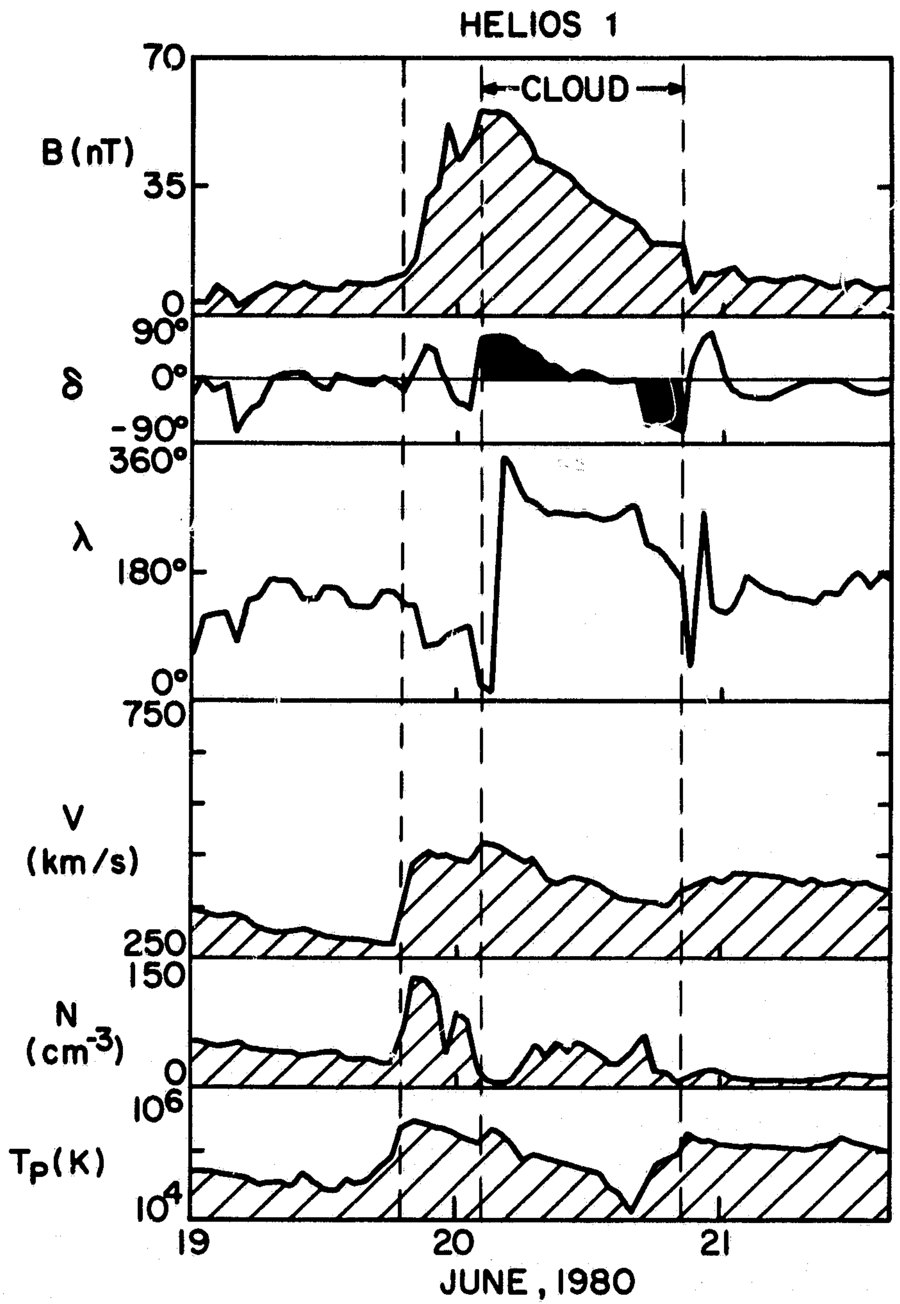

Figure 9: Observation of a "magnetic cloud" with a loop-like field line configuration. A shock, followed by a sheath of strong fields, is driven by the magnetized plasma cloud.

pressure exceeds the plasma pressure in a cloud (Klein and Burlaga, 1982; Parker, 1957). Cosmic rays in such an expanding cloud or in the sheath might be decelerated as proposed by Singer (1958). Detailed studies of the relations between magnetic clouds and cosmic rays have not been made, but they are obviously worth undertaking.

The magnetic cloud in Figure 9 was related to a coronal mass ejection observed near the sun (Burlaga et al., 1982). Specifically, the magnetic cloud was observed by Helios 1 when it was over the west limb of the sun and at a distance of 0.5 AU, and a white light transient (coronal mass ejection) was observed by the earth orbiting spacecraft P78-1 to be moving toward Helios before it arrived at Helios. The time delay between the observation of the coronal mass ejection and the arrival of the magnetic cloud at Helios gives a speed for the cloud in close agreement with the speed of the cloud measured directly at of Helios 1.

A close relation between interplanetary shocks and coronal mass ejections has been found by Gosling et al. (1974), Sheeley et al. (1982) and Schwenn et al. (1982). It remains to be determined whether or not coronal mass ejections are always accompanied by magnetized plasma clouds in the solar wind. Since magnetic clouds and interplanetary shocks are related to coronal mass ejections, and since coronal mass ejections are related to prominences (MacQueen, 1980; Hildner, 1977; Harvey and Sheeley, 1977), we might expect future studies to reveal a correlation between magnetized plasma clouds and prominences. This would confirm the suggestion of Lindeman (1919) and Chapman and Ferraro (1929) that many plasma clouds are related to prominences. It would also be important for understanding the 11-year variations of cosmic rays.

