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by

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Abstract

When Voyager 2 was near 11 AU, the counting rate of nuclei $\gtrsim$ 75 MeV/nucleon decreased during the interval from July, 1982 to November, 1982, and it increased thereafter until August, 1983. The counting rate fluctuated within this "minicycle" with short term decreases lasting 1 to 4 days and recoveries lasting several days. A decrease in cosmic ray flux was generally associated with the passage of an "interaction region" in which the magnetic field strength B was higher than that predicted by the spiral field model, B_p. Several large enhancements in B/B_p were associated with "merged interaction regions" which probably resulted from the interaction of two or more distinct flows. During the passage of interaction regions the cosmic ray intensity decreased at a rate proportional to $(B/B_p - 1)$, and during the passage of rarefaction regions (where $B/B_p < 1$) the cosmic ray intensity increased at a constant rate. The general form of the cosmic ray intensity profile during this $\sim$ 13 month "minicycle" can be described by integrating these relations using the observed B(t), and it can be understood in terms of the sizes and separations of interaction regions. Latitudinal variations of the interaction regions and of the short-term cosmic ray variations were identified by comparing Voyager 2 observations with Voyager 1 observations made at higher latitudes (14° to 20°). The interaction regions were turbulent, with an $f^{-5/3}$ spectrum from at least 3×10^{-4} Hz to f_c (1 to 2) $\times 10^{-6}$ Hz. A break in the spectrum at f_c corresponds to the characteristic width of the interaction regions, and it represents a "stirring scale" for the solar wind. The interaction regions, including merged interaction regions, may be viewed as "turbulent boundary layers" which grow in size with increasing distance from the sun. They act as barriers which impede the net flow of cosmic rays toward the sun.

1. Introduction

At 1 AU, temporal variations in cosmic ray intensity on a scale of the order of days are related to the passage of stationary "corotating streams" and non-stationary "transient flows" (see, e.g., the reviews, by Lockwood, 1971; Rao, 1972; Fisk, 1980, and Burlaga, 1983b). For both types of flows there is a strong correlation between the cosmic ray counting rate C and the strength of the interplanetary magnetic field B: C decreases when a region of enhanced B moves past a spacecraft (Barouch and Burlaga, 1975; Duggal et al., 1983). Regions of enhanced magnetic field were classified by Burlaga and King (1979) as corotating interaction regions (which occur ahead of corotating streams), post-shock flows (including both sheath flows and ejecta), and "cold magnetic field strength enhancements" (which include magnetic clouds). Collectively they are referred to as "interaction regions" (Burlaga and Ogilvie, 1970). The largest decreases in cosmic ray intensity, Forbush decreases, are usually associated with shocks and post-shock flows. Long-lasting Forbush decreases are sometimes observed at 1 AU (Lockwood, 1958, 1960, 1971) and these are related to the passage of a series of shock-associated transient flows (Barouch and Burlaga, 1975).

The 11-year variation in C tends to occur in a series of steps followed by plateaus of nearly constant cosmic ray intensity (Morrison, 1956; Lockwood, 1960; McDonald et al., 1981a; and Webber and Lockwood, 1981, McKibben et al., 1982; and Filius and Axford, 1985). McDonald et al. (1981a,b) showed that when solar activity is increasing the steps in C are observed near the sun first and farther from the sun later, indicating that the agent which produces the steps propagates away from the sun. Burlaga et al. (1984a) showed that near 1 AU the broad steps and plateaus are associated with two different kinds of flow systems. Plateaus in C are observed during the passage of systems of corotating streams and interaction regions, which are distinct, well-ordered flows. Broad steps in C are associated with the passage of a system of transient or mixed flows, which tend to be a complicated set of flows containing shocks together with irregular magnetic fields.

Interplanetary streams and interaction regions are known to evolve dramatically with distance. Isolated streams may "damp out" by momentum exchange with surrounding flows (Holzer, 1979), and they may be decelerated by reverse shocks (Hundhausen, 1973a,b; Gosling et al., 1976). Isolated interaction regions may grow in size and amplitude with increasing distance from the sun (Hundhausen, 1972; Whang 1980, 1984; Pizzo, 1981, 1983), and neighboring interaction regions may coalesce to form larger "merged interaction regions" as slow streams are entrained by faster streams (Burlaga et al., 1983, 1984a; Whang and Burlaga, 1985). These processes are discussed in greater detail in the review by Burlaga (1985). The net result is that, with increasing distance from the sun, interaction regions become a more dominant morphological and dynamical feature, while streams become less important. Transient and corotating streams and interaction regions can interact with one another to produce new kinds of flows and interaction regions in which memory of the source is lost (Burlaga et al., 1983). In this case the distinction between corotating flows and transient flows cannot be made and one must speak of merged interaction regions rather than cororating interaction regions, post-shock enhancements, ejecta, etc.

Since interplanetary flows and interaction regions can change qualitatively with increasing distance R from the sun, their relation to the cosmic ray intensity might also change. In this paper we investigate the relations between C, B and the flow speed V in the region between $\sim$ 10 AU and $\sim$ 15 AU, using data obtained by Voyagers 1 and 2 from June 1, 1982 to August 1, 1983. A strong correlation is found between changes in C and the magnetic field strength: The cosmic ray intensity decreases when an interaction region or merged interaction region moves past the spacecraft, and it increases when a rarefaction region moves by. Thus, the long-term variation in C depends on the field strength in the interaction regions and on the separation of interaction regions. This is discussed quantitatively in Sections 2 and 4. The nature of the interaction regions at these distances (10-15 AU) is discussed in Section 3.

2. Relation between Cosmic Ray Intensity and Magnetic Field Strength

In this section we shall discuss Voyager 2 observations made near the heliographic equatorial plane, between the latitudes of $-3.2°$ and $-1.6°$, from 10.1 AU to 12.2 AU. The intensity of cosmic rays > 75 MeV/nucleon, measured by the Cal Tech/University of New Hampshire/Goddard Space Flight Center experiment in the interval June 11, 1982, to August 1, 1983, is shown in Figures 1 and 2. The magnetic field strength B was measured by the GSFC magnetometer (N. Ness, Principal Investigator). The effect of the large scale gradient in magnetic field strength (Burlaga et al., 1984b) is removed by using the ratio B/B_p, where the value B_p is the spiral field strength (Parker, 1963) with a coefficient determined by Burlaga et al., (1984b) from a fit to the data to be $B_p = 4.75\ (1 + R^2)^{1/2}/R^2$. The ratio B/B_p is related to the variation δB about an average value B_p, by the equation $B/B_p = (B_p + \delta B)/B_p = 1 + \delta B/B_p$. Observations of B/B_p for the interval under consideration are shown in Figures 1 and 2. In the bottom panels of Figures 1 and 2 we show the bulk speed V of the solar wind plasma, measured by the experiment of Bridge et al. (1977). It has been observed that under some conditions V is related to C near 1 AU (see, e.g., the review by Burlaga, 1983b).

The magnetic field strength profiles $B/B_p(t)$ in Figures 1 and 2 show that the solar wind near 10 AU can be partitioned into two types of regions: interaction regions, where $B/B_p > 1$; and rarefaction regions, where $B/B_p < 1$. The average field strength $B/B_p = 1$ is observed only infrequently. Near 1 AU, such a clear division cannot always be made, and it is customary to distinguish between regions in which the speed is low and streams in which V is significantly higher than average for $\sim$ (2-6) days. However, at large distances from the sun, distinct streams cannot always be seen, owing to the erosion and damping isolated flows and to the interaction of neighboring streams. The absence of well-defined streams in the region and interval under consideration is evident from Figures 1 and 2. Thus, we shall consider the relation between the cosmic ray intensity and the interaction regions and rarefaction regions defined by B/B_p.

Comparing the counting rate of cosmic rays with the large-scale fluctuations in magnetic field strength given by B/B_p in Figures 1 and 2, one can see the following basic relations: 1) A decrease in counting rate over an interval of ~ 2 to 4 days is usually related to the passage of an interaction region. 2) An increase in counting rate over an interval of several days is related to the passage of a rarefaction region. 3) The magnitude of a decrease in counting rate tends to be greater for interaction regions with larger B/B_p. 4) The rate of increase in counting rate during the passage of an interaction region is approximately a constant, independent of the magnitude of B/B_p.

A merged-interaction region with exceptionally strong magnetic fields, labeled D in Figure 1, produced a major "step" in the cosmic ray intensity profile, near August 1, 1982. This was followed by a "plateau" in the cosmic ray intensity from August 1982 to mid-February, 1983. During this interval, 11 interaction regions (E through O in Figures 1 and 2) produced decreases in the cosmic ray intensity, and each interaction region was followed by a rarefaction region in which the cosmic ray intensity increased at a fixed rate. The interaction regions were closely spaced, i.e., the duration of the rarefaction regions was relatively short, so there was relatively little time available for recovery of the cosmic ray intensity in this interval. The net effect of the interaction regions balanced that of the rarefaction regions, resulting in a "plateau" in cosmic ray intensity, with fluctuations related to the magnitude of B in the interaction regions. In the interval from February, 1983 to June, 1983, the cosmic ray intensity increased, because the interaction regions were widely spaced, allowing significant time for recovery of the cosmic ray intensity. In other words, the effect of the rarefaction regions outweighed the effect of the interaction regions, resulting in a net increase in the cosmic ray intensity in this interval.

It was noted in our discussion of Figures 1 and 2 that the decrease in cosmic ray intensity is generally larger for interaction regions with stronger B/B_p. Let us denote the difference between the maximum counting rate at the beginning of a cosmic ray intensity decrease and the minimum counting rate at the end of a cosmic ray decrease by ΔC. This value of ΔC

was determined for each of the significant decreases in cosmic ray intensity in Figures 1 and 2, and the maximum value of B/B_p in the corresponding interaction region was also determined in each case. A plot of ΔC versus $(B/B_p)_{max}$ is given in Figure 3, which shows that there is indeed a tendency for ΔC to be larger for interaction regions with stronger fields, but there is significant scatter of the observations about the straight line. The scatter suggests that cosmic ray modulation is not produced directly by $(B/B_p)_{max}$, and it indicates that a linear relation between ΔC and B/B_p is at best a first approximation to a more accurate model. Nevertheless, Figure 3 shows that the decrease in cosmic ray intensity does depend on strength of the magnetic fields in the interaction regions, if only indirectly.

The rate at which the cosmic ray intensity increases during the passage of rarefaction regions appears to be approximately a constant, independent of the nature and "strength" of the preceding interaction regions. The extent to which this is true can be seen in Figures 1 and 2 by comparing the straight line segments drawn through the cosmic ray measurements (all of which have the same slope) with the observations. The recovery rate for these particles > 75 MeV/nucleon is R = 0.003 (counts/sec)/day. Thus, for the recovery we can write $dC/dt = R$.

It is significant that the cosmic ray intensity in Figures 1 and 2 is generally either increasing or decreasing, seldom remaining constant for more than a few days. Similarly, B/B_p is generally either > 1 or < 1, seldom remaining ~ 1 for more than a few days. The counting rate versus time, C(t), appears to be the net result of decreases produced by interaction regions and increases occurring during the passage of rarefaction regions. The relations between changes in counting rate and the magnetic field strength can be expressed by the equations:

1) $$\frac{dC}{dt} = -D\ (B/B_p - 1) \qquad \text{when } B/B_p > 1$$

$$2) \quad \frac{dC}{dt} = R \qquad \text{when } B/B_p \leq 1,$$

where D and R are constants. Equations 1 and 2 express the results derived above: 1) the cosmic ray intensity decreases when an interaction region moves by, and the size of the decrease depends on the strength of the magnetic field; 2) the cosmic ray intensity increases at a constant rate during the passage of an rarefaction region.

