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Abstract

Two time periods are studied for which comprehensive data coverage is available at both 1 AU using IMP-8 and ISEE-3 and beyond using Voyager 1. One of these periods is characterized by the predominance of corotating stream interactions. Relatively small scale transient flows characterize the second period. The evolution of these flows with heliocentric distance is studied using power spectral techniques. The evolution of the transient dominated period is consistent with the hypothesis of turbulent evolution including an inverse cascade of magnetic helicity to large scales. The evolution of the corotating period is consistent with the "entrainment" of slow streams by faster streams in a deterministic model.

1. Introduction

Gosling and Hundhausen (1976) suggested that the interplanetary medium acts like a low pass filter in that short wavelength structures that pass a spacecraft in ~ 1 to 4 days at 1 AU are generally absent in the speed profile at ~ 5 AU. Similar time scales occur in two classes of flows identified by Burlaga (1975), viz. "irregular fluctuations" and "compound streams". "Irregular variations" were defined as relatively small speed changes lasting only one or two days. A "compound stream" is a stream lasting ~ 2-4 days superimposed on another stream; together these structures have a duration of several days. Because the change in bulk speed in "irregular variations" is generally less than the magnetoacoustic speed, Burlaga argued that pressure gradients associated would significantly alter the speed profile as time progressed. On the other hand, Gosling and Hundhausen (1976) and Hundhausen (private communication, 1983) suggested that the disappearance these short wavelength variations in bulk speed was a result of the formation of interacting shock waves. The filtering of short wavelength structures in compound streams discussed by Gosling and Hundhausen (1976). Using Pioneer plasma data and a one dimensional gas dynamic code, they showed that with increasing distance a slower stream ahead of a faster stream might disappear leading to the formation of a single longer wave-length stream.

A related process that can redistribute fluid energy in spatial scale is the observation by Burlaga (1983a) that large pressure waves be found in the outer heliosphere even in the absence of fast streams. Burlaga suggested that these pressure waves can interact with one another to form new configurations. Pizzo (1983) showed quantitatively how this can happen for a series of similar corotating streams. Burlaga et al. (1983a) argued that fast streams might sweep-up pressure waves from different sources (e.g., shocks and slower streams) into a smaller region, and that these pressure waves might coalesce as a result of a magnetohydrodynamic (MHD) interaction to form new structures; a process called "entrainment". Using a 2-D MHD code developed by Pizzo together with IMP-8 data as input, Burlaga et al. (1983b) showed how entrainment can produce qualitative changes in the pressure profile. Burlaga (1983b) suggested that as a result of entrainment small-scale features that move past the spacecraft in an interval of the order of one day are erased, and magnetic energy coalesces to larger scales as the flows move outward. In this view, energy is not necessarily "filtered out" but rather evolves in a deterministic way from a scale of the order of one or two days to larger scales. This scenario is reminiscent of the evolution predicted for three dimensional incompressible isotropic MHD turbulence in which a transfer of magnetic energy from short to long scales is expected (Frisch et al., 1975; Matthaeus and Montgomery, 1980; Matthaeus and Goldstein, 1982; and Montgomery, 1983). However, turbulent evolution is a dynamical process involving a simultaneous transfer of magnetic energy, magnetic helicity and cross helicity (the three invariants of incompressible MHD turbulence) to both larger and smaller scales. One of the objectives of this letter is to investigate the relationship between these two viewpoints in a effort to further our understanding of how the solar wind evolves with heliocentric distance and as well as to explore the extent to which the interplanetary medium behaves as a turbulent MHD fluid.

The framework of this effort is the suggestion by Burlaga (1975) that one might construct models of very general time varying source functions of the solar wind to describe variations in the fluid parameters over intervals of many days. The motivation is that the source function of the solar wind is probably an irregular function reflecting the complexity of the corona. This paper represents a step in such a program. The source function is taken from measurements made at 1 AU and the time interval considered is of the order of 100 days. Comparing the magnetic field profiles measured at 4 AU to ~ 6 AU with the corresponding profiles measured at 1 AU, we show that a transfer of magnetic energy from small scales to large scales does take place at frequencies $\lesssim 10^{-5}$ Hz. Two ways in which this might occur are discussed: entrainment and an inverse cascade in MHD turbulence.