We have been discussing observations made near or within 1 AU. Interplanetary transients and Forbush decreases have been observed beyond 1 AU. Flare-associated shocks observed by Pioneer 10 and Pioneer 11 were investigated in a series of papers (see the reviews by Intriligator, 1977; 1980; Smith and Wolfe, 1977 and 1979; and Smith, 1983). Burlaga et al. (1980, 1981) analyzed multispacecraft observations of flows within 2 AU.

A large Forbush decrease observed at 16 AU by Pioneer 10 and at 7 AU by Pioneer 11, was discussed by Van Allen (1979) (Figure 10) and Pyle et al. (1979). The size of the decreases at these large distances was comparable to that of a corresponding Forbush decrease observed by the Alert neutron monitor. The duration appeared to be longer at larger distances, but this may have been due to the superposition of several effects (von Rosenvinge et al., 1979). The decrease propagated away from the sun at a constant radial speed of 960 km/s, and it extended over at least 160° in longitude. Detailed comparisons of the cosmic ray data with magnetic field and plasma data were not made. A major task for the next few years will be to make detailed joint analyses of Forbush decreases and transient flow configurations with data taken over a wide range of longitudes and radial distances from the sun.

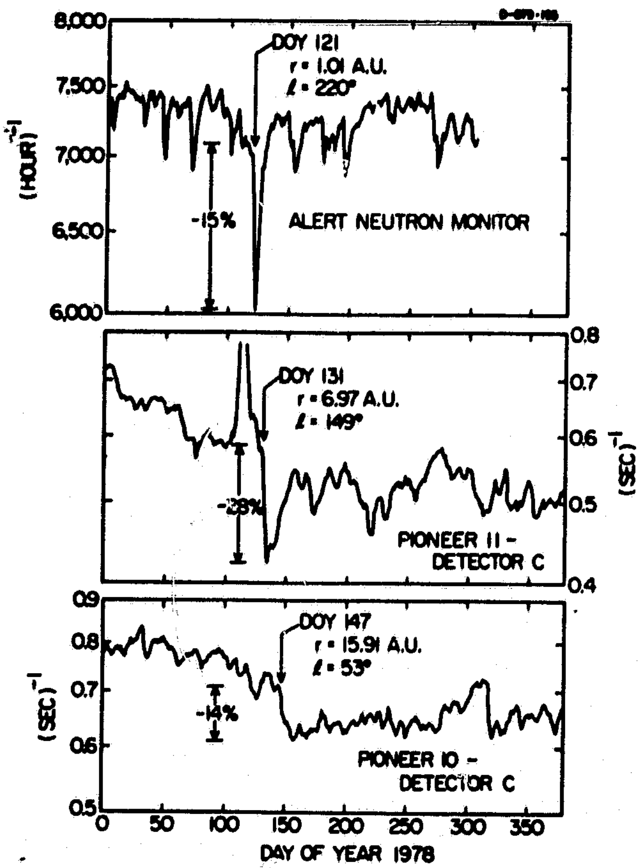

Figure 10: A Forbush decrease at 1 AU, ~ 7 AU, and ~ 16 AU.

4. Systems of Transients and Long-Lasting Forbush Decreases

Lockwood (1958, 1960, 1971) noted the existence of "long-lasting Forbush decreases", and he suggested that they are an important part of the 11-year variation. The occurrence of sequences of closely spaced Forbush decreases, called cosmic ray storms in the early literature (see Sandstrom, 1965), has also been known for many years. Figure 11 shows a long-lasting Forbush decrease in which the cosmic ray intensity is depressed for a month. It has structure which suggests a succession of several Forbush decreases. The decrease in cosmic ray intensity is

