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PRELIMINARY POWER SPECTRA OF THE INTERPLANETARY PLASMA

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ABSTRACT

Spacecraft observations of the solar-wind plasma have been used to estimate power spectra of the denisty of solar-wind protons. An average frequency dependence of $f^{-1.3}$ in the frequency range 10^{-4} to 10^{-3} Hz and a plasma-density correlation length of 10^6 km or more for the structure of turbulence are implied. Both estimates are consistent with results from direct observations of the interplanetary magnetic field and the solar-wind speed and also with data on interplanetary scintillations.

I. INTRODUCTION

This Letter reports preliminary results of the first direct observations of power spectra of the density of the interplanetary plasma, in which a vector-velocity plasma distribution function was used. The preliminary results obtained are consistent with the spectrum reported by Schubert and Coleman (1968), who used Mariner II data from 1962. Their results are in the frequency range $\sim 10^{-6}$ to $\sim 10^{-4}$ Hz and are based on the assumption that the solar-wind flow is radial (they use a speed distribution function). Our initial experimental results imply that the structure of fluctuations in the density of the solar wind is similar to that of the magnetic field and the speed of the solar wind, in agreement with the recent results of Jokipii and Hollweg (1970). They showed that the observed interplanetary scintillation of radio sources is consistent with a plasma-density correlation length of 10^6 km or more independent of the detailed form of the power spectrum at high frequencies. By contrast, earlier analyses (Dennison and Hewish 1967; Cohen *et al.* 1967; Hewish and Symonds 1969) based on scintillations of radio sources inferred a dominant scale (which is often taken to be the correlation length) of 100–200 km. For determining length scales associated with plasma fluctuations, the data on interplanetary scintillations (based on measurements of electron density) are comparable to data on solar-wind protons since the scale of fluctuations is so much larger than the Debye length ($\sim 10^{-2}$ km). Direct observations of the correlation length of the interplanetary magnetic field (Coleman 1966; Jokipii and Coleman 1968) give 10^6 km for the scale size of the magnetic-field fluctuations, and direct measurements of the radial velocity of the solar wind (Coleman 1968) imply a consistent length scale for the speed fluctuations.

II. OBSERVATIONS

For this preliminary analysis power spectra were calculated for nine intervals of Pioneer 6 data on solar-wind protons obtained in 1965 December and 1966 January, with the Ames Research Center (A.R.C.) solar-wind plasma probe. Pioneer 6 (launched 1965 December 16) is an interplanetary space probe in a heliocentric orbit with a radius of ~ 1 a.u. The A.R.C. plasma probe on Pioneer 6 is a multicollector quadrispherical electrostatic analyzer (Wolfe, Silva, and Meyers 1966) covering the range in energy per unit charge (E/Q) from 200 to 10000 V in sixteen logarithmic steps for positive ions. The observations were analyzed by using the calibrated instrument transmission function and a least-squares iteration technique to fit the flight data to an isotropic Maxwellian distribution. In selecting the data the only criterion used was that each of the intervals be of equal length (100 possible data points, i.e., ~half a day) and that the number of data gaps during the interval be ~20 percent or less. These data gaps are of two types. The first are time intervals in which there was no ground tracking. The second are intervals in which data were received but for which a preliminary analysis of the data on a time scale of ~7 minutes showed that during the 7-minute intervals the plasma characteristics were changing so that meaningful plasma parameters could not be determined.

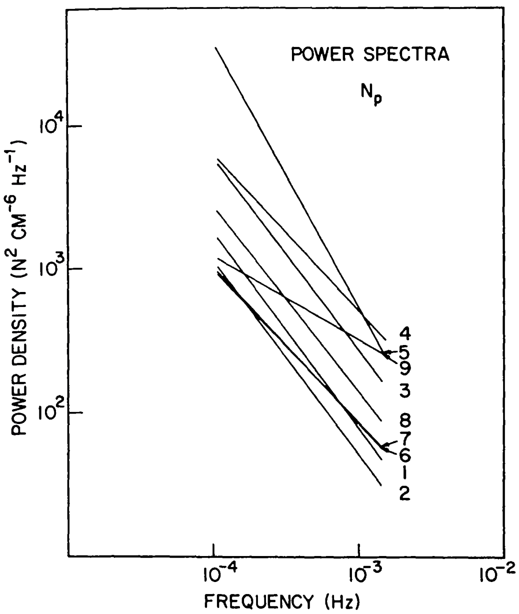

FIG. 1

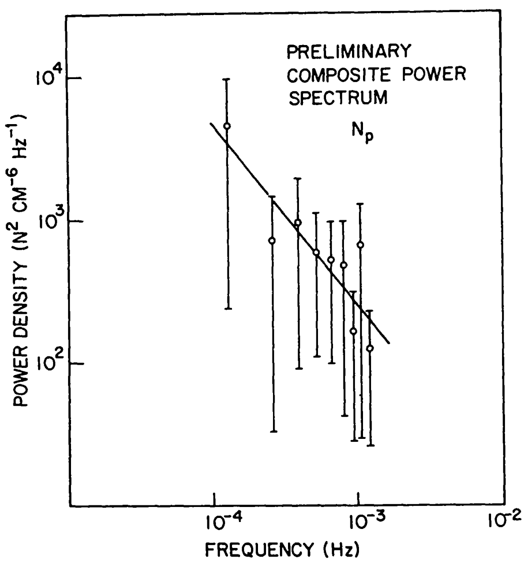

FIG. 2

FIG. 1.—Power spectra of N_p, the number density of protons in the solar wind, for each of the nine data sets listed in Table 1.