2. Observations of the Radial Variation of Magnetic Field Strength Fluctuations

We consider two time intervals in data obtained at 1 AU: Interval A from August 14, 1978 to February 5, 1979; and Interval B from March 29, 1979 to June 30, 1979. Corresponding intervals in data obtained by Voyager 1 between 4.1 AU and 5.2 AU were identified by "corotating" time series of magnetic field strength $|\underline{B}|$ and bulk speed V from the position of Earth to the positions of Voyager 1, assuming a constant solar wind speed of 400 km/s. These "corotated" intervals are September 7, 1978 to February 20, 1979 (Interval A), and April 11, 1979 to July 10, 1979. Magnetic field data for 1 AU were obtained from the NSSDC. They consist of IMP-8 data from the magnetic field experiment of N. Ness and ISEE-3 data from the magnetic field experiment of E. Smith. Magnetic field data from Voyager 1 are from the experiment of N. Ness.

Magnetic field strength versus time for Intervals A and B is shown at the top of Figure 1. Comparing the measurements made at 1 AU with those from Voyager 1, the basic result of this letter begins to emerge. High frequency fluctuations in $|\underline{B}|$ are more prominent at 1 AU than near ~ 5 AU, or conversely low frequency fluctuations in $|\underline{B}|$ are more prominent at larger distances from the sun. This qualitative and subjective result can be expressed more precisely by means of the power spectra for B, which are shown at the bottom of Figure 1.

These power spectra were computed using the Blackman-Tuckey mean-lagged-product technique, with 20 degrees of freedom. The time series at 1 AU were nearly continuous, and at Voyager 1 the data are more than 90% complete. The small data gaps were linearly interpolated. Power levels at Voyager 1 are lower than those at 1 AU, because the interplanetary magnetic field strength decreases with distance from the sun. Our concern is not with the absolute power levels, but rather the relative change in power with frequency at Voyager as compared to that at 1 AU. For example, consider the ratio P of power at 10^{-6} Hz to that at 10^{-5} Hz, P = P(10^{-6} Hz)/P(10^{-5} Hz). In Interval A, this ratio is P ~ 10 at 1 AU and P ~ 60 at Voyager 1, indicating relatively more power at low frequencies at larger distances. Similarly, in Interval B, the ratio is P ~ 10 at 1 AU and P ~ 120 at Voyager 1 showing an even larger enhancement in power at low frequencies at larger distances.

Comparing the power spectra of $|\underline{B}|$ for Intervals A and B (Figure 1) one sees significant differences in the shapes of the spectra measured by Voyager at ~ 5 AU. Whereas the power spectrum is close to $k^{-5/3}$ from 10^{-6} Hz to 10^{-4} Hz for Interval A, it cannot be described by a power law for Interval B. In Interval B, there is an "excess" of magnetic energy near periods of ~ 4 to 10 days and a "deficit" of energy near periods of 2-3 days, but there is no such distribution of energy for Interval A. These differences can also be inferred in the time series B(t) measured by Voyager 1 (Figure 1). In Interval B there are large recurrent enhancements and depressions in magnetic field strength with a half-period of the order of 10 days, while there are few large amplitude changes with separations of the order of a day or two. By contrast, in Interval A there is a broad spectrum of fluctuations with neither an excess of power near 10^{-20} days nor a deficit near 2 to 3 days. At 1 AU, the shape of power spectra for $|\underline{B}|$ measured in Interval A is similar to that for Interval B. In both cases, at frequencies greater than $\sim 3 \times 10^{-6}$ Hz the spectrum is close to a $k^{-5/3}$ law.