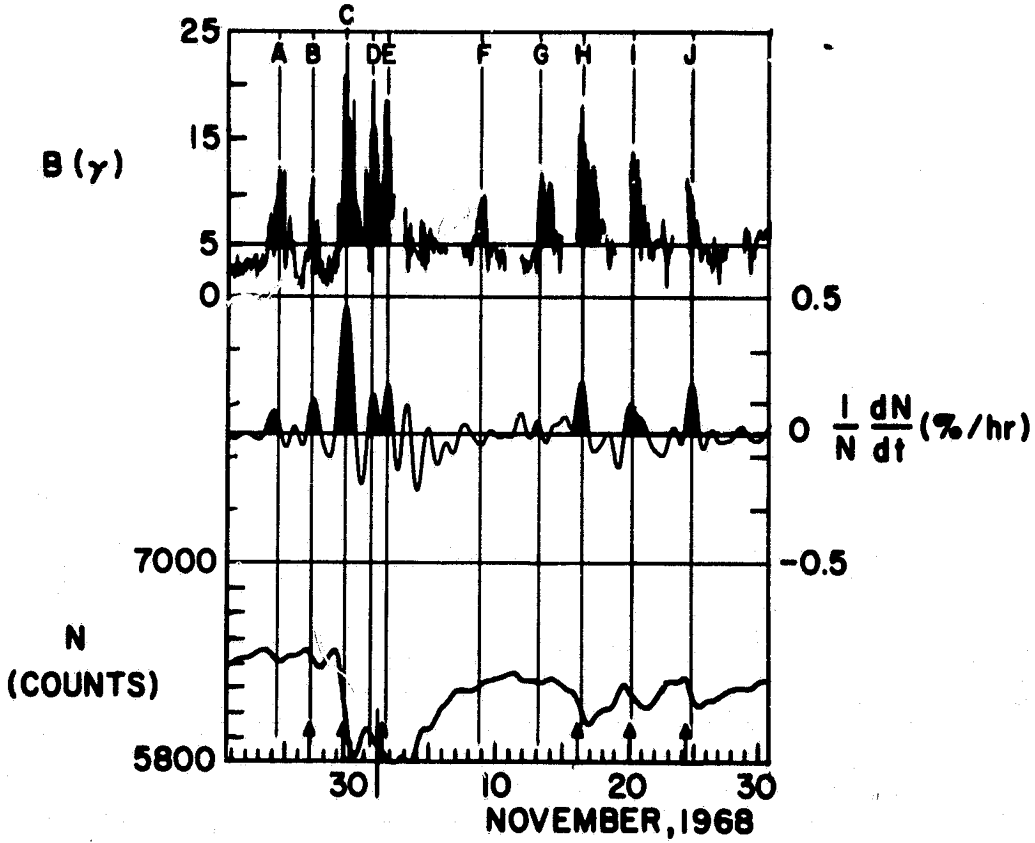

Figure 11: A long-lasting Forbush decrease at 1 AU, with associated enhancements in magnetic field strength and times of SSC (arrows).

long-lasting because the Nth Forbush decrease occurs before the recovery of the (N-1)th Forbush decrease is complete. The strength of the interplanetary magnetic field is high at the times of the largest decreases in cosmic ray intensity. The arrows at the bottom of the figure indicate the times of geomagnetic storm sudden commencements, hence the passage of interplanetary shocks. The major decreases in cosmic ray intensity follow the arrival of shocks. Based on these and other similar observations, Barouch and Burlaga (1975) concluded that long-lasting Forbush decreases are due to the passage of several transient magnetic field enhancements. This may be regarded as confirmation of the hypothesis that cosmic ray storms are due to the passage of several magnetized plasma clouds in close succession.

The above results, together with the observations of recurrent streams associated with 27-day variations discussed in Section 2, show that it is meaningful to speak of a "system of transient flows" and a "system of corotating flows", each lasting for one or more solar rotations. The problem of understanding long-term variations in cosmic ray intensity can be approached by examining the effects of these two extreme types of flow systems on cosmic rays.

A system of transient flows can follow a system of corotating flows and vice-versa. An example of this is shown in Figure 12 from Burlaga et al. (1982). For two months prior to January 1, 1978, a system of corotating flows was observed by Voyager 2, as indicated by the presence of stream interfaces and the absence of shocks not associated with interfaces. For nearly three months after January 1, 1978, a system of transient flows was observed, as indicated by the presence of shocks and the absence of stream interfaces. The system of corotating flows produced corotating Forbush decreases, but no net reduction in the cosmic ray intensity. The system of transient flows, on the other hand, did produce a permanent reduction in the cosmic ray intensity.

The effects described above may also be seen by examining other time intervals in Figure 12, and additional observations showing the same effects have been discussed by McDonald et al. (1982) and Burlaga et al.

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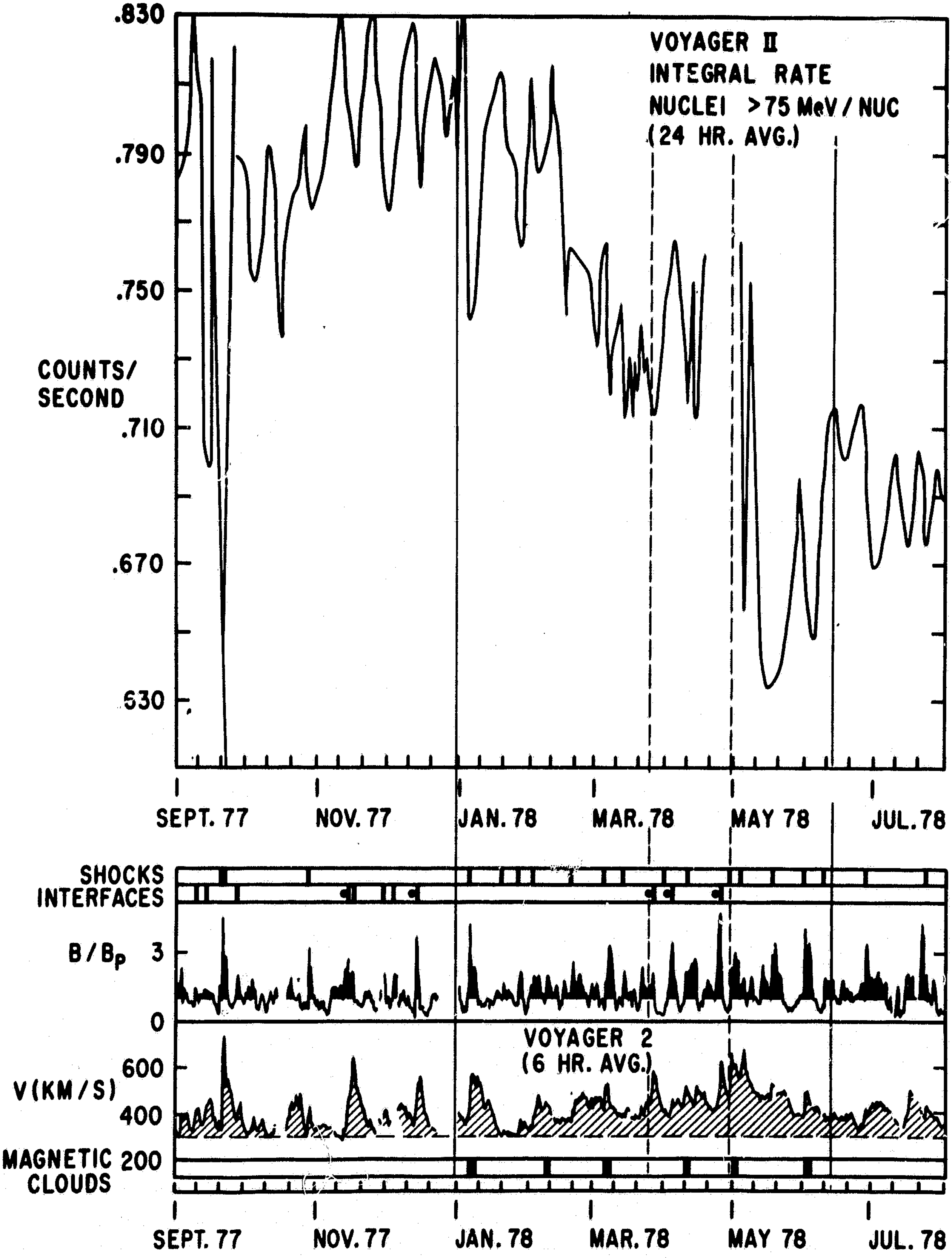

