

# STATISTICAL PROPERTIES OF MHD FLUCTUATIONS ASSOCIATED WITH HIGH-SPEED STREAMS FROM HELIOS-2 OBSERVATIONS

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**Abstract.** A variance analysis of Helios-2 magnetic data has been used to derive several statistical properties of MHD fluctuations associated with the trailing edge of a given stream observed in different solar rotations. Such properties are derived both as a function of distance from the Sun and as a function of the frequency range included in the sample. The most noticeable result is that the radial gradients of various parameters, such as anisotropy and normalized power of the fluctuations, depend from frequency range. In particular the variation with distance of the normalized power does not correspond, for periods  $\leq 1$  hr, to what is expected from WKB propagation effects.

## 1. Introduction

Investigations of MHD fluctuations in the solar wind started with the early work of Coleman (1966, 1967) and Unti and Neugebauer (1968). Since then, the work of Belcher and Davis (1971), followed by numerous others (Burlaga and Turner, 1976; Denskat and Burlaga, 1977; Bavassano *et al.*, 1978), pointed out that fluctuations of Alfvénic type are mostly found in association with the trailing edges of high-speed streams. These observations have in turn stimulated much theoretical work on the waves, their propagation in the nonhomogeneous and expanding solar wind and their possible role in heating solar wind ions (for reviews of these works see Hollweg, 1978; and Barnes, 1979).

The fluctuations exhibit a power spectrum extending over many frequency decades (Coleman, 1968) so that it is natural to describe the medium as a turbulent medium rather than trying to compare the data with the picture of single Alfvén waves. A recent critical analysis of the observations in terms of the equations of incompressible MHD turbulence (Dobrowolny *et al.*, 1980a) has shown that the presently known statistical properties of Alfvénic fluctuations can be naturally accounted for in such a framework. It indeed appears that the trailing edges of high speed streams (because of the high degree of incompressibility of the observed fluctuations) can be ideal regions for studying fundamental properties of fully developed incompressible MHD turbulence, a subject which, because of the difficulty of laboratory experiments, is not as developed as that of hydrodynamic turbulence. Some indications drawn from present solar wind observations, as to the nonlinear state of MHD turbulence, have in fact stimulated recent theoretical developments on the subject (Dobrowolny *et al.*, 1980b; Mangeney *et al.*, 1982).

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It is from the above point of view that we found it important to take up again a systematic investigation of statistical properties of incompressible fluctuations (eigenvalues and eigenvectors of the variance matrix, variances of various fluctuating components) associated with the trailing edges of the high-speed streams.

What we propose to discuss, using Helios-2 observations, are variations of statistical properties of the fluctuations with frequency (at a given distance from the Sun) and with distance (in a given frequency range).

Variations with frequency are already contained in the work of Belcher and Davis (1971), who used different time intervals as their statistical basis. However, both in this work and in the others quoted previously, the statistical sample used embraces in general regions of the solar wind with different characteristics and which are therefore likely not to be homogeneous in their fluctuation content.

On the contrary, in the present work, our data refer to the trailing edge of a given stream taken at different distances from the Sun. Therefore our statistical sample is quite homogeneous, in comparison with those of other works, as we are focusing actually on the same turbulent region convected in time at different distances from the Sun. Variations of properties of Alfvénic turbulence with distance, for the range of heliocentric distances covered by the Helios spacecraft, have been considered by Denskat *et al.* (1981) and Denskat and Neubauer (1982). The most recent of these works concentrates on features of the wave power spectrum, pointing out some quite interesting results. These works, again, embrace large periods of observations and do not follow our idea of having a sample as homogeneous as possible.

The statistical properties we will be discussing in this paper are: ratios of eigenvalues, denoting anisotropy of the fluctuations; minimum variance direction, total power and compressibility of the fluctuations.

## 2. Magnetic Field Data Analysis

For our study on interplanetary magnetic field fluctuations we have used the magnetic data of Helios-2. This spacecraft, launched on 15 January, 1976, has been injected in a solar orbit having an aphelion of 0.98 AU and a perihelion of 0.29 AU, with an orbital period of about six months. A description of the instrumentation and data reduction is given by Searce *et al.* (1975), Bavassano (1976), Villante and Mariani (1977).