Now compare the spectra measured at 1 AU with those measured at Voyager. In Interval A the 1 AU and Voyager 1 spectra have the same form at frequencies $> 10^{-6}$ Hz, and the difference in power levels decreases as one goes to frequencies below $\sim 3 \times 10^{-6}$ Hz. Thus, the relative changes in the power at long wavelengths with increasing distance occurs only at periods $\geq$ 4 days. In Interval B, on the other hand, the 1 AU and Voyager spectra have different forms at all frequencies above 10^{-6} Hz. In particular, there is a significant increase in the difference between the 1 AU and Voyager 1 power levels as one goes from $\sim 10^{-6}$ to 8×10^{-6} Hz, and it appears that there is a loss of energy at periods between ~1.5 days and ~5 days as the plasma moves from 1 AU to ~ 5 AU. The physical significances of these differences will be discussed in the next section.

One approach to classifying the differences between Intevals A and B is to recall the two types of flow systems distinguished by Burlaga et al. (1982) and Burlaga (1983), viz. the well-known systems of corotating or recurrent flows and systems of transient flows. Systems of transient flows may contain shocks, flare ejecta, magnetic clouds, short-lived streams, etc., i.e., a mixture of non-recurrent flows and field patterns that are observed at a given point for at least two solar rotations. Goldstein et al. (1983) have discussed systematic differences in the statistical properties of the magnetic field for these two types of systems. Interval B resembles a system of corotating flows in this respect, while Interval A is more like a system of transient flows.

3. Discussion of Possible Physical Processes

The differences between the Voyager 1 spectra for Intervals A and B suggest that at least two physical processes may be involved in changing the distribution of power in $|\underline{B}|$ at frequencies $\lesssim 10^{-5}$ Hz as the flows move from 1 AU to ~ 5 AU; one being dominant in Interval A the other in Interval B. The simple power law spectrum observed over a wide range of frequencies by Voyager 1 in Interval A and the irregularity of the corresponding B(t) profile suggest that turbulent processes are involved in this interval. On the other hand, the regularity of the B(t) profile observed by Voyager 1 in Interval B and the lack of a simple power law fit to the corresponding spectrum of magnetic fluctuations suggests that deterministic MHD flow models and the concept of entrainment might be more appropriate for this interval. In this section we explore these ideas further. Since neither the theory of MHD turbulence nor that of entrainment is well-developed, our discussion is necessarily qualitative. Our aim is to gain some insight and to stimulate further studies, rather than to provide a definitive interpretation of the observations.

Turbulence theories generally identify three frequency or wavelength ranges. Of central importance is the "inertial range". The inertial range is bounded at longer wavelengths by the correlation length which is a measure of the scale of the energy containing structures. At the small wavelength boundary of the inertial range, the spectrum is exponentially damped by dissipative processes, this is the dissipation range and will not concern us here. Quantitative predictions for MHD turbulence, are difficult to obtain, however, some turbulence models predict an inertial range spectrum of $k^{-5/3}$ (Kolmogoroff, 1941a,b; Obukhov, 1941) or $k^{-3/2}$ (Kraichnan, 1965) for isotropic (incompressible) MHD turbulence. In the long wavelength regime, Frisch et al. (1975) and Montgomery et al (1978) have conjectured that a k^{-1} spectrum will form. Accompanying the k^{-1} spectrum these conjectures predict an inverse cascade of magnetic helicity. This inverse cascade should be initially apparent at scales somewhat longer than the correlation length.

For the data in Interval A, the correlation lengths, as defined by Batchelor (1970) and Matthaeus and Goldstein (1982), are 0.19 AU at 1 AU and 0.15 AU at Voyager, corresponding to 1.56×10^{-5} Hz and 2.0×10^{-5} Hz, respectively. The power in the fluctuations of all components of $\underline{B}$ (specifically, the trace of the spectral tensor S_{ij}) is shown as a function of frequency in Figure 2. A $k^{-5/3}$ spectrum is observed at scales smaller than the correlation length both at 1 AU and at Voyager, consistent with the presence of an inertial range of turbulence. Note that the $k^{-5/3}$ spectrum extends over a broader frequency range at 5 AU than at 1 AU, which suggests that turbulence occurs over a broader range of spatial scales at ~ 5 AU. At scales longer than the correlation length, the spectra can be approximated by a k^{-1} law, again consistent with the presence of turbulence. There is also evidence for an inverse cascade of magnetic helicity in the power spectrum of the wave number times magnetic helicity (kH_m) shown in Figure 2. A peak in kH_m is observed near the correlation length at 1 AU and it extends to lower frequencies in the Voyager spectrum. Thus, the spectra in Figure 2 for Interval A are consistent with the expectations MHD turbulence theory. At the very least, one can conclude that turbulence theory provides a language and quantitative measure suitable for describing these observations.