FIG. 2.—Preliminary composite power spectrum of N_p for 1965 December and 1966 January. The individual data points represent the average value (Blackman and Tukey 1959; Coleman 1968) of the number-density fluctuations in the solar wind at each of the frequencies shown and are based on the nine data sets in Fig. 1. For a discussion of the precise meaning of the error bars, see text. Curve was obtained by calculating the mean slope from the slopes of the nine data sets (see text).

The power spectra were calculated according to the method of Blackman and Tukey (1959) where the power spectrum $P(f)$ is expressed as the Fourier transform of the correlation function $C(\tau)$, where $C(\tau) = \langle \delta X(t) \delta X(t + \tau) \rangle$.

Figure 1 shows best-fit curves of power as a function of frequency for the number density of solar-wind protons in the frequency range from $\sim 10^{-4}$ to $\sim 10^{-3}$ Hz for each of the nine individual data sets used in this preliminary analysis. The "equivalent" number of degrees of freedom and the slope of each of these curves are listed in Table 1. In general the slopes of the nine curves are quite similar, whereas the levels of power differ considerably. These variations probably reflect the lower-frequency power associated with the stream structure of the solar wind (e.g., typical solar-wind sectors can be ~3–7 days wide so that a 2-day separation between data sets represents different locations within the stream structure). This illustrates the preliminary nature of this analysis and the need for future studies involving more data on the solar wind.

It also illustrates that there are real changes in power level in the frequency range 10^{-2} to 10^{-5} Hz (as deduced from magnetometer data) over periods of several days and that this variation may be significant in many uses of the observations. It should not be suppressed by averaging over long periods unless the range of fluctuation is also recorded.

Figure 2 shows the preliminary composite power spectrum for the number density of solar-wind protons for 1965 December and 1966 January in the frequency range from $\sim 10^{-4}$ to $\sim 10^{-3}$ Hz ($f = \frac{1}{2}V_w q/\pi$, where V_w is the solar-wind speed and q the wavenumber). The individual data points represent the average value (obtained from the procedures of Blackman and Tukey 1959 and Coleman 1968) of the fluctuations in number density in the solar wind at each of the frequencies shown and are based on the nine individual data sets in Figure 1. The large error bars associated with each data point represent the limits within which 68 percent of the data will lie for a χ^2 distribution when the degrees of freedom are determined (Blackman and Tukey 1959; Coleman

TABLE 1

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

Data Set (1)	Date (2)	Equivalent No. of Degrees of Freedom (3)	Slope (4)	Average Number Density of Protons (cm^{-3}) (5)	Average Streaming Velocity ($km\ sec^{-1}$) (6)
1	1965 December 21	15.6	−1.4	6.7	340
2	1965 December 22–23	12.9	−1.3	4.3	421
3	1965 December 24–25	17.6	−1.3	7.3	435
4	1966 January 3–4	10.2	−1.1	6.5	378
5	1966 January 6–7	10.9	−1.8	10.7	337
6	1966 January 8–9	9.6	−1.1	6.3	456
7	1966 January 10–11	11.6	−1.1	3.8	409
8	1966 January 12	11.6	−1.3	7.1	345
9	1966 January 12–13	10.2	−0.6	10.0	335

NOTE.—Number of the data set in column (1) refers to number of the corresponding curve plotted in Fig. 1. Column (2) is the date the observations were made by the Ames Research Center solar-wind plasma probe on Pioneer 6. The "equivalent" number of degrees of freedom is listed in column (3) 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 for each of the individual data sets shown in Fig. 1. Columns (5) and (6) list the average number density of protons in the solar wind and the average bulk velocity, respectively.

1968) by taking the data to be continuous from 1965 December 21 to 1966 January 14. This is clearly an overestimate of the errors associated with the average points defined by only the nine individual data sets (i.e., nine half-day intervals rather than roughly twenty-three days). In addition, as discussed above, the slopes of the nine data sets in Figure 1 are quite similar, but the levels of power vary widely. This variation in the level of power at a given frequency is also reflected in these error bars.

The curve in Figure 2 of power density as a function of frequency was obtained by naïvely calculating the mean slope from the slopes of the nine individual data sets. This gives a slope of -1.3 ± 0.1 for the curve in the frequency range shown. Note the small error (± 0.1) associated with this slope. Based on these data, the range of variations in slope that would be expected for any *one* measurement is -1.3 ± 0.3.

The preliminary composite power spectrum shown in Figure 2 represents the average property of the density fluctuations in the solar wind in this frequency range. The $f^{-1.3}$ dependence of this curve implies that the structure of fluctuations in this frequency interval for the number density of solar-wind protons is similar to that of the magnetic field and the speed of the solar wind (Coleman 1966; Jokipii and Coleman 1968; Coleman 1968). Obviously there must be a peak in power below 10^{-4} Hz. This characteristic frequency determines a characteristic length, $L \simeq 10^6$ km ($=\frac{1}{2}V_w/\pi f = 1/q$) which should be the correlation length (the scale beyond which the two-point correlation function falls quickly to zero) of the density fluctuations in solar-wind protons in the absence of very large peaks in power at higher frequencies.

III. SUMMARY

The observation of turbulence in the solar wind is of considerable astrophysical significance. The preliminary composite power spectrum for the density of protons in the solar wind presented above indicates that the structure of proton-density fluctuations is comparable to that previously reported for the interplanetary magnetic field and the solar-wind speed. The preliminary data presented in Figure 2 show a frequency dependence of $f^{-1.3}$ and imply a plasma-density correlation length $L > 10^6$ km (.01 a.u.). These data and the data on the interplanetary magnetic field imply large-scale turbulence in the solar wind. It is anticipated that additional data on plasma fluctuations in the solar wind at these frequencies and other frequencies, as well as at various times throughout the solar cycle, will substantially add to our understanding of the role of turbulence and its astrophysical effects.

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