Figure 12:

(1932, 1983a, 1983b). Summarizing, 1) there exist systems of corotating flows lasting at least two solar rotations which perturb the cosmic ray intensity profile but cause no net reduction in intensity, 2) there exist systems of transient flows (associated with shocks) lasting at least two solar rotations which do cause a net reduction in cosmic ray intensity, and 3) these two kinds of flow systems can exist side by side.

A geometrical picture of the interplanetary medium suggested by these observations is illustrated schematically by Figure 13. It is assumed for simplicity that the sun and interplanetary medium can exist in one of two extreme states: a "quiet state" in which the solar wind consists of corotating flows and no transients, while the sun has stationary coronal holes but no active regions; and a "disturbed state" in which the solar wind consists of transient flows with no corotating streams, while the sun has many sources of activity ejecting magnetized plasma clouds at random but no sources of stationary flows. Assume that the sun has been in the quiet state for many months, so that the solar wind has a simple spiral geometry as illustrated by the single spiral in Figure 13a. Now assume that the sun suddenly goes into a disturbed state, emitting magnetized plasma clouds which fill an increasing volume as illustrated by the shaded area in Figure 13b. Assume that after $\sim$ 2 solar rotations the sun returns to its quiet state. The ensemble of magnetized plasma clouds, shocks, etc., fills a shell which moves outward at $\sim$ 400 or 500 km/s, and it is followed by an ordered spiral configuration as illustrated in Figure 13d. In this scenario, a spacecraft would observe a sequence of corotating flows, followed by a sequence of transient flows, followed in turn by another sequence of corotating flows. This picture is consistent with observations in Figure 12 and the other similar observations that have been referenced above. It is also consistent with the general idea of a shell of turbulent magnetic fields discussed by Morrison (1954, 1956); and Lockwood (1971).

The effect of a shell corresponding to a system of transients is essentially that which the early investigators proposed, viz. a long-term reduction in cosmic ray intensity. It supports the view that all long-term reductions in cosmic ray intensity are caused by such shells

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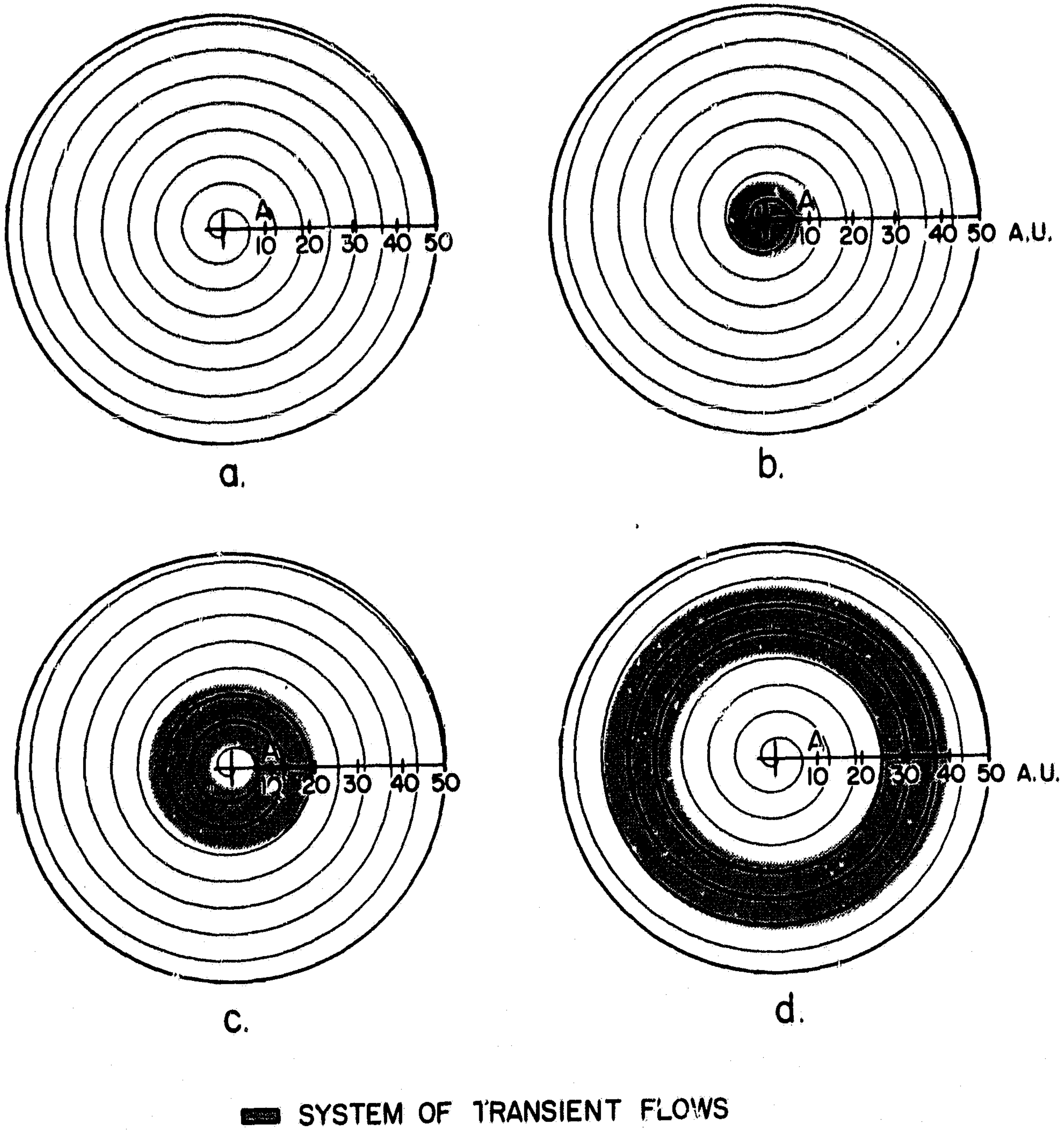