In deterministic models, (e.g., Hundhausen, 1972; Pizzo, 1983; Burlaga, 1983) one speaks of flows, flow interactions, pressure waves and interactions of pressure waves, all on a scale of ≥ 1 day. These models usually consider only isolated streams or binary interactions. Power spectra are generally not discussed in regard to such models. The models consider forces due to gradients in magnetic and thermal pressures. Fluctuations in the direction of B and forces associated with the curvature of magnetic field lines are of no dynamical importance in such models. Alfvénic fluctuations, having apparent frequencies < 1 day, are treated either as waves propagating on a background field or as inertial range turbulence.

For a single stream at 1 AU, two scales are important: the duration (or time or passage) of the stream and the duration of the associated interaction region. The duration of a large stream is typically of the order of several days and that of an interaction region is ~ 1 day. In general, there are other structures present including small streams with time scales of the order of 4 or 5 days and "irregular fluctuations" with time scales of ~ 1 or 2 days, as discussed in the introduction, so that a spectrum for a time series of ~ 100 days at 1 AU, might contain power at all frequencies between 10^{-6} Hz and ~ 10^{-5} Hz, as we have seen in Figure 1. The corresponding speed profile for Interval B at 1 AU, (Figure 3) explicitly shows streams and "irregular variations" with scales ranging from ~ 1 day to ≥ 10 days.

As the flows move to larger distances, carrying the magnetic field patterns with them, the large fast flows overtake small slow flows, bringing interaction regions and pressure waves closer together so that they may coalesce to form larger pressure waves and interaction regions. This process of "entrainment" of small-scale structures by large-scale structures transfers magnetic energy from scales of ~ 1 to 4 days to larger scales. Fast flows are decelerated as they do work against pressure gradients, and slow flows are accelerated by the pressure gradients of opposite sign, so that the result is a new speed profile characterized by an absence of large peaks or troughs, with the same mean speed as observed at 1 AU (see Figure 3). Thus, "entrainment can qualitatively account for the changes in speed profile, and it provides a natural explanation for the Voyager 1 spectrum in Interval B (Figure 1), which shows a deficit of energy at scales of ~ 1 to 4 days and an excess of energy at scales of ~ 10 days.

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Figure Captions

Figure 1. Top. $|\underline{B}|$ versus t observed at 1 AU by IMP-8 and ISEE-3 for two time intervals, and similar results obtained by Voyager 1 between 4 AU and ~ 5 AU for two corresponding intervals determined from corotation delays.

Bottom. Power spectra of $|\underline{B}(f)|$ (in nT^2) for the time series shown at the top of the figure.

Figure 2. The trace of the reduced power spectral matrix of the components of $\underline{B}$. The triangles and circles are the positive and negative values of the reduced helicity spectrum multiplied by frequency, $fH_m(f)$.

Figure 3. The bulk speed versus time observed at 1 AU by IMP-8 and ISEE-3 and between 4 AU and 5 AU by Voyager 1 for the intervals described in Figure 1.