Given $B/B_p(t)$ and some initial value of C, it is possible to integrate equations 1 and 2 to obtain a cosmic ray intensity profile C(t). The result of this integration, obtained using C(t = 0) = 0.47 counts/sec, D = 0.004 (counts/sec/day) and the magnetic field data from Figures 1 and 2, is shown in the lower panel of Figure 4. The corresponding observations for the interval August 11, 1982 to July 1, 1983, from Figures 1 and 2, are shown in the upper panel of Figure 4. In general, there is good agreement between the results of the model and the observation. There are some differences in detail, the most significant being the size of the decreases in December, 1982 and January, 1983, which suggest that events associated with high speed streams could be modeled more accurately. The important result, however is that variations with a scale of six months to one year, can be modeled as the result of the effects of a series of events with time scales of the order of days. The modulation near 11 AU is the result of a delicate balance between decreases in intensity caused by interaction regions and increases in intensity associated with rarefaction regions.

3. Merged Interaction Regions

It was shown above that decreases in cosmic ray intensity near 11 AU are related to the passage of interaction regions. The largest decreases were related to the passage of merged interaction regions, and it is of interest to examine some merged interaction regions in more detail in order to better understand their structure, to see how they can vary with latitude, and to look for characteristics that might be responsible for the scattering of cosmic rays. Since we cannot discuss all of the interaction regions in Figures 1 and 2, three were selected which are representative of large merged interaction regions.

Merged corotating interaction region.

Event V is shown in Figure 5, where δ and λ are respectively the elevation and azimuth angles of the magnetic field in heliographic coordinates (see Burlaga, 1985), N/N_o is the density relative to N_o (cm^{-3}) = 6 x $[R(AU)]^{-2}$ corresponding to a density of N_o = 6 particles/cm^3 at 1 AU, T_p is the proton temperature, and V is the bulk speed. The vertical lines show two forward shocks (F_1 and F_2) and one reverse shock (R). Shock F_1 occurred in a data gap, and its existence is inferred on the basis of the observation of an increase in B, N, T_p and V across the gap, which is consistent with the passage of a forward fast shock. This existence of this shock as well as F_2 and R is supported by the observation of "spikes" in the intensity of 0.5 - 1.4 MeV protons at the indicated times which are typical of shock-accelerated particles (Gold and Krimigis, private communication). The spectra of these spikes are flat, which is taken as an indication that the shocks are probably corotating. Thus, it is likely that this merged interaction region was produced by the interaction of two corotating streams.

Note that three well-defined, magnetic sectors are seen in the merged interaction region in Figure 5. In an ordinary interaction region, no more than two sector polarities are observed. The negative sector from June 15 to June 20, 1983, in which the magnetic direction is sunward, is probably in the remnant of a corotating stream that produced F_2, and R. The boundary of this sector on June 15 is associated with a drop in N and an increase in T_p, which might represent the remnant of a stream interface marking the front of the stream. The earlier positive sector from June 11 to June 15 is probably in the remnant of a corotating stream that produced F_1 and the boundary of this sector on June 11 might represent the front of the stream. Shock F_1 has propagated into the negative polarity sector preceding this stream, from June 6 to June 11. It is significant that the interaction has not destroyed or even significantly disturbed the sector pattern.

The effect of this merged interaction on the cosmic ray intensity is shown at the top of Figure 5 and in Figure 2. There was possibly a small decrease in cosmic ray intensity following the arrival of the shock F_1 and the corotating interaction region of the first stream. A moderate decrease in cosmic ray intensity followed shock F_2, corresponding to the passage of doubly shocked plasma where the interaction region of the second corotating stream overlapped with that of the first stream. The moderate size of the net decrease in counting rate is related to the moderate increase in magnetic field strength in this merged interaction region ($(B/B_p)_{max} \approx 3$) in agreement with Figure 3. The time profile of cosmic ray intensity shown in Figure 3, which was observed near 11 AU, is analogous to that of a "corotating Forbush decrease" seen at 12 AU (Burlaga, 1983), the difference being that the 2-step decrease observed at 11 AU is due to a "merged corotating interaction region" while at 1 AU the decrease is usually associated with an isolated interaction region.

Transient stream overtaking a corotating interaction region.

Event O in Figure 6 shows a very large, fast compound stream. Fast streams are rare at distances $\gtrsim$ 10 AU, and they are likely to be in part the result of a violent transient disturbance on the sun. The complex variations in the magnetic field direction shown in this Figure also indicate a complex interaction of flows which include one or more large transient streams. (It is difficult to sort out the separate flows and interactions in this case with only data from Voyager 2. One needs data from other spacecraft at smaller distances and an MHD model of streams in order to interpret the profiles in Figure 6.)

The narrow region with very strong fields on January 16 and 17, 1983, is a result of the interaction of a fast forward shock F_2 with a fast reverse shock R. (Shock F_2 was observed on hour 6 onJanuary 16, and R occurred in a data gap between hours 2 and 14 on January 17.) The likelihood of such interactions in the outer heliosphere has been discussed on theoretical grounds by several authors, and evidence for such an interaction involving corotating shocks has been published (see Burlaga, 1985). This case is notable because the shock F_2 is probably a transient and because of the proximity of F_2 and R.

The effect of the complex interaction region in Figure 6 on the cosmic ray intensity is shown at the top of Figure 6 and in Figure 2. The counting rate dropped abruptly by a relatively large amount when the strong fields associated with the doubly shocked plasma between F_2 and R moved past the spacecraft on January 16, and it remained low where the speed was high. The recovery occurred in the interval where the speed and magnetic field strength were decreasing. Note that the recovery rate is comparable to that following the other interaction regions in Figures 1 and 2. There is no indication that the recovery time following a transient interaction region is unusually long at this distance, in contrast to the suggestion of Van Allen (1979).

Magnetic cloud overtaking a corotating interaction region.

A notable feature of event D, shown in Figure 7, is the magnetic cloud on August 4-8, 1982, which is identified on the basis of the south to north variation of the magnetic field direction, the relatively high magnetic field strength, the low density and the low temperature (see Burlaga, 1985 and Burlaga and Behannon (1982) for references to earlier observations of magnetic clouds). The high field strengths in the cloud are presumed to be partly the result of injection of magnetic flux at the sun. It is notable that a magnetic cloud evidently can remain stable out to $\sim$ 11 AU (assuming that it originated at the sun), after a propagation time of approximately a month. Burlaga et al. (1981) and Burlaga and Behannon (1982) suggested that the front and rear of a magnetic cloud expand into the ambient median at a rate of $\sim V_A/2$ where V_A is the ambient Alfvén speed. Assuming $V_A/V \sim 0.1$, $V \sim 500$ km/s and a transit time past a spacecraft of 1 AU of $\sim$ 1 day, one expects the transit time past a spacecraft at $\sim$ 11 AU to be $\sim$ 4 days, in good agreement with the observed duration of the magnetic cloud in Figure 7. This is additional evidence for the expansion of magnetic clouds.

A transient shock (T) probably passed the spacecraft during a data gap on August 1. Its presence is inferred from the increase in B, N, T and V seen in Figure 7, and from the observation of a "spike" observed in the intensity of 0.5 - 1.4 MeV protons (Gold and Krimigis, private communication) which is generally indicative of shock-accelerated particles. The shock is identified as a transient shock (as distinct from a corotating shock) on the basis of the spectrum of the energetic particles. We tentatively associate this shock with the magnetic cloud, i.e., we assume that near the sun it was driven by the magnetic cloud, but it was probably detached from the magnetic cloud when observed by Voyager 2.

A stream-stream interface (I) (Burlaga, 1974), which is indicative of a corotating interaction region (Burlaga, 1985), was observed by Voyager 2 near the end of August 2, as indicated by the maximum in B, the drop in N, the increase in T and the increase in V. A forward shock (F) on July 31 and a reverse shock R on July 8, which were identified by the changes in B, N, T and V and by peaks in the (1-10 MeV) particles, probably represent the corotating forward and reverse shocks associated with the corotating interaction region that is marked by the interface. If this is so, then shock T must have passed the stream interface and moved nearly through the corotating interaction region, which would explain why the magnetic field strength at the interface I is significantly higher than one expects for an isolated corotating interaction region (Burlaga and King, 1979), because the shock would have compressed the field by a factor of 2 or so. The reverse shock must have passed through the magnetic cloud, compressing the magnetic fields in it, which would explain for the relatively high field strength in the magnetic cloud at this large distance from the sun. Thus the unusually large strength of the magnetic field and the duration of the strong field region in event D, as well as the variations in N, T, V, δ and λ, can be understood as the result of the interaction of a magnetic cloud with a corotating stream and interaction region.

The shocks F and T did not produce a large decrease in cosmic ray intensity (see the top panel of Figure 7 and in Figure 1), but the cosmic ray intensity did decrease significantly during the passage of the "shocked interaction region" following the interface I. The intensity did not decrease further when the magnetic cloud moved by, even though the field strength was relatively high in the cloud. This suggests that the modulation is related to small-scale turbulent fluctuations in the magnetic field, which are large in "merged interaction regions" but small in magnetic clouds, rather than to the magnetic field strength or large-scale gradients in B. Thus, there are exceptions to Equation 1, and it would be desirable in future studies to replace this approximate relation by one which relates $\frac{dC}{dt}$ directly to the fluctuations in $\underset{\sim}{B}$.

The recovery in cosmic ray intensity following the passage of the merged interaction is of intereat in regard to the issue of whether or not the recovery time of a Forbush decrease at large distances is unusually long (Van Allen, 1979). Note that the recovery rate during the passage of the rarefaction region which followed the merged interaction region was essentially the same as that given by Equation 2, which would not give an unusually long recovery time. On the other hand, the cosmic ray intensity did not recover to the value preceding the merged interaction region until seven months later. In our view, the long interval with low cosmic ray intensity is due to the passage of many interaction regions in close succession, rather than a result of the slow recovery of a Forbush decrease following a shock. The cosmic ray intensity profile from July, 1982 to April, 1983 is more nearly related to that of a "long-lasting Forbush decrease" at 1 AU (Barouch and Burlaga, 1975) than to a single "Forbush decrease" at 1 AU.

4. Latitude Variations of the Magnetic Field and Cosmic Ray Modulation

The observations discussed above were made by Voyager 2 at latitudes between -3.2° and -1.6° as the spacecraft moved from 10.1 AU to 12.2 AU. At the same time, observations of magnetic fields and energetic particles were being made by Voyager 1 at higher latitudes, from 13.9° on July 1, 1982, and 19.8° on July 1, 1983, as the spacecraft moved from 13.5 AU to 16.7 AU, respectively. There are no plasma measurements from Voyager 1. These date enable us to answer the following questions: Was the magnetic field profile the same at those high latitudes as it was near the ecliptic? Was the relation between cosmic ray intensity and magnetic field strength the same at Voyager 1 as it was at Voyager 2?

Observations of the magnetic field strength measured by Voyager 1 from July 1, 1982 to July 1, 1983, are shown in Figures 8 and 9. The magnetic field strength measured by Voyager 2 is shown again, at the bottom of Figures 8 and 9 so that it can be compared directly with the Voyager 1 data. Note that the time axis for the Voyager 2 data has been slipped in time to partly compensate for the transit time delay of material moving from Voyager 2 to Voyager 1. Since the latitudinal structure of the solar wind is not known, one cannot compute a meaningful "corotation delay". The shifts used in Figures 8 and 9 (different in each case) were determined subjectively to give the best alignment between the magnetic field profiles from the two spacecraft.

In the interval from July 1 to December 1, 1982, (Figure 8) there was a poor correlation between the magnetic field strength profiles observed by Voyagers 1 and 2. The differences cannot be eliminated by changing the delay time or even by using a variable delay, and such large differences are not likely to be the result of radial evolution of the flows. Thus, there were probably large latitudinal gradients in magnetic field structures with a scale of the order of 1-2 AU, during this particular interval.

