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# IN SITU OBSERVATIONS OF THE SCALE-SIZE OF PLASMA TURBULENCE IN THE ASTEROID BELT (1.6–3 ASTRONOMICAL UNITS)

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## ABSTRACT

*Pioneer 10* observations from the Ames Research Center Plasma Analyzer experiment between 1 and 3 a.u. in 1972 have been used to estimate the power spectra of the streaming speed of solar wind protons. A power-law spectrum is obtained in the $\sim 10^{-4}$ to $\sim 10^{-3}$ Hz frequency range which is similar to that obtained for the solar wind proton number density and streaming speed at 1 a.u. in 1965 December and 1966 January. The power spectra indicate that significant turbulence on the scale of $\sim 10^6$ km or more is present throughout this range of heliocentric distances, implying the importance of the role of large-scale turbulence between 1 and 3 a.u. The power spectra also present qualitatively information concerning the cosmic-ray diffusion tensor at these extended distances.

*Subject headings:* cosmic rays — interplanetary medium — solar system — solar wind — turbulence

## I. INTRODUCTION

The direct measurement of the scale-size of plasma turbulence throughout the solar system and the determination of the levels of power associated with the turbulence are important for our understanding of many phenomena including the propagation and modulation of cosmic rays in the solar system (Jokipii and Coleman 1968; Jokipii 1973; Mathews, Quenby, and Sear 1971; Völk 1974), the influx of interstellar matter into the solar system (Jokipii 1973), the formation of the solar system including the major planets and the asteroid belt (Alfvén 1954; Alfvén and Arrhenius 1970), and the evolution and significance of magnetohydrodynamic modes and instabilities (Jokipii 1973). Previously, direct observations of the solar wind have indicated the importance of fluctuations and broadband turbulence in the interplanetary plasma (Coleman 1968; Intriligator and Wolfe 1970; Cronyn 1972; Jokipii 1973) and the interplanetary magnetic field (Coleman 1966; Jokipii and Coleman 1968; Jokipii 1973). All of these observations, however, were obtained in the vicinity of 1 a.u. from the Sun (Coleman *et al.* 1969 reported on the magnetic field fluctuations out to 1.5 a.u. using *Mariner 4* data), and all of these measurements were obtained in the ecliptic plane. The ground-based interplanetary scintillation observations (Cohen *et al.* 1967; Dennison and Hewish 1967; Jokipii 1973) of compact radio sources provide indirect information on plasma fluctuations within 1 a.u. since these measurements are integrated along the line of sight with the contributions closest to the Sun weighted the most. To date, therefore, the spatial variation and evolution of the turbulent fluctuations over large heliocentric distances or out of the ecliptic plane have not been determined. The *Pioneer 10* solar wind observations provide our first opportunity for studying the role of turbulence in the extended regions of our solar system with in situ measurements.

## II. OBSERVATIONS

*Pioneer 10* was launched from Earth to Jupiter on 1972 March 3 and covered the greatest range of heliocentric distance of any spacecraft to date. *Pioneer 10*, having successfully encountered the Jovian environment, is currently beyond 5 a.u. from the Sun. Figure 1 shows the *Pioneer 10* trajectory. The Ames Research Center Plasma Analyzer on *Pioneer 10* consists of two concentric quadrispherical electrostatic analyzers with multiple collectors (Wolfe *et al.* 1974*a*, *b;* Intriligator and Wolfe 1974). The measurements employed in this study are the solar wind proton data obtained with detector B, the analyzer having five collector plates, each with an associated electrometer amplifier. The solar wind proton observations were analyzed using the calibrated instrument transmission function and a least-squares iteration technique to fit the flight data to an isotropic Maxwellian distribution. The power spectra were calculated according to the method of Blackman and Tukey (1959).