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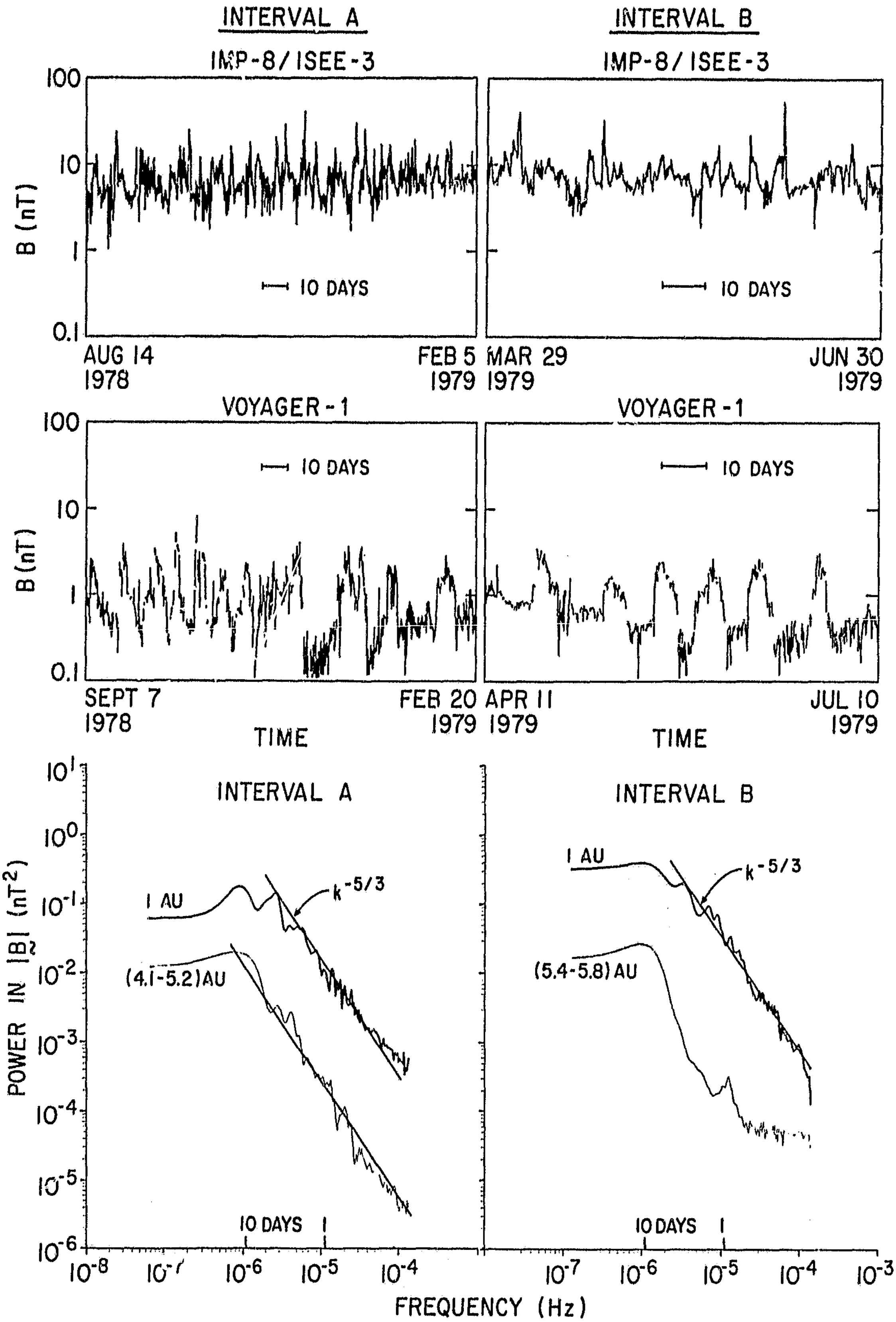