Figure 13: A shell of transients.

(i.e., by systems of transients, in our language), but further studies of spacecraft data using observations taken over many years must be made before this view is confirmed.

With in situ measurements, it is possible to examine in what sense the magnetic fields in the large-scale shells (systems of transients) differ from magnetic fields in systems of corotating flows. Figure 14 shows the results of an analysis by Goldstein et al. (1983) for two time intervals, one corresponding to the observation of a system of transients from January-March, 1979, and the other corresponding to the observation of a system of corotating flows in the following months of April-June, 1979. Three curves are shown for each interval as a function of frequency: the power in the magnitude of $\mathbf{B}$; the power in the fluctuations of all components of $\mathbf{B}$ (the trace of the spectral tensor $S_{ii}(k)$; and the curve $kH_M(k)$, where H_M is the magnetic helicity (Matthaeus et al., 1982, Matthaeus and Goldstein, 1982). Magnetic helicity is a measure of the degree to which the magnetic field is bent or twisted. Thus, the presence of large scale magnetic loops, tightly-wound helices, or small-scale Alfvénic fluctuations would be seen as a relatively large kH_M at the appropriate frequency. Figure 14 shows that in the "corotating interval", the power spectra for the field strength is not described by a simple power law; there is a large peak in the power at $\sim$ 10 days, which corresponds to ordered pressure waves associated with the interaction regions of corotating flows. In contrast, the power spectra for the magnitude and direction of the fields are both described by a power law. There is significantly more magnetic helicity of low frequencies in the transient interval than in the corotating. Thus, the spectral signatures at the two classes of flows are distinctly different. Their relation to compressible MHD turbulence remains to be explored.

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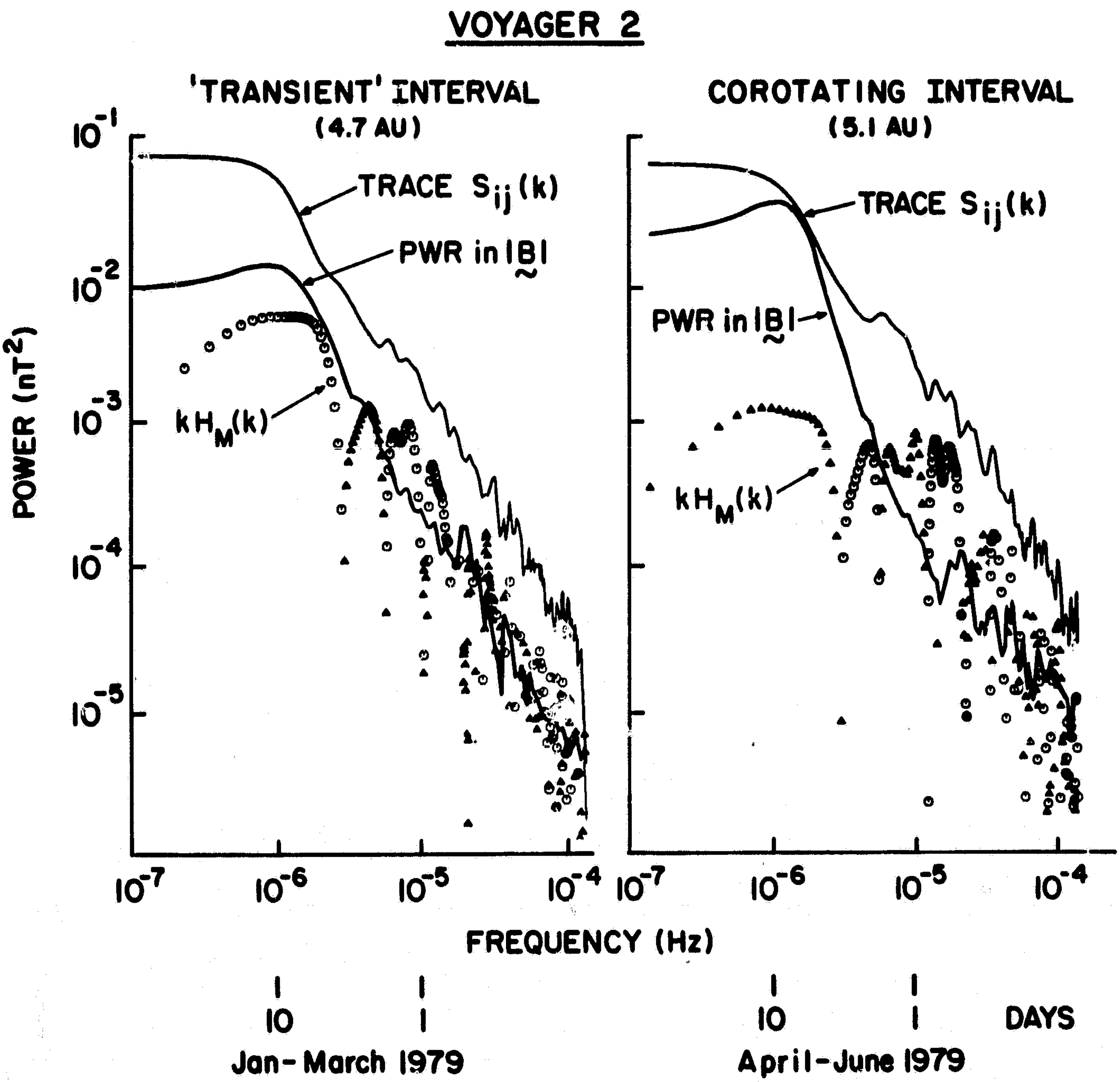