Figure 2 shows power spectra in the frequency range of $\sim 10^{-4}$ to $\sim 10^{-3}$ Hz calculated using observations of the streaming speed of solar wind protons obtained by the Ames Research Center Plasma Analyzer on *Pioneer*

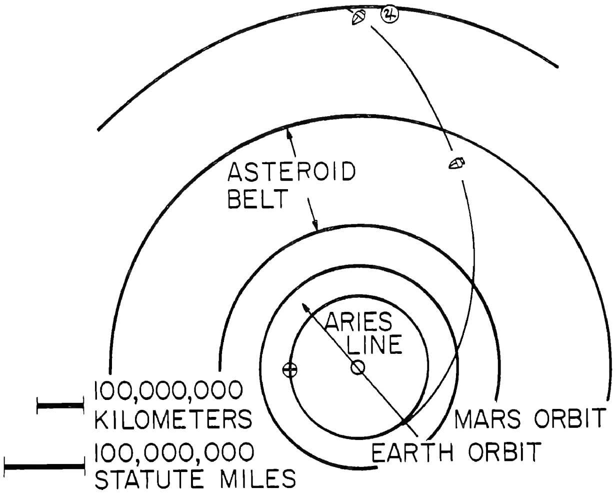

FIG. 1.—The *Pioneer 10* trajectory. Launch 1972 March 3; encounter 1973 December 3.

*10* on 1972 May 28, July 6, and August 7, when the spacecraft was at a heliocentric distance of approximately 1.6, 1.9, and 2.2 a.u., respectively. Intriligator (1972) showed that in the frequency range of $10^{-4}$ to $10^{-3}$ Hz the slopes were similar for the power spectra curves of the number density of solar wind protons and the three components of the solar wind velocity. The observations of the solar wind streaming speed used to calculate the power spectra in figure 2 are comparable to the radial component of the solar wind velocity in Intriligator (1972). The time interval included for each of the days in figure 2 is approximately 6 hours (89 possible points, spaced 4 minutes apart). Each of the curves in figure 2 is based on a power estimate at the following frequencies: $2.3 \times 10^{-4}$ Hz, $4.5 \times 10^{-4}$ Hz, $6.8 \times 10^{-4}$ Hz, $9.0 \times 10^{-4}$ Hz, $1.1 \times 10^{-3}$ Hz, $1.4 \times 10^{-3}$ Hz, $1.6 \times 10^{-3}$ Hz, $1.8 \times 10^{-3}$ Hz, $2.0 \times 10^{-3}$ Hz, and $2.3 \times 10^{-3}$ Hz. The power estimate at a given frequency ($n$) covers the frequency range from the adjacent lower frequency ($n - 1$) to the adjacent higher frequency ($n + 1$). For example, the power estimate at $4.5 \times 10^{-4}$ Hz covers a frequency range extending from 2.3 to $6.8 \times 10^{-4}$ Hz. Table 1 lists some additional relevant parameters for each of the power spectra in Figure 2. Column (3) in table 1 lists the "equivalent" number of degrees of freedom and reflects the presence of the number of data gaps and their distribution within each data set (Blackman and Tukey 1959). Column (4) lists the slope of the power spectra for each of the data sets. Column (5) lists the mean solar-wind streaming speed for each of the data sets. In column (5) the high mean streaming speed (635 km $s^{-1}$) recorded on 1972 August 7 by *Pioneer 10* was associated with the series of large solar flares on the Sun earlier in the month (*Solar-Geophysical Data* 1973). Column (6) lists the total rms fluctuations in solar wind streaming speed for each of the data sets. The high value of 162 in column (6) associated with the August flares is the one exception to the apparent trend of a decrease in the total rms fluctuations as a function of increasing heliocentric distance. It should be noted that the slopes of each of the curves in figure 2, including the slope of the curve associated with the August events, are quite similar but that the levels of power of the curves vary considerably reflecting the lower-frequency power associated with the high-speed stream structure of the solar wind. Both of these results are similar to our previous results in 1965 December and 1966 January at 1 a.u. in this frequency range (Intriligator and Wolfe 1970) and in the higher frequency ($\sim 10^{-3}$ to $\sim 10^{-2}$ Hz) range (Intriligator 1975).