In the interval from December 1, 1982 to August 1, 1983, (Figure 9) when Voyagers 1 and 2 were farther apart in both latitude and radius, the correlation between the magnetic field strength profiles was better than in Figure 8. There are significant differences in the size and shape of the strong-field regions, indicating latitudinal gradient in B. Nevertheless several of the major interaction regions can be seen at both latitudes, the difference in latitude being 17° to 18° in the interval considered.

A better understanding of the latitudinal structure of interactions can be derived by considering solar observations, more detailed data from Voyagers 1 and 2, data from other spacecraft, and MHD models, but we shall not digress to discuss this topic. For our purpose, the important point is that Voyagers 1 and 2 observed different magnetic field profiles. We may ask whether the cosmic ray profiles differed correspondingly and whether the model derived from Voyager 2 data (Equations 1 and 2) is applicable to the Voyager 1 data.

The energetic particle observations (> 75 MeV/nucleon) from Voyager 1 for the interval August 1, 1982 to August 1, 1983, are shown at the top of Figures 8 and 9. In general, the long-term intensity versus time relation is very similar to that observed by Voyager 2 (compare with Figures 1 and 2). There was a large, abrupt decrease in August, 1982 and the intensity remained low for the most part through November, 1982; there were two large decreases in January and February, 1983; and there was a recovery from February to August, 1983. Figures 8 and 9 show that the large decreases in cosmic ray intensity are related to the passage of interaction regions, and Figure 3 shows that the size of each decrease ΔC is roughly proportional to the maximum magnetic field strength in the corresponding interaction region, as observed by Voyager 2. The counting rate at Voyager 1 increased at a constant rate during the passage of rarefaction regions, again in agreement with the Voyager 2 results. In general, the cosmic ray variations and the relation between cosmic ray intensity and magnetic field strength were similar at Voyagers 1 and 2, despite the separation in latitude.

The short-term variations in cosmic ray intensity (of the order of several days) were significantly different at Voyagers 1 and 2, especially from August to December 1982. This is associated with the corresponding differences in magnetic field strength profiles at different latitudes, as discussed earlier. It is of interest to determine whether the Voyager 1 cosmic ray counting rate can be derived from the corresponding magnetic field strength profiles using Equations 1 and 2, which were derived from Voyager 2 data. Using $G(t = 0) = 0.47$ counts/sec, $R = 0.003$ counts/sec/day and $D = 0.005$ (counts/sec/day, the equations were integrated to give the result at the bottom of Figure 10. This model curve agrees well with the observations reproduced in the top of Figure 10, except for some details. Thus, again the long term variations in cosmic ray intensity, with a time scale of several months, can be reproduced as the result of a balances between decreases due to interaction regions and increases related to the passage of rarefaction regions. The cosmic ray intensity remained low when there were large closely spaced interaction regions and it increased when there were smaller more widely spaced interaction regions.

5. Magnetic Field Spectra and Turbulence

The modulation process described above considers that changes in cosmic ray intensity are related to specific features in the interplanetary magnetic field. On the other hand, Voyager 1 and 2 observations in the interval July to December, 1982 show that essentially the same long-term ($\sim$ 6 months) changes in cosmic ray intensity can be produced by distinctly different magnetic field configurations, suggesting that there are some general features of flow systems that are important, as discussed by Burlaga et al. (1984a) and Burlaga and Goldstein (1984). Goldstein et al. (1984) have identified some differences in the magnetic field spectra of corotating and transient systems observed $\lesssim$ 5 AU, and they suggested that transient and mixed systems are turbulent and that this turbulence is related to the cosmic ray modulation. We must now ask how this view, which is basically statistical, can be reconciled with the deterministic results discussed above.

Let us compare spectra of the magnetic fields observed by Voyagers 1 and 2 for an interval containing many transient flows with the spectra for an interval containing mostly corotating flows. We consider power spectral density of fluctuations in the components of B (trace of the power spectral matrix), the magnitude of B, and the magnetic helicity times frequency. The spectra were computed from one hour average data using the Blackman-Tukey method with 20 degrees of freedom, without detrending or filtering the data. Details of this approach are given in Matthaeus and Goldstein (1982). Figure 11 shows spectra computed from Voyager 2 data for the intervals June 1 to November 1, 1982 (transient flows) and March 1 to August 1, 1983 (corotating flows). Figure 12 shows spectra computed from Voyager 1 data for the corresponding intervals July 1 to November 11, 1982 and March 11 to August 1, 1983, respectively.

The spectra of fluctuations in the components of B are given by the upper curves of Figures 11 and 12, and the spectra of fluctuations in the magnitude of B are given by the lower curves. Positive values of magnetic helicity are denoted as circles, negative values as triangles. The plot shows $fH_m(f)$ where $H_m(f)$ is the reduced magnetic helicity spectrum as defined by Goldstein et al. (1982). Assuming that plasma is convected past the spacecraft at the mean solar wind speed in the interval, $\bar{V}$, the frequency f_c corresponding to the correlation length L, is $f_c = \bar{V}/L$, and this is shown by the arrows in Figures 11 and 12. The basic result is that in all of the intervals the spectra have the form $f^{-5/3}$ over two decades of frequency for $f > f_c$. The coefficient -5/3 implies that both corotating and transient flows are representative of fully developed turbulence (see the review by Montgomery, 1983).

The $f^{-5/3}$ spectrum begins near f_c, which is $\sim$ (1 to 2) x 10^{-6} Hz, or $f_c^{-1} \sim$ (5 to 10) days. This is approximately equal to the widths of the interaction regions, consistent with the idea (Goldstein et al., 1984; Burlaga and Goldstein, 1984); that the interaction regions are a source of turbulence and that the width of an interaction region represents a "stirring scale." An interaction region can be viewed as a "turbulent boundary layer" whose width increases with distance from the sun.

The shocks that bound an interaction region are one possible source of turbulence, and one expects f_c to decrease as the shocks move apart. At a distance $\gtrsim$ 25 AU, where all of the wind has been shocked at least once, (Burlaga, 1983a), one expects the wind to be turbulent everywhere, at all frequencies $\gtrsim$ (26 days)$^{-1}$. At 11 AU, however, the turbulence should be "patchy" in this view, being confined to the interaction regions but not to the rarefaction regions.

The nature of fluctuations in compression and rarefaction regions at different distances from the sun is a topic in itself. Here we shall discuss one interaction region observed by Voyager 2 (June 13, hour 0427 to June 14, hour 0821, 1983 and the rarefaction region following it (June 17, hour 0401 to 1553, 1983), which serve to illustrate the basic characteristics of corotating interaction regions and rarefaction regions near 11 AU. The magnetic field spectra, computed as described above using 96 sec averages, are shown in Figures 13a and 13b, respectively. The power levels in the interaction region are more than an order of magnitude larger than those in the rarefaction region. Thus, spectra for an interval containing both the interaction region and the rarefaction region would be dominated by power from the interaction region, as asserted above. A $f^{-5/3}$ spectrum is observed above 3×10^{-4} Hz in fluctuations of both the components and magnitude of B in the interaction region, whereas a f^{-1} spectrum is observed above $\sim 5.3 \times 10^{-4}$ Hz in the rarefaction region. Thus, the interaction region is turbulent, but the rarefaction region is not. Assuming that these results are general for observations near 10 AU, the spectra at $f \gtrsim 1\text{-}2 \times 10^{-6}$ Hz in Figures 11 and 12 should be understood as spectra of turbulence in interaction regions near 10 AU.

The spectral results are consistent with the model presented above. Decreases in cosmic ray intensity are related to the passage of interaction regions, and the spectra show that these interaction regions are turbulent, in the sense that they have a Kolmogoroff spectrum. Thus, the decreases in cosmic ray intensity are related to large local "patches" of turbulence in the interplanetary magnetic field. We have not determined whether fluctuations in the direction of the field, the magnitude of the field or both, are responsible for the scattering. The recovery in intensity near 10 AU occurs during the passage of rarefaction regions when the level of fluctuations is low and the spectra of the magnetic field fluctuations are not representative of fully developed turbulence.

6. Summary

It was shown that the modulation of $\gtrsim$ 75 MeV/nucleon particles between 10.1 AU and 16.7 AU, from June 1, 1982 to August 1, 1983, was related to the passage of interaction regions and rarefaction regions. When a turbulent interaction region moved past the spacecraft, the cosmic ray intensity decreased by an amount proportional to the strength of the magnetic field in the interaction region, and when a rarefaction region moved past the spacecraft the cosmic ray intensity increased at a constant rate. The cosmic ray intensity versus time over this one-year time interval was the result of a balance between these competing effects operating on a scale of the order of several days.

Three examples of merged interaction regions (MIR's) were described. Although a definitive analysis requires observations closer to the sun and MHD modeling, plausible models for nature of these interaction regions could be derived from the Voyager observations. One of the MIR's was probably the result of a fast corotating stream overtaking a slower corotating stream, and it produced a decrease in the cosmic ray intensity which is the analog of a "corotating Forbush decrease" at 1 AU. Two corotating forward fast shocks followed by one corotating reverse shock were observed, and strong magnetic fields were produced as the shock from the second stream moved into the interaction region of the preceding flow. Three sectors were identified in the merged interacton region, indicating that interactions among corotating streams do not necessarily disrupt the sector structure near 10 AU. A second MIR was probably the result of a fast transient stream overtaking a corotating interaction region. Strong magnetic fields were produced as the transient shock moved through the corotating reverse shock and into the corotating interaction, i.e., the field between these two shocks was probably compressed first by stream steepening, then by the corotating reverse fast shock, and again by the transient transient fast forward shock. The merged interaction region was more effective in modulating cosmic rays than the isolated corotating shock. The magnetic field direction in this case was highly variable, and a clear sector structure was not observed. A third MIR was probably the result of a magnetic cloud overtaking a corotating interaction region which was bounded in front by a corotating fast forward shock. Again a transient fast forward shock, presumably originally driven by the magnetic cloud, propagated into the corotating interaction, producing very strong magnetic fields. The corotating reverse shock was observed behind the magnetic cloud, suggesting that it propagated through the cloud and compressed the normally strong magnetic fields of a magnetic cloud. The observation of a magnetic cloud near 11 AU is itself interesting, for it provides further evidence for the stability of magnetic clouds and for radial expansion of magnetic clouds at a rate of the order of the Alfvén speed. The double shocked magnetic fields were more effective in modulating cosmic rays than either the corotating shock or the magnetic cloud.

Interaction regions and merged interaction regions appear to be a local source of turbulence in the outer heliosphere, and the width of an interaction region is related to the correlation length, which gives the lower limit of the inertial range of the turbulence. As the interaction regions expand in size with increasing distance from the sun, the lower limit of the $f^{-5/3}$ dependence of the spectral energy density decreases. This turbulence is probably the cause of the decreases in the cosmic ray intensity near 10 AU, although the specific scattering mechanism was not identified in this study.

The long-term modulation is related to the strength of the magnetic field in the interaction regions (which is presumably related to the level of turbulence) and to the separation of interaction regions. When systems of corotating interaction regions are present, the separation between interaction regions is relatively large, and recovery of cosmic ray intensity is the dominant effect. When transients are present, the separation between interaction regions is smaller and the amplitude is larger, so the cosmic ray intensity tends to decrease or remain low.