During the primary mission of Helios-2 (January to April, 1976) we have selected, by inspection of hourly averages of the solar wind data of the Max-Planck plasma experiment on Helios-2 as distributed to Helios investigators (see also Schwenn *et al.*, 1977), a high-velocity stream which is observed by the spacecraft during three successive solar rotations at different distances from the Sun. The three periods of the stream observation begin on days 48, (17 February), 74 (14 March), and 103 (12 April) of 1976, at heliocentric distances of about 0.89, 0.68, and 0.31 AU, respectively. Figure 1 gives the ecliptic projection of the spacecraft trajectory from day 20 to day 120, 1976. The solar wind velocity profile is only slightly changing between the first two periods considered, whereas more pronounced differences are present for the third period.

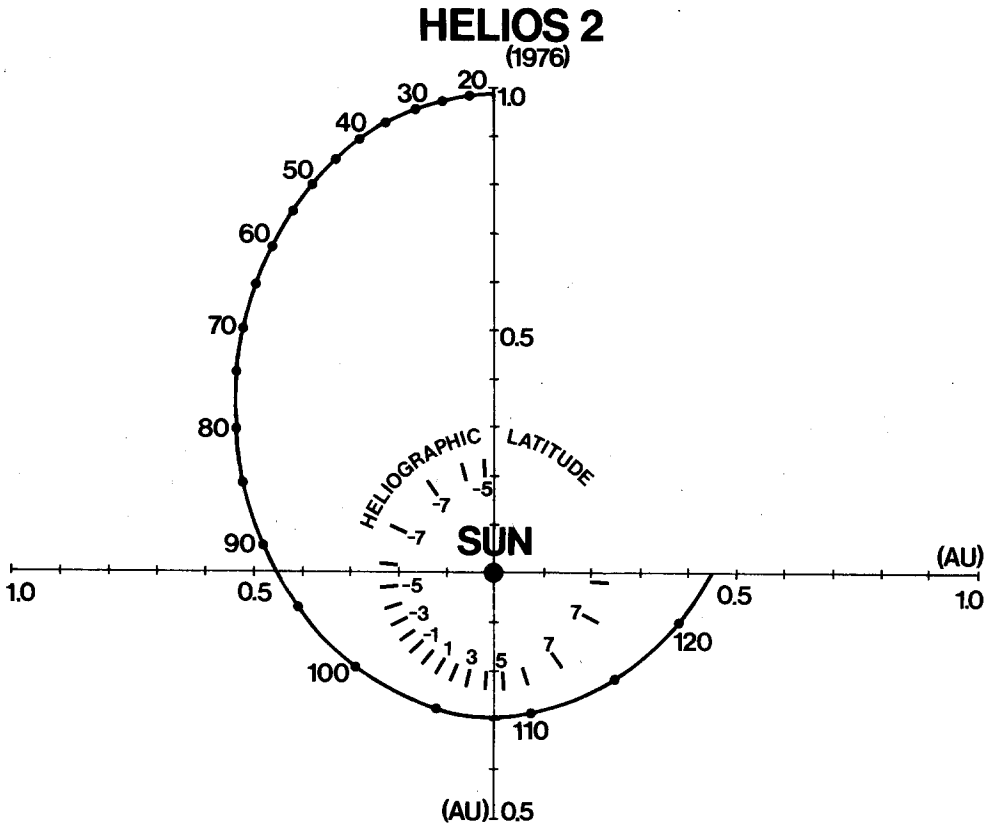


Fig. 1. Projection on the ecliptic plane of the orbit of Helios-2 for the first four months of 1976.

For this stream we have performed a systematic study of the properties of the variance matrix of the magnetic field using 6 s average data.

In order to search for a dependence of the properties of the fluctuations from the frequency range, the variance matrix has been evaluated over time intervals of different duration.

More precisely, we have chosen as time basis the following five values: 168 s, 8 min, 22.5 min, 1 hr, 3 hr. We recall that Belcher and Davis (1971) give results referring to time bases of 168.75 s, 22.5 min, and 3 hr, so that some comparison with them becomes possible (although their statistical sample is not as homogeneous as ours). When the time basis increases we gain informations about the fluctuations at lower frequencies but, due to the fact that in all cases we start from 6 s data, the contribution of higher frequencies remains. Since the power spectrum of the magnetic fluctuations decreases rapidly with increasing frequency (Coleman, 1968), we expect however that the lower frequencies included dominate in any given time basis.