Figure 14: Power spectra of the magnetic field for a system of transient flows and a system of corotating flows.

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5. Eleven-year Variations

We now return to the problem of the 11-year variation of cosmic ray intensity, illustrated in Figure 15 from McKibben et al. (1982). One sees the well-known pattern of maxima in the cosmic ray intensity near minima in the solar activity cycle, and vice-versa. It should also be noted that the variation is not exactly sinusoidal: 1) The decreases tended to occur in a few large steps in 1955–1957 (Lockwood, 1958, and 1960) and in 1978–1980 (McDonald et al., 1981a), but more gradually in 1965–1969; and 2) There were large fluctuations in the intensity on a scale of < 1 year throughout the interval.

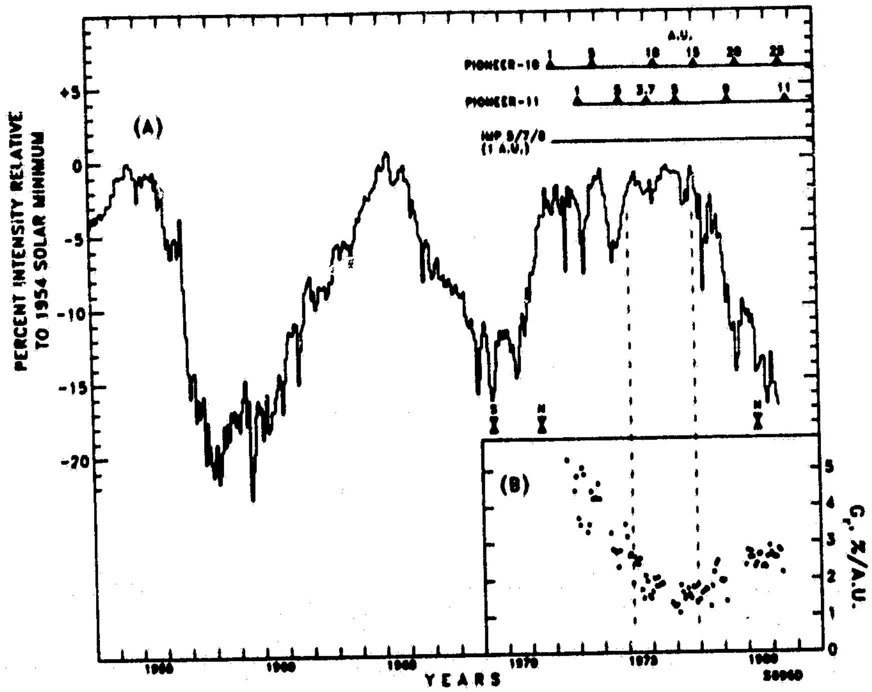

Figure 15: (A) Solar cycle variations of cosmic ray intensity. The insert (B) shows measurements of the radial gradient G_r.

Three explanations of the 11-year variation have been proposed. Parker (1963) suggested a quasi-stationary model in which diffusion by small-scale fluctuations in the magnetic field and convection by the solar wind are the dominant processes. A second explanation, advocated by Isenberg and Jokipii (1979), Jokipii and Davila (1981), and Jokipii and Thomas (1981) is that the 11-year variation is due to drifts in the large-scale gradients in the magnetic field (see the reviews of Jones, 1983, Fisk, 1979, and McKibben, 1981). A third explanation, offered by Morrison (1956) before the solar wind was discovered, is that the 11-year variation is due to diffusion in a large ($\sim$ 100 AU) shell of turbulent magnetic fields made up of intermediate-scale magnetized plasma clouds ejected from flares or prominences.

Studies of the 11-year variations in the bulk speed, magnetic field strength and power in the small-scale fluctuations in the magnetic field, failed to support attractive the model of Parker (see Lockwood, 1971; Rao, 1972; King, 1981, and Quenby, 1983). There is evidence against the large-scale drift model (Newkirk and Lockwood, 1981; Evenson et al., 1979; Lee and Fisk, 1981), but there is also evidence for large-scale 3-dimensional effects by (Hundhausen, 1979; Hundhausen et al., 1981, and Duggal et al., 1981), so the case is not yet closed. There is increasing evidence in support of the view that the 11-year variation is caused by intermediate scale disturbances corresponding to transient flows associated with solar activity. Hedgecock (1975) noted that there is more power at such scales ($\sim 10^{-5}$ Hz) at solar maximum than at solar minimum. Burlaga and King (1979) found that during years when the cosmic ray intensity was low the enhancements in interplanetary magnetic field strength were more often associated with shocks (and thus with transient flows) than when the cosmic ray intensity was high. Newkirk (1975) and Newkirk et al. (1981) suggested that such magnetic field strength enhancements, or other modulation agents of a similar scale, might be related to coronal transients, which are related to prominences and solar flares whose frequency changes with solar activity.