Figure 1

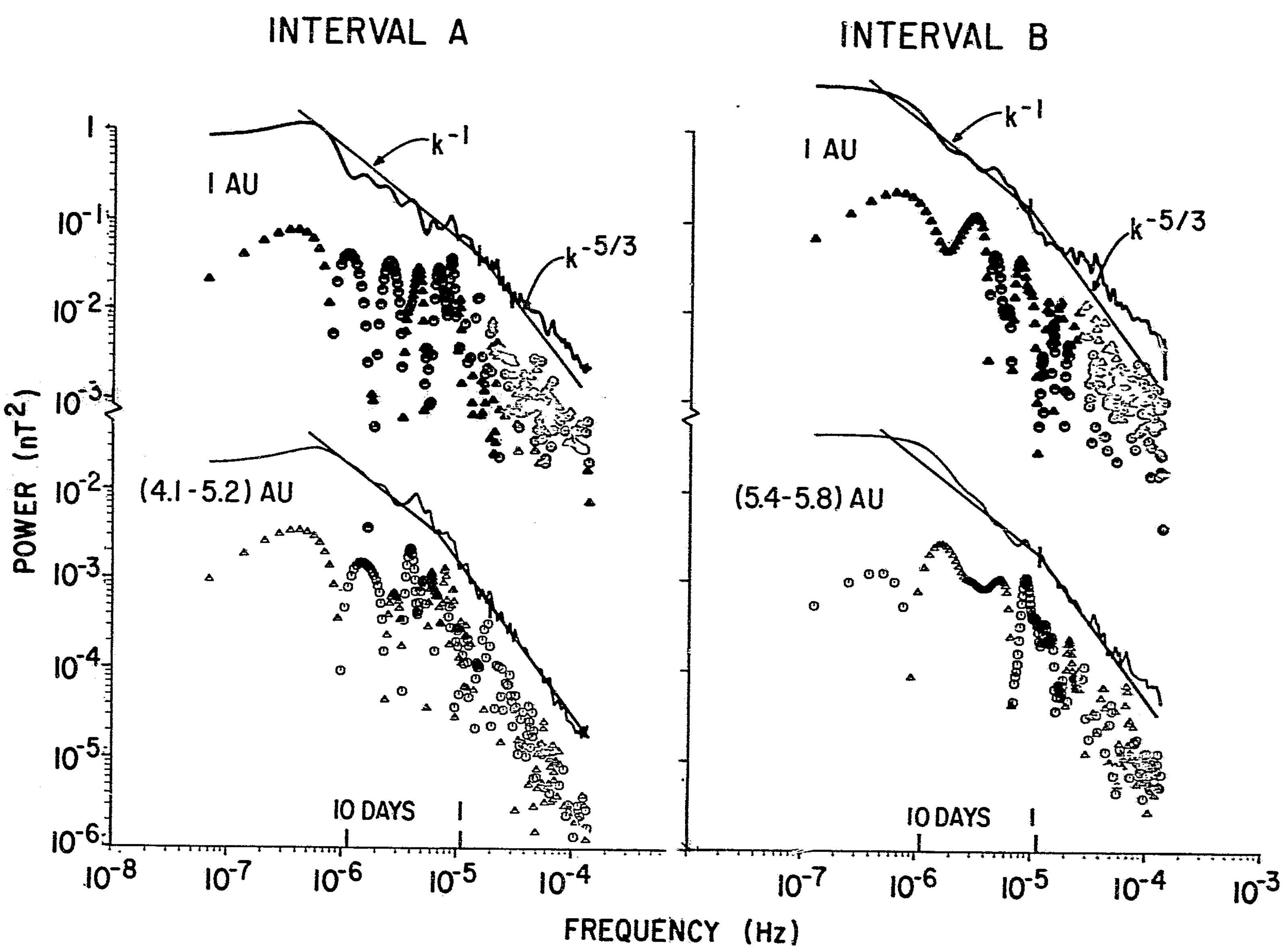
INTERVAL A
INTERVAL B
POWER (nT²)
1 AU
(4.1-5.2) AU
(5.4-5.8) AU
k⁻¹
k⁻⁵/³
10 DAYS
FREQUENCY (Hz)