Significant differences in the magnetic field strength profiles were observed by spacecraft separated in latitude by $\sim 17°$ in one 5-month interval, but not in a neighboring 6-month interval. Corotating interaction regions were more prominent in the latter interval, and they presumably related to streams and coronal holes extending from the ecliptic to higher latitudes. Despite latitudinal differences in the magnetic field strength profiles in the first interval, the cosmic ray intensity profile was qualitatively the same at the two latitudes on a time scale of the order of months. Thus the long-term modulation appears to be related to the statistical pattern of occurrence and strength of the interaction regions, or to the "intermittency" of the turbulence (Batchelor, 1970). Corotating systems with order on a large scale and with relatively large rarefaction regions near 10 AU, allow a recovery of cosmic ray intensity. On the other hand, when the sun is more active over a suitable range of latitudes and produces transient flows of smaller size in addition to evolving corotating flows, the interaction regions are more closely spaced and less regular. Even when individual flows do not extend over a wide range of latitudes, the general nature of the flows may be the same over a wide range of latitudes. These transient or mixed flow systems are associated with a relatively low level of cosmic ray intensity.

Acknowledgments. The magnetic field data and plasma data presented in this paper are from the Voyager magnetometer and the Voyager plasma science instrument. We thank the Principal Investigators, N. F. Ness, H. S. Bridge, and their Co-Investigators for providing us the data. L. Klein helped with the programming involved in this study.

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Figure Captions

Figure 1 — Voyager 2 observations of the counting rate of nuclei > 75 MeV/nucleon (top), magnetic field strength B relative to the spiral field strength B_p (middle), and bulk speed (bottom) from June 1, 1982, to December 1, 1982.

Figure 2 — Same as Figure 1, for December 1, 1982 to August 1, 1983.

Figure 3 — Decrease in couting rate ΔC corresponding to the passage of an interaction region with maximum field strength B/B_p.

Figure 4 — Voyager 2 observations of the counting rate of nuclei > 75 MeV/nucleon (top) reproduced from Figures 1 and 2, and counting rate derived from Equations 1 and 2 using the magnetic field strength given in Figures 1 and 2 (bottom).

Figure 5 — A merged interaction which is probably the result of an interaction region produced by a fast corotating stream overtaking and merging with an interaction region produced by a slower corotating stream.

Figure 6 — A merged interaction region which is possibly the result of a transient flow overtaking a corotating interaction region. Note the doubly shocked plasma between F_2 and R, and the radial magnetic field in the low density "wake" W of the transient stream.

Figure 7 — A merged interaction region which is probably the result of a magnetic cloud interacting with a corotating interaction region.

Figure 8   Voyager 1 observations of the counting rate of nuclei $>$ 75 MeV/nucleon (top) and normalized magnetic field strength (middle), together with Voyager 2 observations of the normalized magnetic field strength (bottom) shifted in time to compensate for the propagation time between the two spacecraft. The large difference between the Voyager 1 and 2 magnetic field strength profiles is the result of the latitudinal separation of the spacecraft. Evidently, large latitudinal gradients in magnetic field can exist.

Figure 9   Same as Figure 8, for the period December 1, 1982 to August 1, 1983. The large merged corotating interaction regions and those associated with two very fast transient streams extend over a wide range of latitudes in this case.

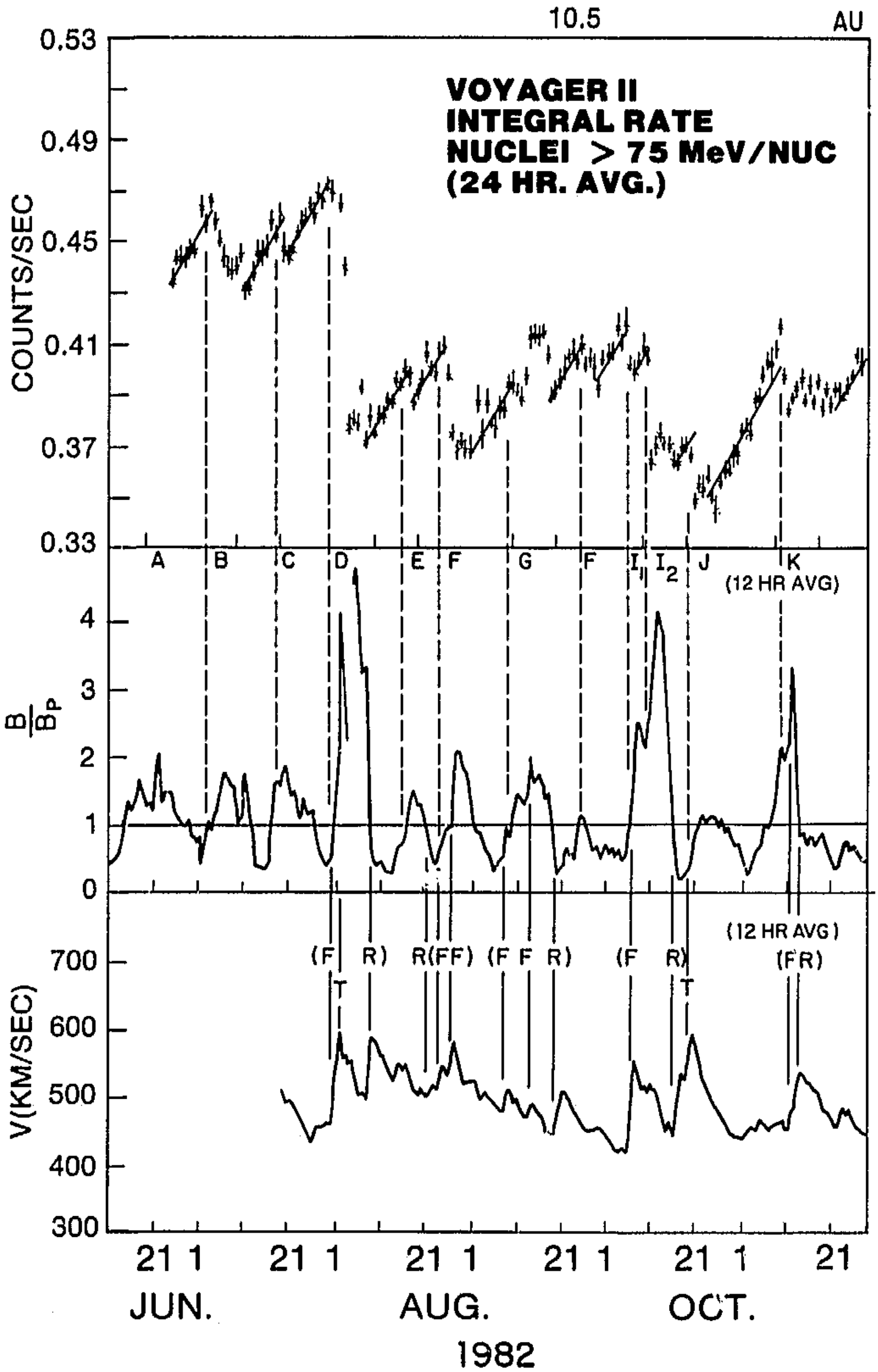
Figure 10   Voyager 1 observations of the counting rate of nuclei $>$ 75 MeV/nucleon (top) and the counting rate derived from Equations 1 and 2 using the magnetic field strength given in Figures 8 and 9.

Figure 11   Spectra of fluctuations in the magnetic field direction (upper curve in each panel), magnetic field strength (lower curve in each panel), and magnetic helicity (circles and triangles) derived from Voyager 2 data for the "mixed flow system" from June 1 to November 1, 1982 (left) and for the corotating flow system from March 1 to August 1, 1983.

Figure 12   Same as Figure 11 for the Voyager 1 data for the intervals July 1 to November 11, 1982 (left) and March 11 to August 1, 1983.

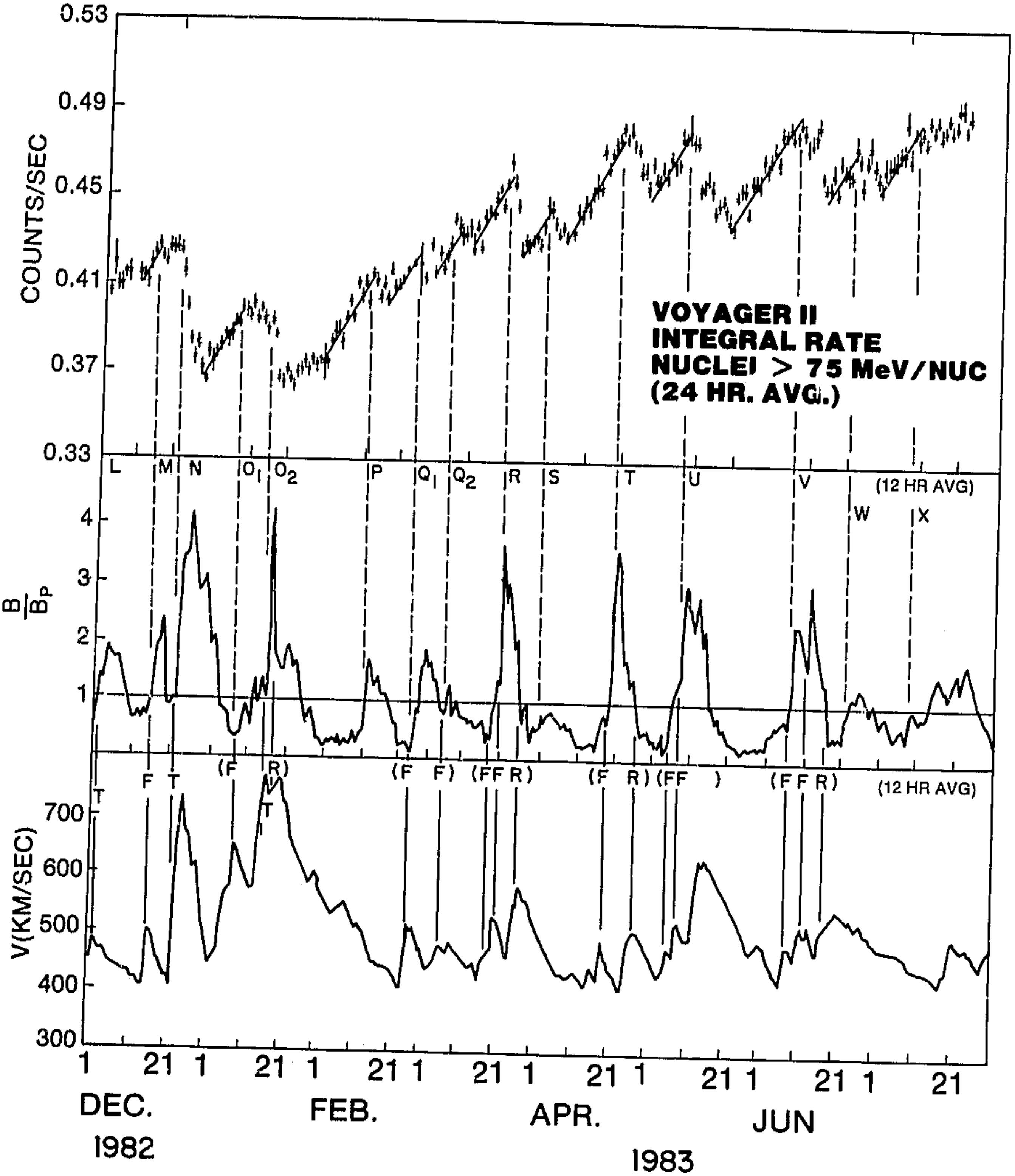
Figure 13 a. (left panel) Spectra (see Figure 11) for the merged interaction region from June 13, hour 0427, to June 14, hour 0821, 1983.

b. (right panel) Spectra for the rarefaction region from June 17, hour 0401, to June 17, hour 1553, 1983.