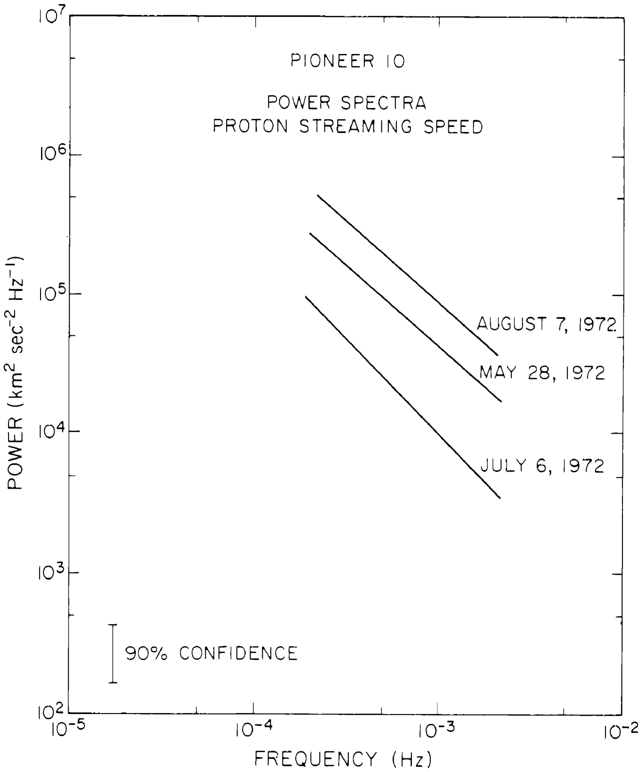

FIG. 2.—Power spectra of the solar wind proton streaming speed for the first three data sets listed in table 1.

Figure 3 shows two power spectra of the solar-wind streaming speed that are based on observations of the solar wind obtained by the Ames Research Center Plasma Analyzer on *Pioneer 10* on 1972 October 28 and November 11 at heliocentric distances of approximately 2.9 and 3.0 a.u., respectively. Each of the power spectra in figure 3 is based on approximately 8.3 hours of data (50 possible points, spaced 10 minutes apart). Each of the curves in figure 3 is based on a power estimate at the following frequencies: $8.7 \times 10^{-5}$ Hz, $1.7 \times 10^{-4}$ Hz, $2.6 \times 10^{-4}$ Hz, $3.5 \times 10^{-4}$ Hz, $4.3 \times 10^{-4}$ Hz, $5.2 \times 10^{-4}$ Hz, $6.1 \times 10^{-4}$ Hz. $6.9 \times 10^{-4}$ Hz. $7.8 \times 10^{-4}$ Hz, and $8.7 \times 10^{-4}$ Hz. Table 1 lists some additional relevant parameters for the power spectra in figure 3.

TABLE 1

RELEVANT PARAMETERS FOR EACH OF THE DATA SETS USED IN THIS ANALYSIS

| Date (1) | Distance from the Sun (a.u.) (2) | Equivalent No. of Degrees of Freedom (3) | Slope (4) | Mean Streaming Speed (km $s^{-1}$) (5) | Total rms Streaming Speed Fluctuation (km $s^{-1}$) (6) |
|---|---|---|---|---|---|
| 1972 May 28............... | 1.6 | 16.9 | −1.1 | 332 | 133 |
| 1972 July 6................ | 1.9 | 15.3 | −1.4 | 371 | 68 |
| 1972 August 7............. | 2.2 | 13.9 | −1.2 | 635 | 162 |
| 1972 October 29............ | 2.9 | 8.9 | −1.7 | 384 | 56 |
| 1972 November 11.......... | 3.0 | 7.7 | −1.4 | 364 | 19 |