The importance of the propagation of disturbances associated with flares and sunspot number was shown indirectly by Hatton (1980) and Nagashima and Morishita (1980), respectively. Figure 16 from Hatton shows that there is a correlation between the variations of cosmic ray intensity and variations in the number of flares of importance $\leq$ 1, illustrating well-known relation between cosmic ray intensity and solar activity. If the effects of the flares on cosmic rays are assumed to be occurring only after a finite time after the flare, corresponding to a disturbance propagating at the solar wind speed, then the relation between the cosmic ray intensity and the flares is significantly improved, as indicated at the bottom of Figure 16.

Direct and convincing evidence that the 11-year variation is due to disturbances which propagate away from the sun is shown in Figure 17 from McDonald et al. (1981a), based on simultaneous data from Helios 1 and 2 between 0.3 and 1 AU, and from Pioneer 10 between 12 AU and 20 AU. The cosmic ray flux is higher at Pioneer 10 than at Helios owing to the large-scale gradient (see the insert of Figure 15 for measurements of the gradient made by McKibben et al., 1982). Apart from this, however, the general shape of the profile measured by Helios is very similar to that measured by Pioneer 10. Assuming no propagation effect (no time delay between the spacecraft) and allowing for the radial gradient, the Helios profile gives the dotted curve in Figure 17, which differs systematically from the Pioneer 10 observations. If one assumes that the changes in cosmic ray flux propagate outward at a speed of 500 km/s again allows for the radial gradient, one gets the dashed curve in Figure 17. This curve is in good agreement with the Pioneer observations, showing that changes associated with the 11-year variation do propagate away from the sun at the solar wind speed. A similar conclusion was arrived at by Webber and Lockwood (1981).

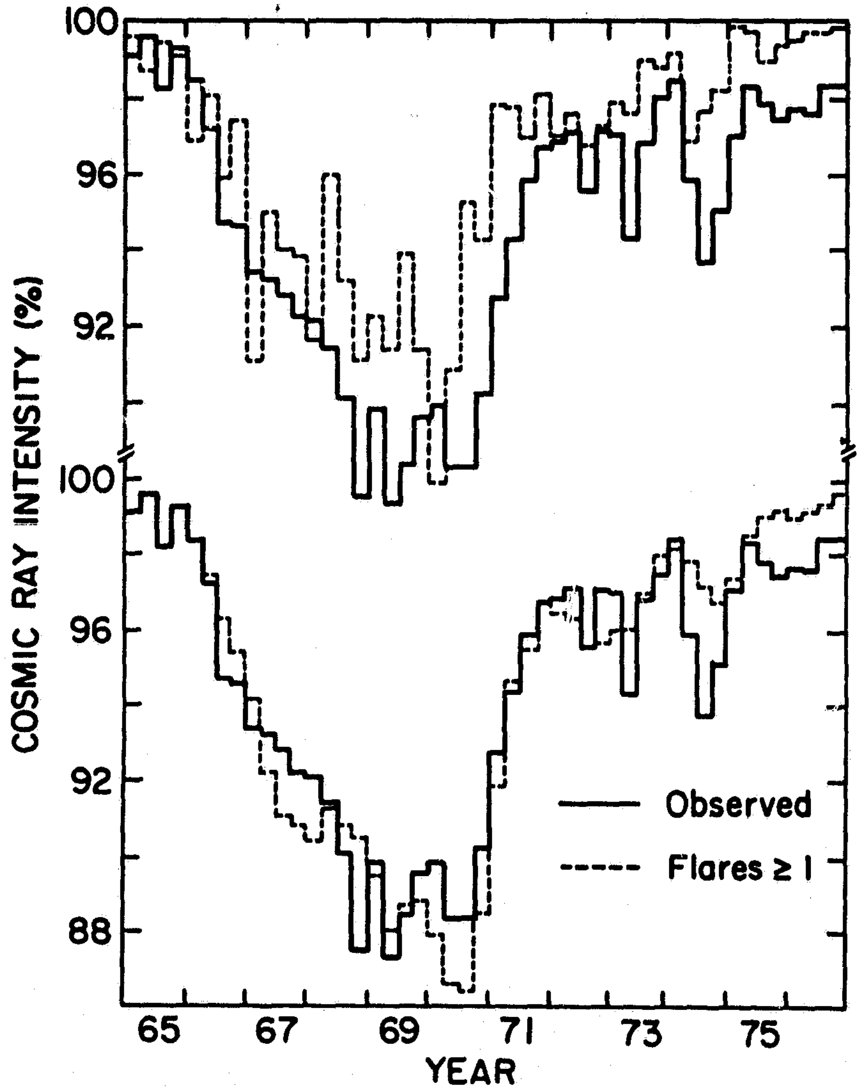

Figure 16: Cosmic ray intensity (solid lines) and the number of flares of importance ≥ 1 plotted inversely (dashed lines) without a time delay (top) and with a time delay (bottom).