10.5
AU
VOYAGER II
INTEGRAL RATE
NUCLEI > 75 MeV/NUC
(24 HR. AVG.)
COUNTS/SEC
0.53
0.49
0.45
0.41
0.37
0.33
A
B
C
D
E
F
G
F
I1
I2
J
K
(12 HR AVG)
B/BP
4
3
2
1
0
(F
T
R)
R(FF)
(F
F
R)
(F
R)
T
(12 HR AVG)
(FR)
V(KM/SEC)
700
600
500
400
300
21
1
21
1
21
1
21
1
21
1
21
JUN.
AUG.
OCT.
1982

Figure 1



VOYAGER II
INTEGRAL RATE
NUCLEI > 75 MeV/NUC
(24 HR. AVG.)
COUNTS/SEC
0.53
0.49
0.45
0.41
0.37
0.33
L M N O1 O2 P Q1 Q2 R S T U V W X
(12 HR AVG)
B/Bp
4
3
2
1
(F R) (F F) (FF R) (F R) (FF) (F F R)
F T T T
(12 HR AVG)
V(KM/SEC)
700
600
500
400
300
1 21 1 21 1 21 1 21 1 21 1 21 1 21 1 21
DEC.
1982
FEB.
APR.
1983
JUN

Figure 2

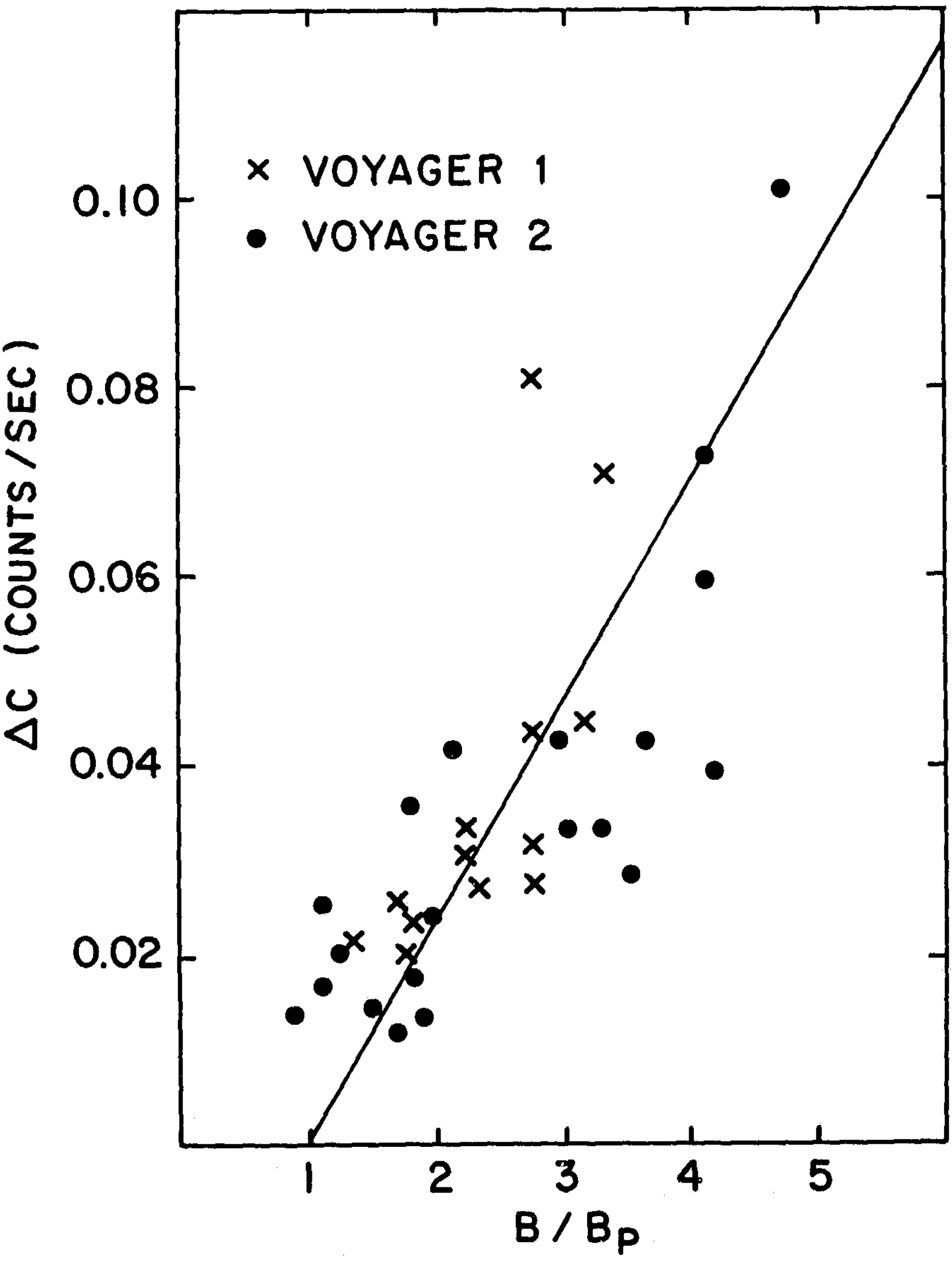
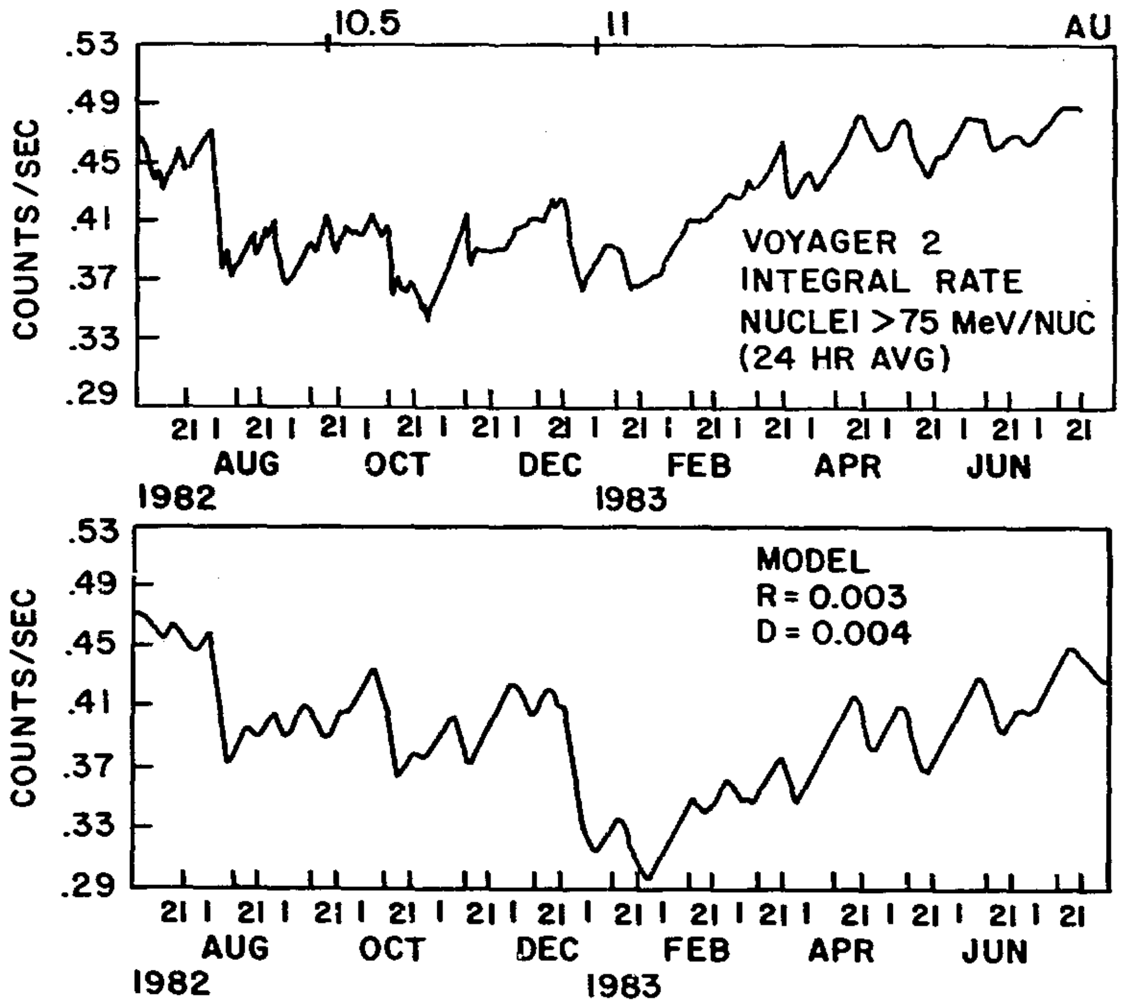

× VOYAGER 1
● VOYAGER 2
0.10
0.08
0.06
0.04
0.02
ΔC (COUNTS/SEC)
1
2
3
4
5
B / B_P

Figure 3



10.5
11
AU
.53
.49
.45
.41
.37
.33
.29
COUNTS/SEC
VOYAGER 2
INTEGRAL RATE
NUCLEI >75 MeV/NUC
(24 HR AVG)
AUG
OCT
DEC
FEB
APR
JUN
1982
1983
MODEL
R = 0.003
D = 0.004

Figure 4

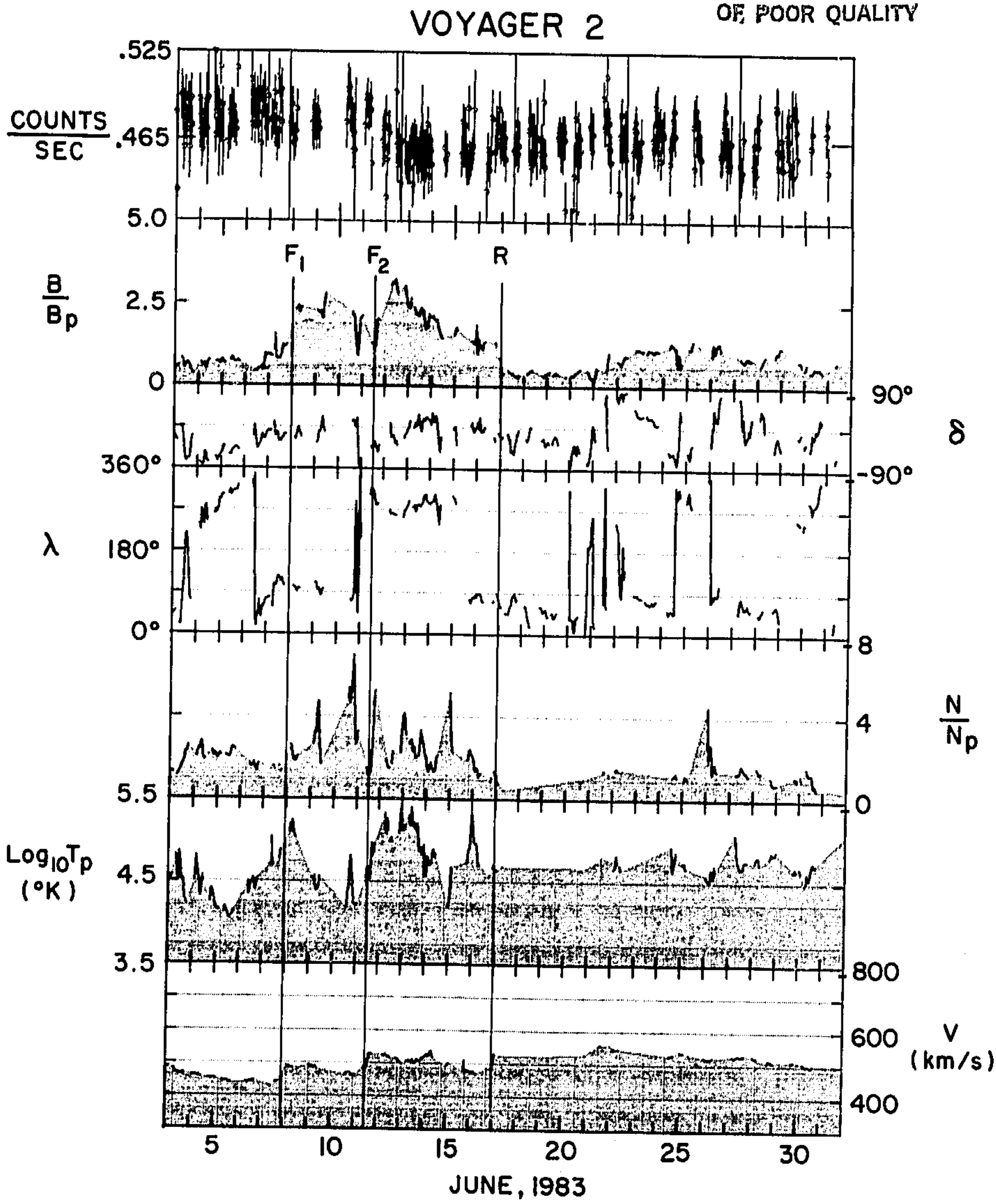

VOYAGER 2
COUNTS/SEC
.525
.465
5.0
F1
F2
R
B/Bp
2.5
0
90°
δ
-90°
360°
λ
180°
0°
8
4
N/Np
0
5.5
Log10Tp (°K)
4.5
3.5
800
600
V (km/s)
400
5
10
15
20
25
30
JUNE, 1983