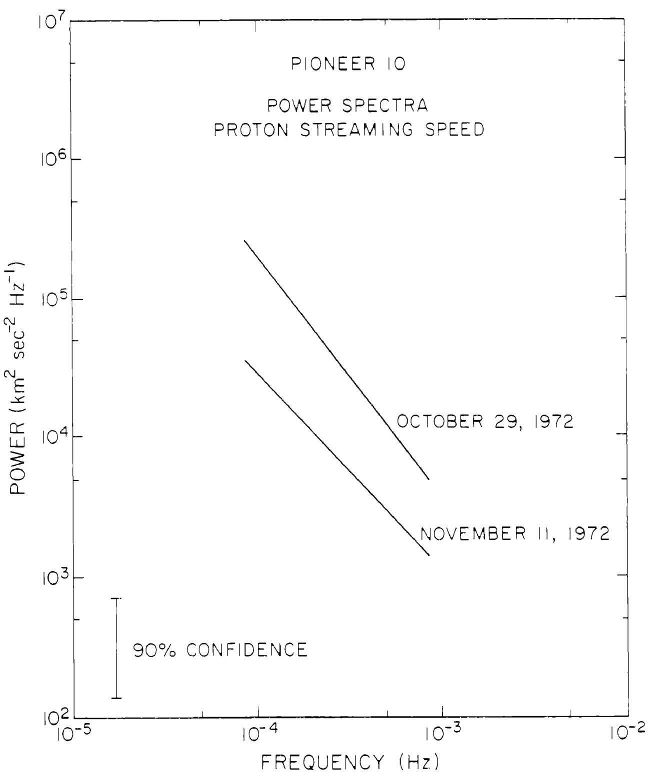

FIG. 3.—Power spectra of the solar wind proton streaming speed for the last two data sets listed in table 1.

The difference in the time intervals and sampling rates upon which the power spectra were based in figures 2 and 3 reflects the particular data mode of the Ames Research Center Plasma Analyzer during the respective phases of the *Pioneer 10* mission. As is the case in figure 2, the slopes of the curves in figure 3 are quite similar, though the levels of the power vary.

### III. DISCUSSION

Each of the curves in figures 2 and 3 indicate that there is a power-law frequency dependence between $\sim 10^{-4}$ and $\sim 10^{-3}$ Hz of the power spectra of the solar wind streaming speed between 1 and 3 a.u. for the time intervals shown in 1972. This power-law frequency dependence is similar to that obtained at 1 a.u. in 1965 and 1966 for both the solar-wind-proton number density and velocity components (Intriligator and Wolfe 1970; Intriligator 1972). If we assume that, as is the case at 1 a.u., the frequency dependence in the $\sim 10^{-4}$ to $\sim 10^{-3}$ Hz frequency range of the power spectra of the solar-wind-proton speed is similar to that of the power spectra of the solar-wind-proton number density, then each of the power spectra in figures 2 and 3 imply that there is significant large-scale turbulence between 1 a.u. and 3 a.u. That is, as with the power spectra of the solar-wind-proton number density (Intriligator and Wolfe 1970), each of the curves in figures 2 and 3 indicate that there must be a peak in power below $\sim 10^{-4}$ Hz. This characteristic frequency implies a characteristic length $L \simeq 10^6$ km $\simeq 0.01$ a.u. $(=\frac{1}{2}V_w/\pi f = 1/q$, where $V_w$ is the solar-wind streaming speed, $f$ the characteristic frequency, and $q$ the wavenumber) which should be the correlation length (the scale beyond which the two-point correlation function falls quickly to zero). Therefore, this preliminary analysis indicates that large-scale turbulence plays a significant role in the solar system at extended heliocentric distances.

Based on the *Pioneer 10* power spectra in figures 2 and 3 and on the total rms fluctuations listed in table 1, it is tempting to infer a general tendency for the level of power to decrease with increasing heliocentric distance; however, at present a definite statement cannot be made due to the problem of sorting out temporal and spatial variations. The 1972 August 7 data presented above are an excellent example of a temporal variation. The temporal variations in the level of power at 1 a.u. are well documented (Intriligator and Wolfe 1970; Intriligator 1972; Intriligator 1975) and have been attributed to the lower frequency power associated with the high-speed stream structure. Analyses of additional power spectra at these extended heliocentric distances, and preferably a comparison of simultaneous power spectra at two different heliocentric locations, are needed before we can ascertain if there are significant spatial variations in the level of power.