Figure 2

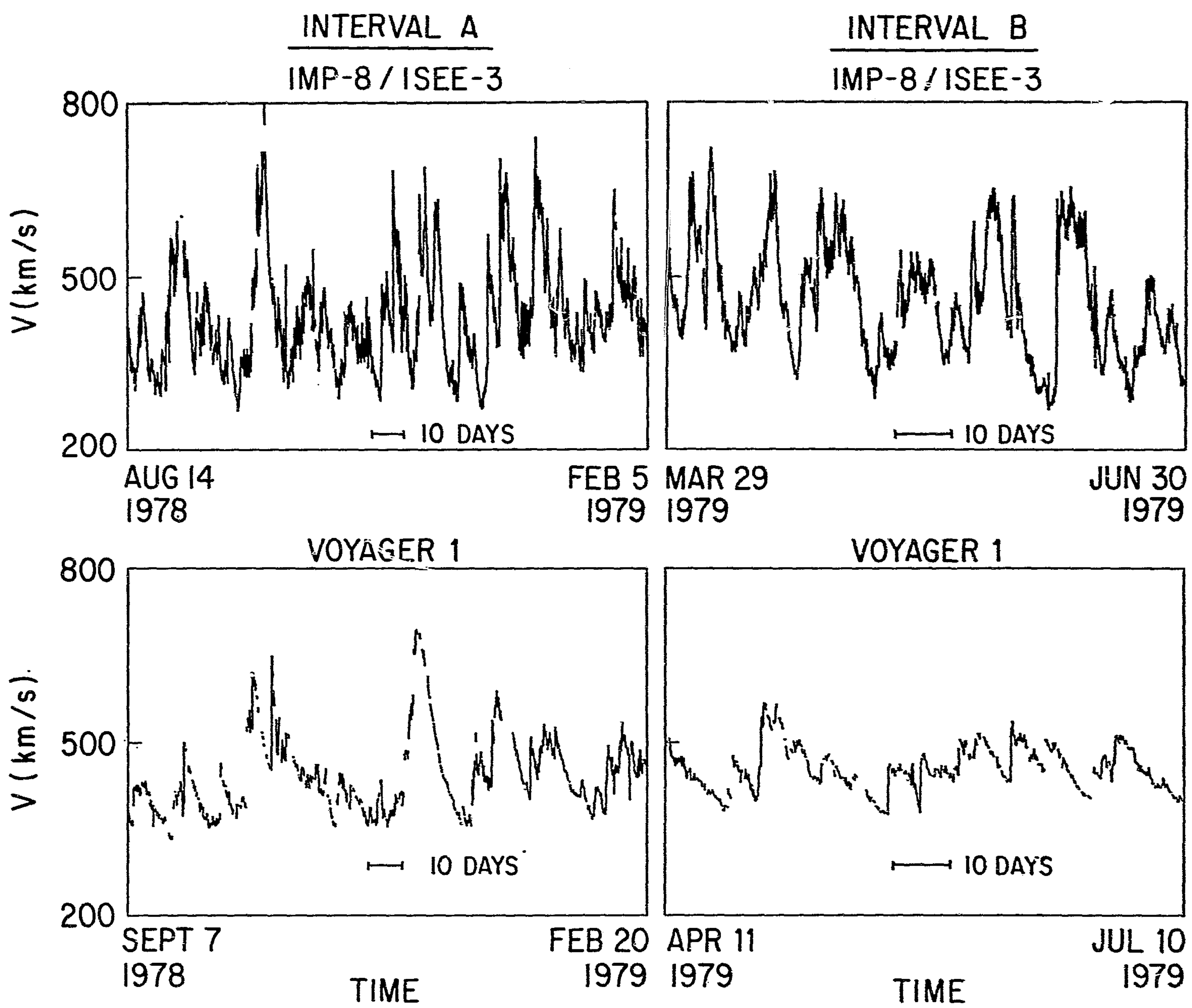
INTERVAL A
IMP-8 / ISEE-3
INTERVAL B
IMP-8 / ISEE-3
800
500
200
V (km/s)
10 DAYS
10 DAYS
AUG 14
1978
FEB 5
1979
MAR 29
1979
JUN 30
1979
VOYAGER 1
VOYAGER 1
800
500
200
V (km/s)
10 DAYS
10 DAYS
SEPT 7
1978
FEB 20
1979
APR 11
1979
JUL 10
1979
TIME
TIME

Figure 3