Figure 5

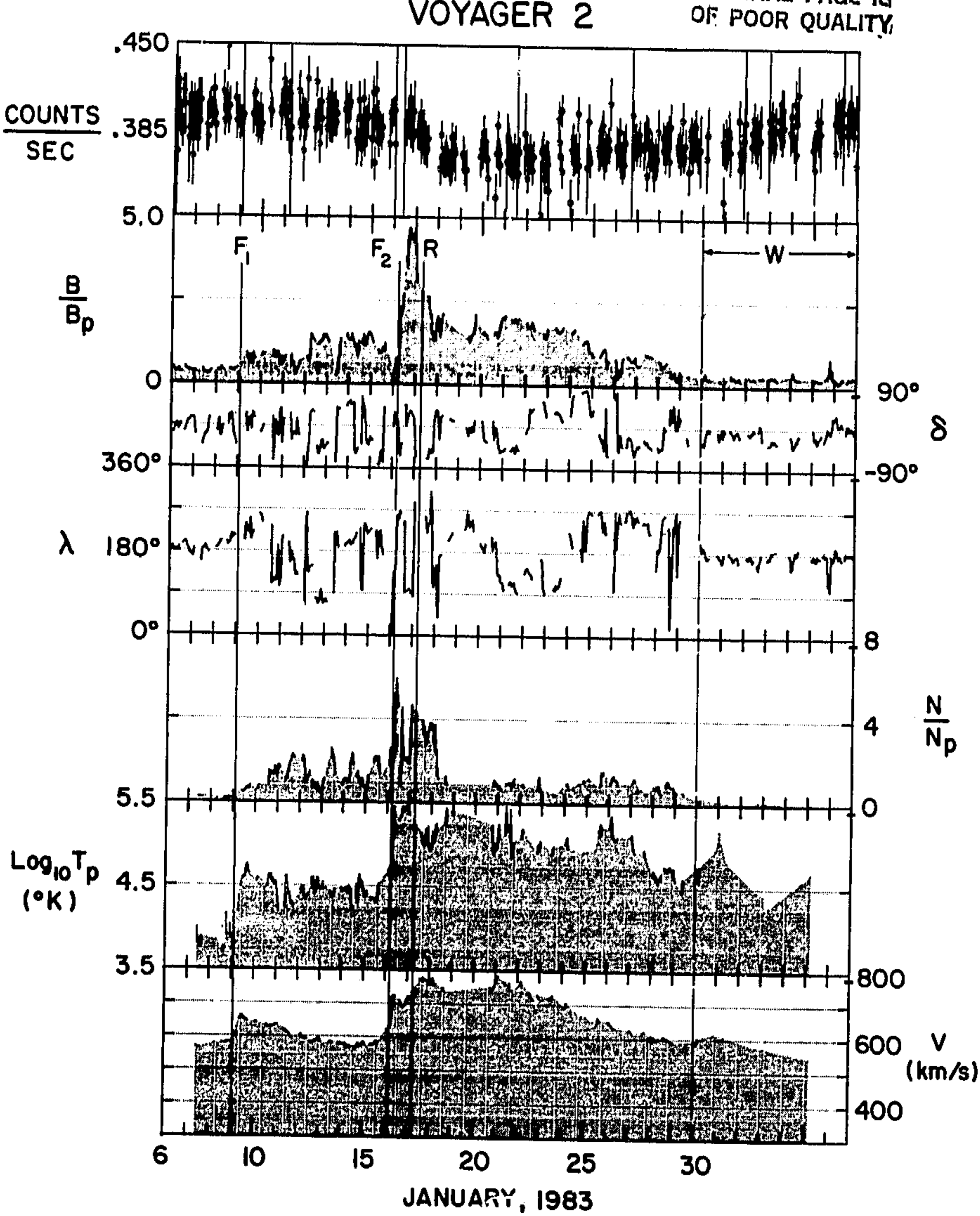

VOYAGER 2
COUNTS / SEC
.450
.385
5.0
F_1
F_2
R
W
B / B_p
0
90°
δ
360°
-90°
λ
180°
0°
8
N / N_p
4
5.5
0
$Log_{10}T_p$ (°K)
4.5
3.5
800
600
V (km/s)
400
6
10
15
20
25
30
JANUARY, 1983

Figure 6

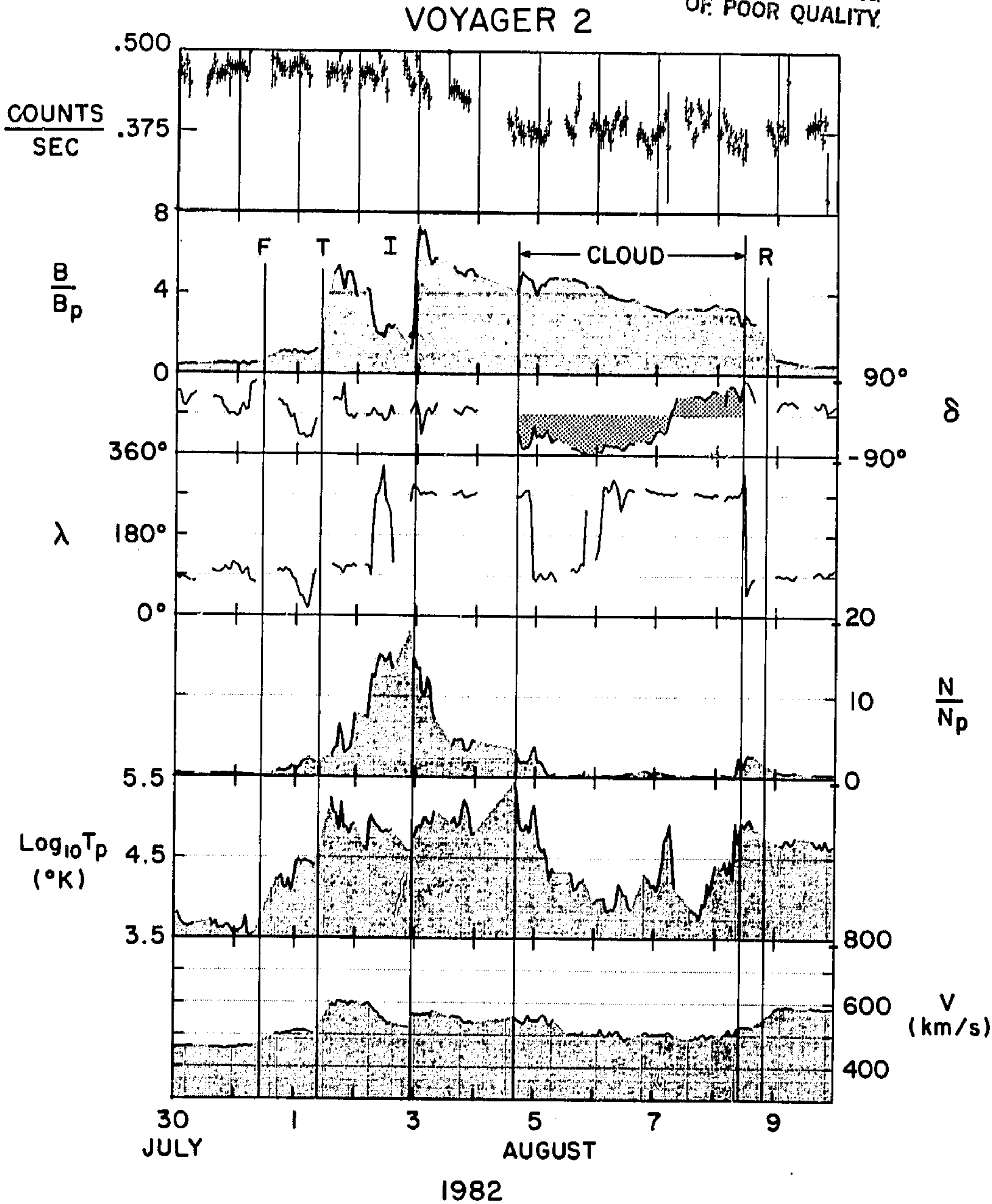
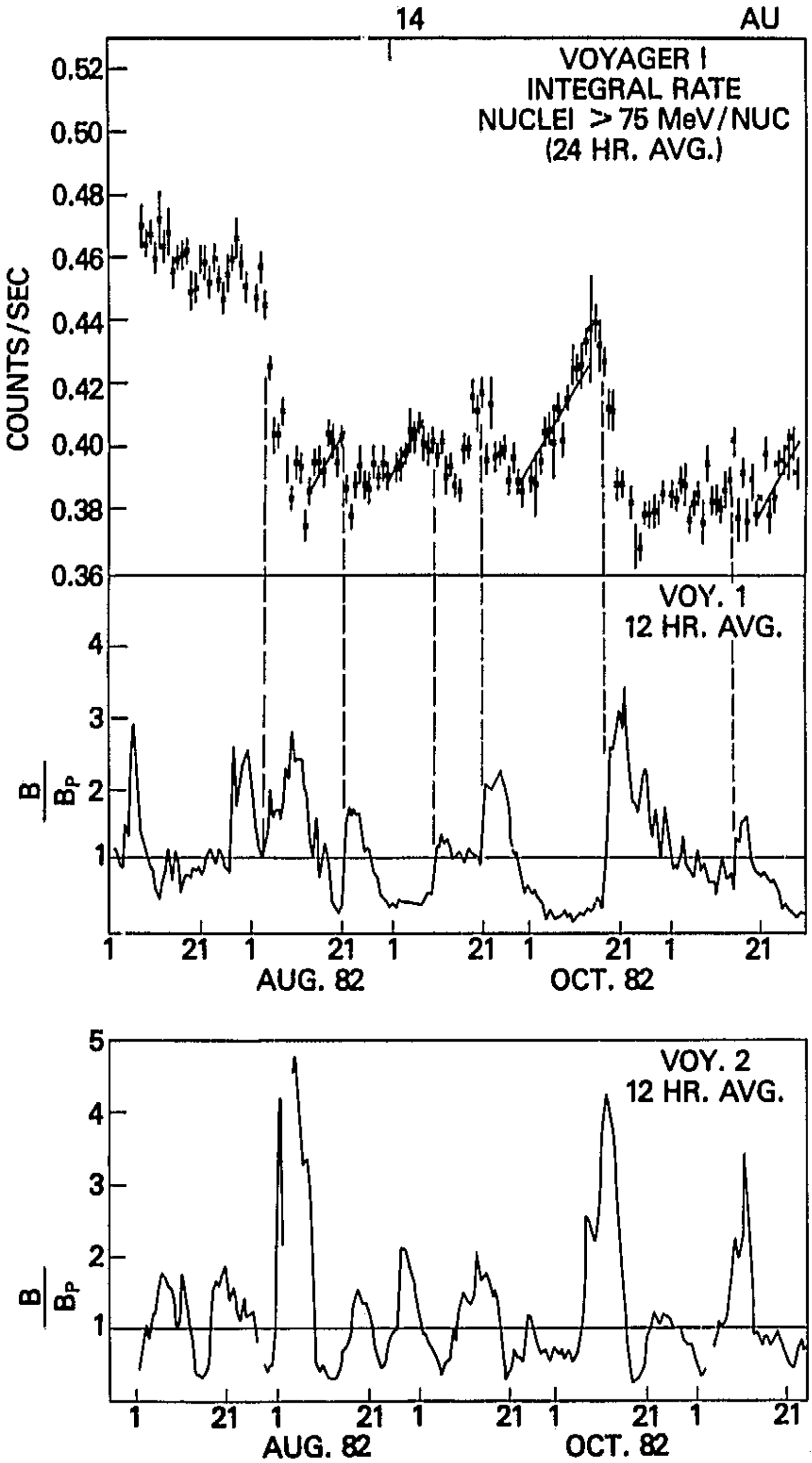