The power spectra presented above qualitatively provide information concerning the cosmic-ray diffusion tensor between 1.6 and 3 a.u., which should contribute to our understanding of the surprisingly small radial gradient in the cosmic-ray intensity measured by the *Pioneer 10* experimenters (Van Allen 1972; McKibben *et al.* 1973; Simpson 1974; Teegarden *et al.* 1973; McDonald 1974). The *Pioneer 10* cosmic-ray observations span the energy and spatial regions where modulation effects were thought to be the most important and where gradients were expected to be the largest, yet these observations indicate that the gradient in cosmic-ray intensity between 1 and 5 a.u. in 1972 and 1973 is on the order of only a few percent. The curves in figures 2 and 3 indicate that both the slope and the variations in the levels of power of the power spectra of the solar-wind-proton streaming speed between 1 a.u. and 3 a.u. in 1972 are similar to that observed previously in this frequency range at $\sim 1$ a.u. The power spectra of the solar-wind-proton streaming speed and the power spectra of the interplanetary magnetic field are similar at 1 a.u. (Coleman 1966, 1968; Jokipii and Coleman 1968; Intriligator and Wolfe 1970; Jokipii 1973). Therefore, the power spectra in figures 2 and 3 most likely imply a power-law slope and similar variations in the power levels of the magnetic field power spectra between 1 and 3 a.u. in 1972. Since the diffusion tensor describing the motion of cosmic rays in the solar system can be estimated from the power spectrum of the interplanetary magnetic field (Jokipii and Coleman 1968; Mathews *et al.* 1971; Jokipii 1973, Völk 1974), the shape and levels of power of the power spectra presented above qualitatively provide information concerning the cosmic-ray diffusion tensor at extended heliocentric distances. One should also note that based on several hundred daily samples of the solar wind speed obtained at *Pioneer 10* and *Pioneer 11*, Collard and Wolfe (1974) have reported that there does not appear to be any significant variation in the average value of the solar wind speed between 1 and 5 a.u. (although they do find that the deviations to higher and lower speeds are less at a greater radial distance from the Sun). This provides information on an additional quantity that affects the diffusion tensor.

Alfvén (1954) suggested that the asteroids may have been produced by condensation of interplanetary matter rather than by the fragmentation of a planet. Alfvén and Arrhenius (1970) discuss the present state of the asteroid belt in terms of this accretion model. They discuss jet streams in interplanetary space with a constant injection of plasma during a given time resulting in the production of grains and ultimately the formation of a planet. The in situ observations in the asteroid belt of the power spectra of the solar-wind-proton streaming speed presented above in figures 2 and 3 imply the existence of large scale ($L \gtrsim 0.01$ a.u.) plasma turbulence in the asteroid belt. This large-scale turbulence may affect the rate of accretion and the formation of grains.

## IV. SUMMARY

Jokipii (1973) has reviewed the studies of broad-band turbulence in the solar wind as an example of astrophysical plasma turbulence. He discusses the role of turbulence in the solar system and summarizes some of the theoretical studies on the evolution of various types of fluctuations with heliocentric radius.

Previously, direct observations of the solar wind have indicated the importance of fluctuations and turbulence in the interplanetary plasma. These observations, however, were obtained in the vicinity of 1 a.u. and in the ecliptic plane. As a result, the spatial variation and evolution of the turbulent fluctuations over large heliocentric distances have not been determined.

The *Pioneer 10* plasma observations are the first in situ solar-wind plasma measurements at large heliocentric distances. In this study we find that in the frequency range of $\sim 10^{-4}$ to $\sim 10^{-3}$ Hz there is no apparent change over large heliocentric distances in the shape of the power spectrum associated with fluctuations in the solar-wind streaming speed. That is, there is a power-law frequency dependence in the $\sim 10^{-4}$ Hz to $\sim 10^{-3}$ Hz frequency range. As at 1 a.u., there are wide temporal variations in the levels of power at extended heliocentric distances, and additional studies are needed before it can be ascertained if there are significant spatial variations in the levels of power. The constancy of the power-law slope in this frequency range implies that large-scale plasma turbulence plays an important role in the solar system out to heliocentric distances of at least 3 a.u. This result also tends to minimize within 3 a.u. the significance of the effects on the scale-size of plasma turbulence of various magnetohydrodynamic instabilities and other processes, including the possible effects of the influx of interstellar hydrogen (Jokipii 1973). The power spectra presented above also provide information concerning the cosmic-ray diffusion tensor at large heliocentric distances. It is anticipated that further analyses of both the spatial and temporal fluctuations in the solar wind plasma at large heliocentric distances will substantially contribute to our understanding of the solar system and astrophysical plasmas.

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