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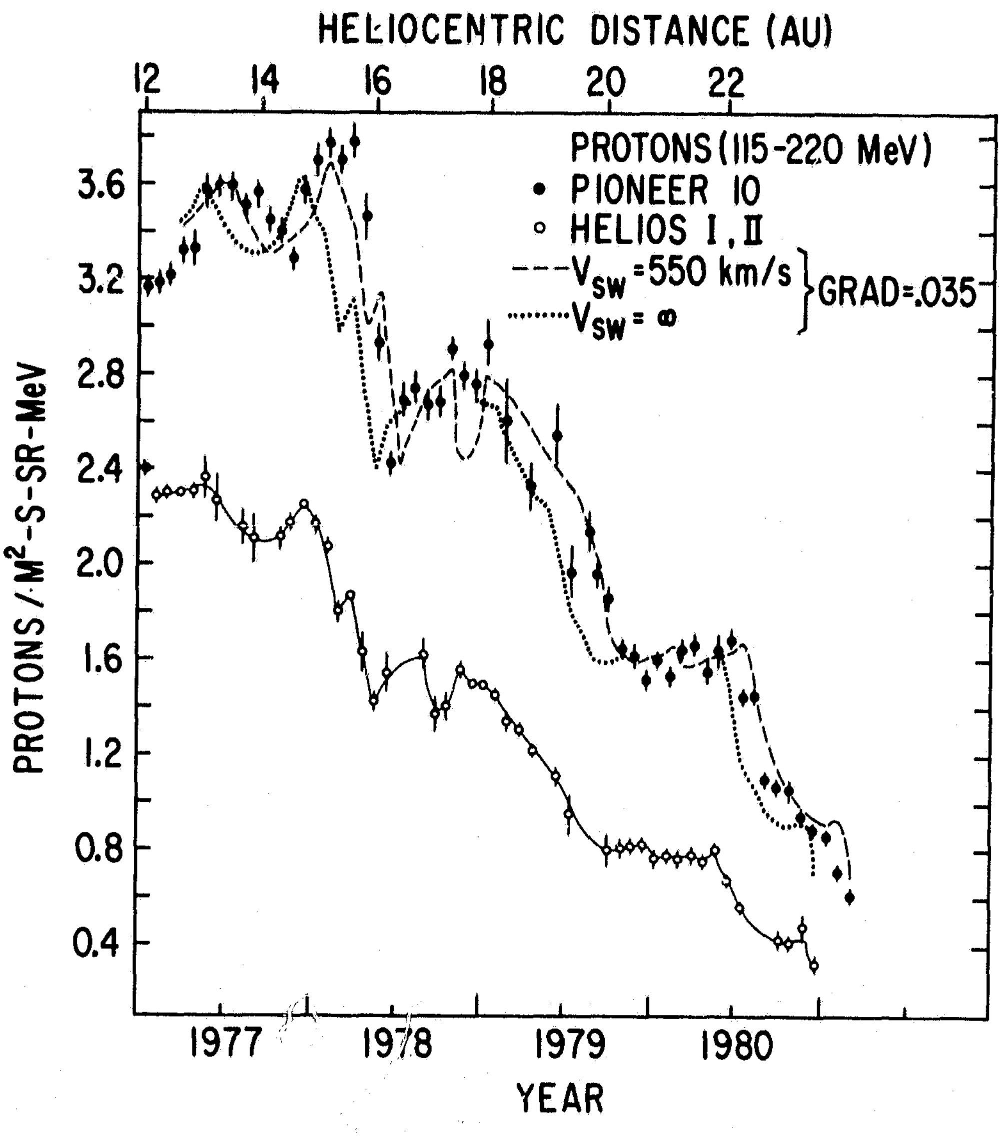

Figure 17: Observations showing that the 11-year variation propagates away from sun.

There remains the question of the nature of the disturbances which cause the long-term reductions in cosmic ray flux. McDonald et al. (1981a) suggested that shock waves are a basic cause of the modulation. The problem was investigated further by McDonald et al. (1982) and Burlaga et al. (1982, 1983b), who showed that the modulation was caused by systems of transient flows. For example, the step in the cosmic ray intensity profile at the beginning of 1978, which marked the beginning of the present 11-year cycle, was caused by a system of transients discussed above in regard to Figure 12. Specifically, their evidence suggests that the modulation is caused by diffusion in shells of turbulent magnetic fields made up of transient streams, magnetic clouds and shocks. We have come full circle back to the early ideas, but now our understanding is based on direct observations of the solar wind plasma and magnetic fields rather than inference and speculation.

Many questions and problems remain to be investigated. Systems of transients and systems of corotating flows are only two extreme states of the solar wind, and flow systems consisting of mixtures of transient and corotating flows frequently occur (these too were imagined by Morrison, 1956). The investigation of these systems, their effects on cosmic rays, and their relation to 11-year variations has only begun. Interplanetary dynamical processes can significantly modify the turbulent shells as they move away from the sun. For example, Burlaga et al. (1983a) showed how a single fast corotating stream apparently overtook and compressed a shell consisting of several transients into a very thin region (B in Figure 7), which caused an abrupt and permanent decrease in cosmic ray intensity in mid-1980 (see Figure 17 and Figure 7). The possibility that such interactions might occur had been suggested by Parker (1963), Newkirk (1975) and McDonald et al. (1981a). Similarily, interactions among transients have been discussed by Dorman (1963), Hakamada and Akasofu (1982), and Burlaga et al. (1983c). The nature of such interactions as a function of distance from sun, the corresponding magnetic field configurations, and their effects on cosmic rays are all problems which are being investigated and that one can expect to be solved with the spacecraft data which are available and which will be obtained in the years ahead.

6. Conclusion

Considerable progress is being made in understanding the variability of cosmic rays on all time scales and over a wide range of distances from the sun. Similarly, progress is being made in understanding the structure and dynamics of the interplanetary magnetic field and plasma. These two activities are developing synergistically, observations and theory in one field complementing those of the other. Observations being made from an extraordinary network of deep space probes have provided new information and a fresh perspective, but earth based measurements and spacecraft measurements near 1 AU continue to be invaluable for many types of investigations.

The ideas of corotating and transient flows, which have a long and interesting history, remain as key concepts. Our understanding of them continues to grow deeper, as is characteristic of most important ideas. Systems of such flows and interactions among these types flows are clearly important for understanding long-term cosmic ray variations. Their relation to solar activity is beginning to be explored using new kinds of solar and coronal data that have recently become available. Analysis of these and other problems, particularly using the data obtained from spacecraft, should provide many significant new insights in the near future.

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