VOYAGER 2
COUNTS
SEC
.500
.375
8
B
Bp
4
0
F
T
I
CLOUD
R
90°
δ
-90°
360°
λ
180°
0°
20
10
N
Np
0
5.5
Log10Tp
(°K)
4.5
3.5
800
600
V
(km/s)
400
30
JULY
1
3
5
AUGUST
7
9
1982

Figure 7



14
AU
VOYAGER I
INTEGRAL RATE
NUCLEI > 75 MeV/NUC
(24 HR. AVG.)
COUNTS/SEC
0.52
0.50
0.48
0.46
0.44
0.42
0.40
0.38
0.36
VOY. 1
12 HR. AVG.
B/B_P
4
3
2
1
1
21
1
21
1
21
1
21
1
21
AUG. 82
OCT. 82
5
VOY. 2
12 HR. AVG.
B/B_P
4
3
2
1
1
21
1
21
1
21
1
21
1
21
AUG. 82
OCT. 82

Figure 8

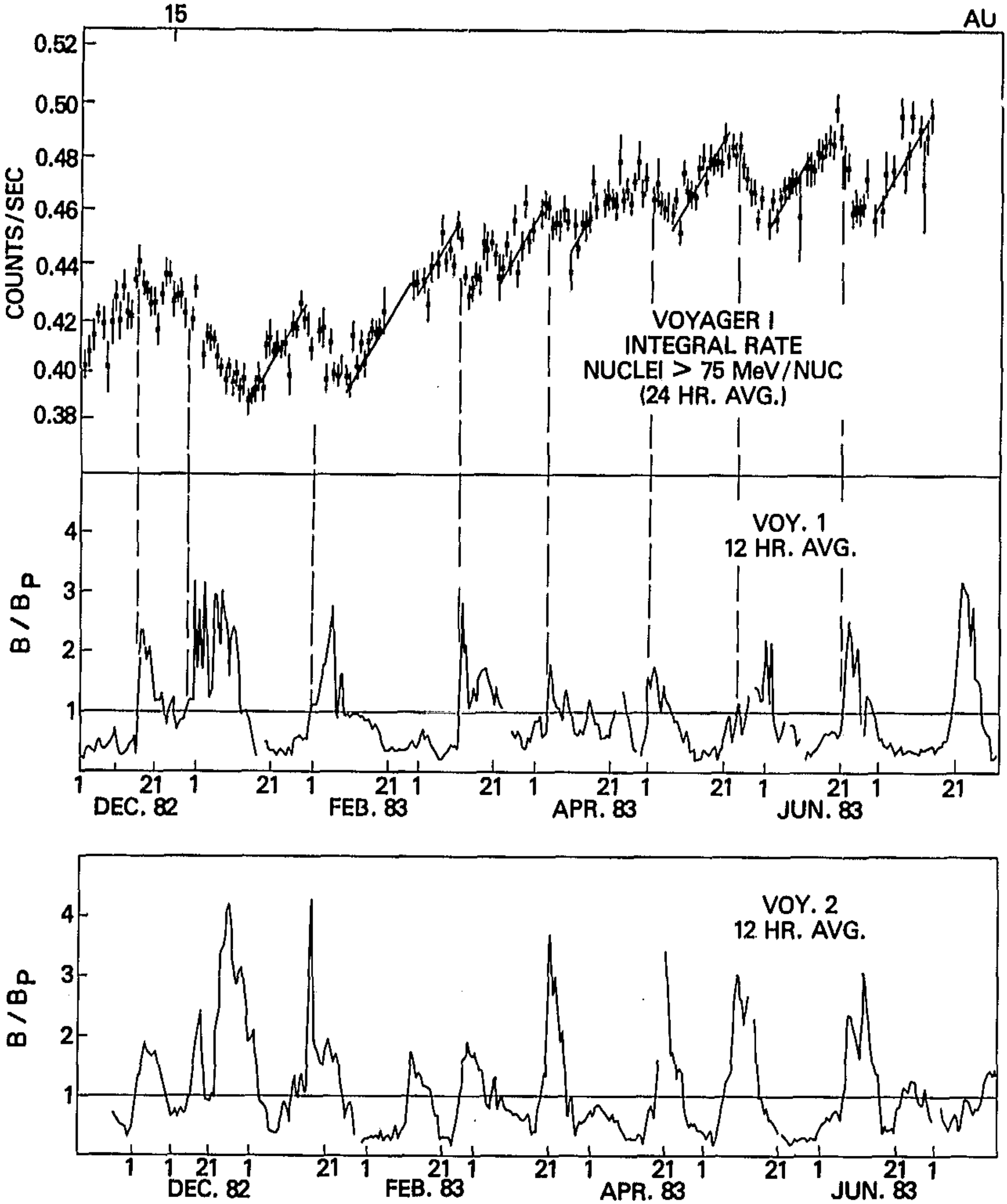

15
AU
0.52
0.50
0.48
0.46
0.44
0.42
0.40
0.38
COUNTS/SEC
VOYAGER I
INTEGRAL RATE
NUCLEI > 75 MeV/NUC
(24 HR. AVG.)
VOY. 1
12 HR. AVG.
B / B_P
4
3
2
1
1 21 1 21 1 21 1 21 1 21 1 21 1 21 1 21
DEC. 82
FEB. 83
APR. 83
JUN. 83
VOY. 2
12 HR. AVG.
B / B_P
1 1 21 1 21 1 21 1 21 1 21 1 21 1 21 1
DEC. 82
FEB. 83
APR. 83
JUN. 83

Figure 9

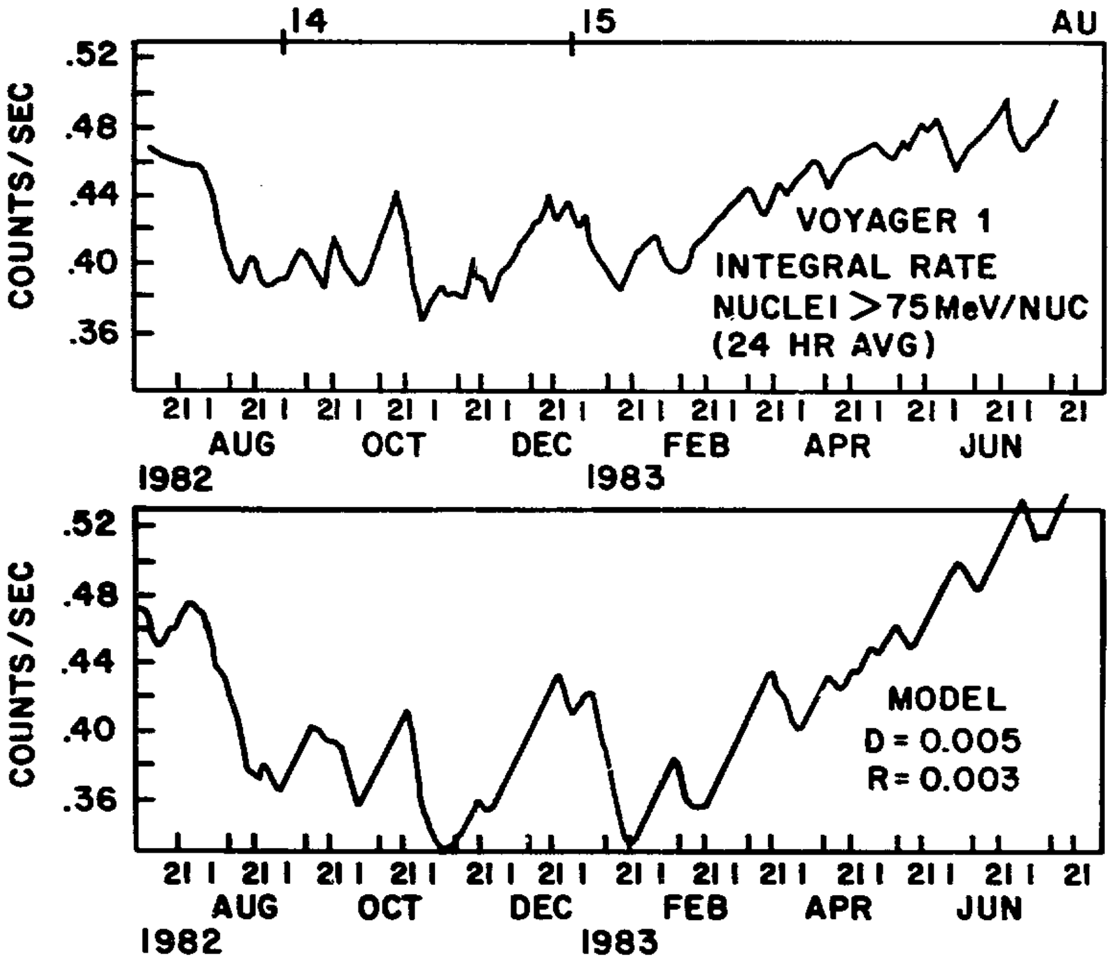

14
15
AU
COUNTS/SEC
.52
.48
.44
.40
.36
VOYAGER 1
INTEGRAL RATE
NUCLEI >75MeV/NUC
(24 HR AVG)
AUG
OCT
DEC
FEB
APR
JUN
1982
1983
COUNTS/SEC
MODEL
D = 0.005
R = 0.003

Figure 10

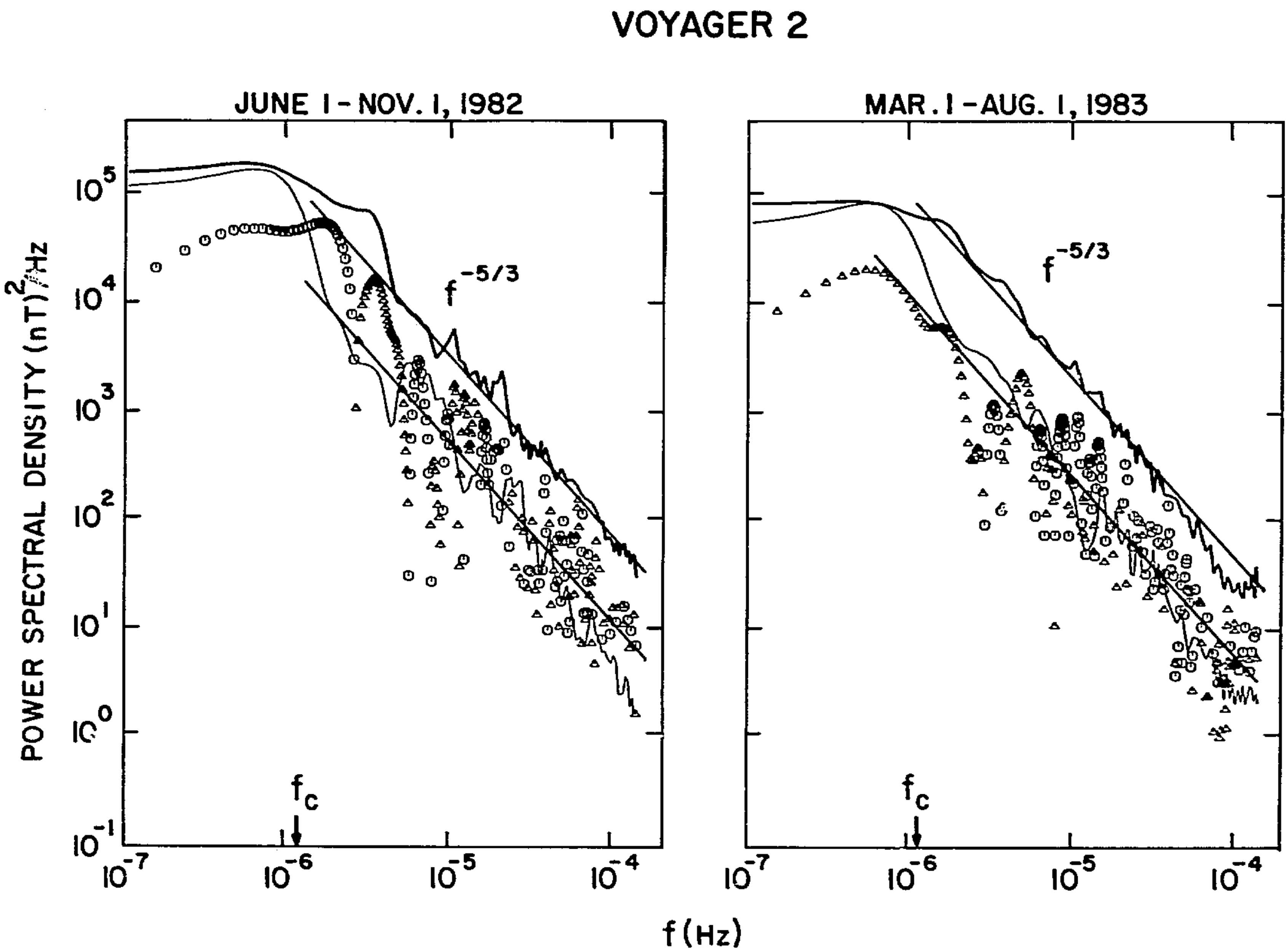

VOYAGER 2
JUNE 1 - NOV. 1, 1982
MAR. 1 - AUG. 1, 1983
POWER SPECTRAL DENSITY (nT)²/Hz
f(Hz)
f^-5/3
f_c
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-7
10^-6
10^-5
10^-4

Figure 11

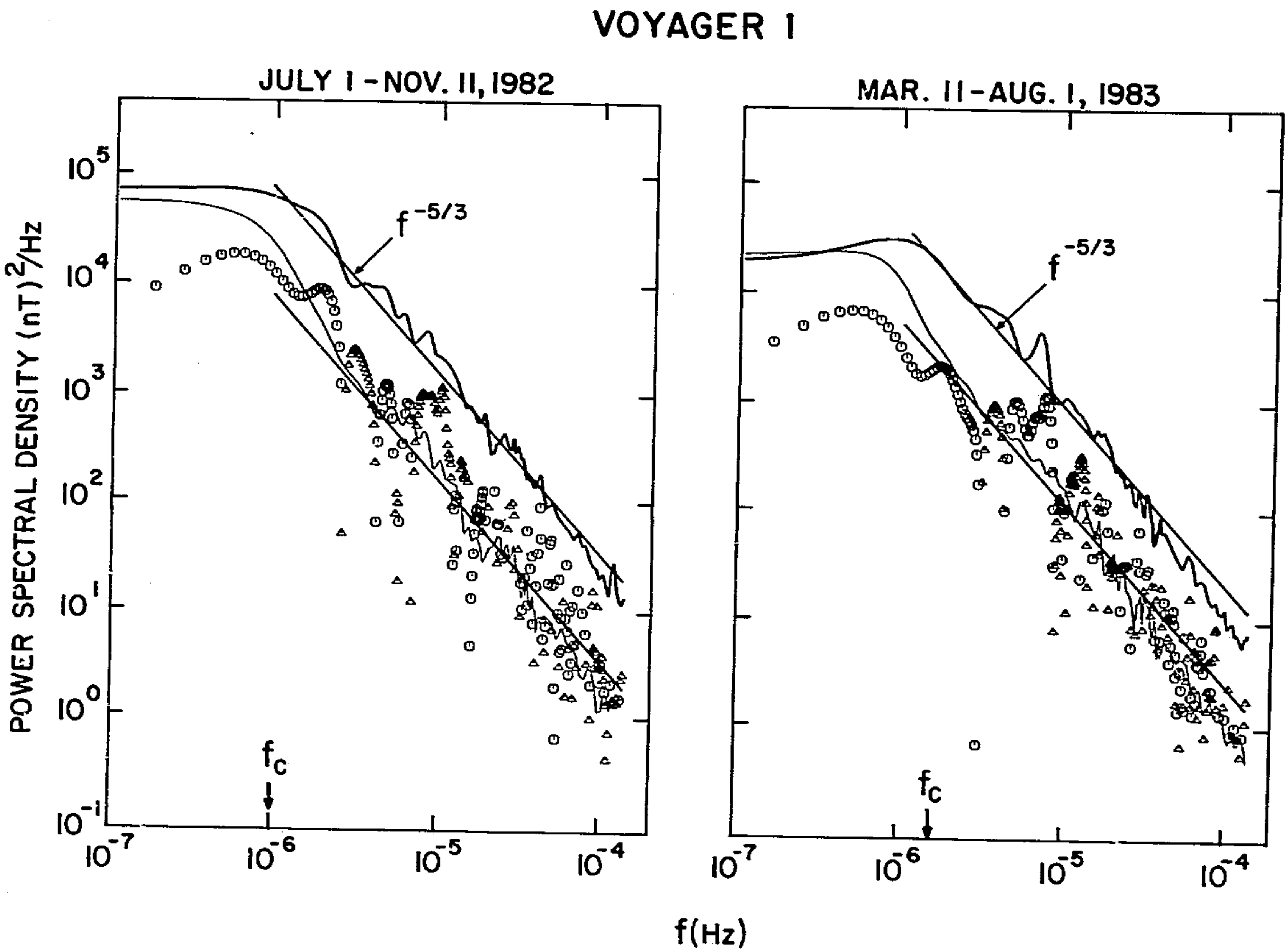

VOYAGER 1
JULY 1 - NOV. 11, 1982
MAR. 11 - AUG. 1, 1983
POWER SPECTRAL DENSITY (nT)²/Hz
f(Hz)
f^-5/3
fc
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-7
10^-6
10^-5
10^-4

Figure 12

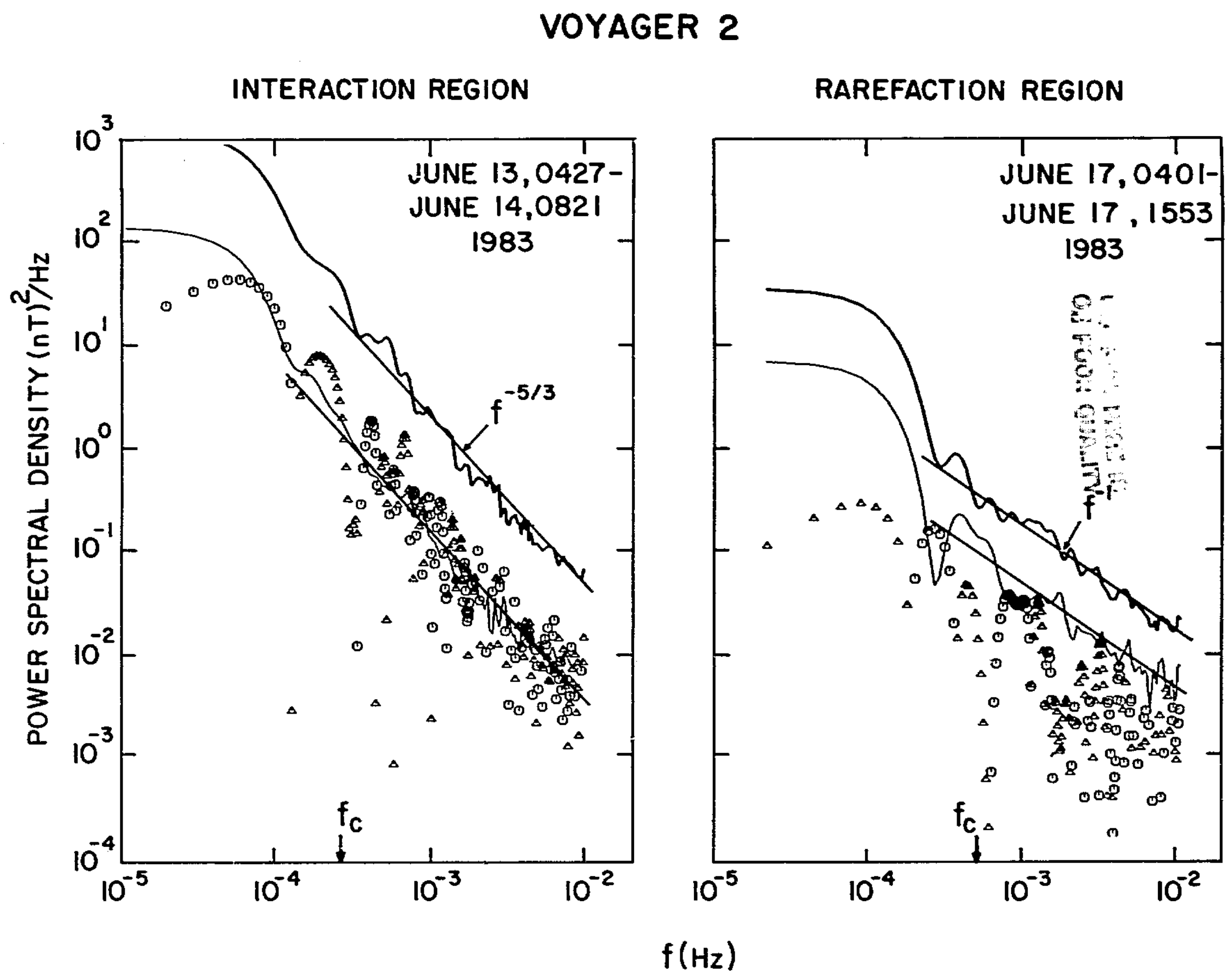

VOYAGER 2
INTERACTION REGION
RAREFACTION REGION
JUNE 13, 0427-
JUNE 14, 0821
1983
JUNE 17, 0401-
JUNE 17, 1553
1983
f^-5/3
f
fc
POWER SPECTRAL DENSITY (nT)²/Hz
f (Hz)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
OF POOR QUALITY

Figure 13

BIBLIOGRAPHIC DATA SHEET

1. Report No. TM 86193	2. Government Accession No.	3. Recipient's Catalog No.
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