A comparison between the results obtained during the three encounters of the spacecraft with the stream at different distances from the Sun allows an investigation of the radial dependence of the variance matrix characteristics (assuming the turbulence to be

in a stationary state and that variations with heliographic latitude are absent, or not important).

The high frequency limit of the investigated frequency band depends on the time resolution of the data. Using 6 s averages, we are analyzing only frequencies below  $\sim 8 \times 10^{-2}$  Hz in the satellite frame of reference. In the solar wind frame of reference the proton gyrofrequency corresponding to the observed field intensities (see Table I)

TABLE I  
Periods used in the analysis

Time interval	Heliocentric distance (AU)	Heliog. long. interval	Heliog. latitude	Magnetic field intensity (nT)	Proton gyrofrequency (Hz)
50 00:00– 51 22:30	0.87	25.5°	–6.6°	6.8	0.10
76 00:00– 78 00:00	0.65	25.2°	–7.2°	10.5	0.16
105 00:00–108 21:00	0.29	25.1°	3.5°	41.7	0.64

varies from  $\sim 0.10$  to  $\sim 0.64$  Hz. Taking into account that the solar wind flow is highly superalfvénic, the Doppler effect causes a strong shift toward higher frequencies when the fluctuations are observed in the satellite frame (except for waves propagating nearly perpendicular to the solar wind streaming direction). In conclusion we can say that we are observing fluctuations having a frequency in general well below the proton gyrofrequency.

In a first phase of our investigation we have determined the variance matrix characteristics for extended periods of time, including all the stream structure from the initial rise in solar wind speed to the end of the trailing edge. From this extended analysis we have then selected, for each stream observation, one period for which the Alfvénic character of the fluctuations was more evident. Having used only magnetic data, the criterion of choice was based on a comparison of our results with those obtained from previous investigations (see references in Section 1) about magnetic field variability and properties of the variance matrix in regions with Alfvénic fluctuations. Consistently with the known property that incompressible fluctuations of Alfvénic type are mostly associated with the stream trailing edges, our selected periods were all in the initial part of the trailing edge of the chosen stream. To have homogeneous sets of data the duration of these periods was furthermore chosen so as to account for the different rotational velocity of the Sun as seen from Helios at the different times of stream encounters. In other words our analysis refers to periods of different duration, ranging from about two days to little less than four days, in such a way that the angular extent in heliographic longitude seen from Helios during each period is approximately the same. (We add that no substantial differences were obtained by using the same duration, e.g., two days, at the different distances.) In Table I we give the selected periods and the corresponding heliocentric distance, heliographic longitude interval and heliographic latitude.

Finally, note that in our variance matrix computation no attempt has been made to separate dynamic from static (purely convected) structures. However, a recent study on

the power spectra of the fluctuations using the same sample of data (Bavassano *et al.*, 1982) has indicated that throughout the frequency range of interest the spectral properties are typical of an MHD spectrum.

**3. Variations with Distance of Statistical Properties of MHD Fluctuations**

For the periods of Table I we have calculated eigenvalues ( $\lambda_1, \lambda_2, \lambda_3$ ) and eigenvectors of the variance matrix. If we define  $\lambda_1 \geq \lambda_2 \geq \lambda_3$ , the eigenvector associated with  $\lambda_3$  defines the minimum variance direction. This is well defined when  $\lambda_3 \ll (\lambda_2, \lambda_1)$  and then the ratio  $\lambda_2/\lambda_1 \lesssim 1$  denotes the degree of anisotropy of the magnetic fluctuations (in the plane perpendicular to the minimum variance direction). The angle between minimum variance direction and average magnetic field will be denoted by  $\vartheta$ .

Figure 2 gives the histograms of the ratios  $\lambda_2/\lambda_1, \lambda_3/\lambda_1$  and the angle  $\vartheta$  obtained for the three periods of observation of the stream listed in Table I and referring to a time basis of 22.5 min. The range of  $\vartheta$  has been divided in equal intervals of  $\cos \vartheta$  to account for solid angle effects. Histograms aligned on the same column refer to the same quantities at the three different heliocentric distances.

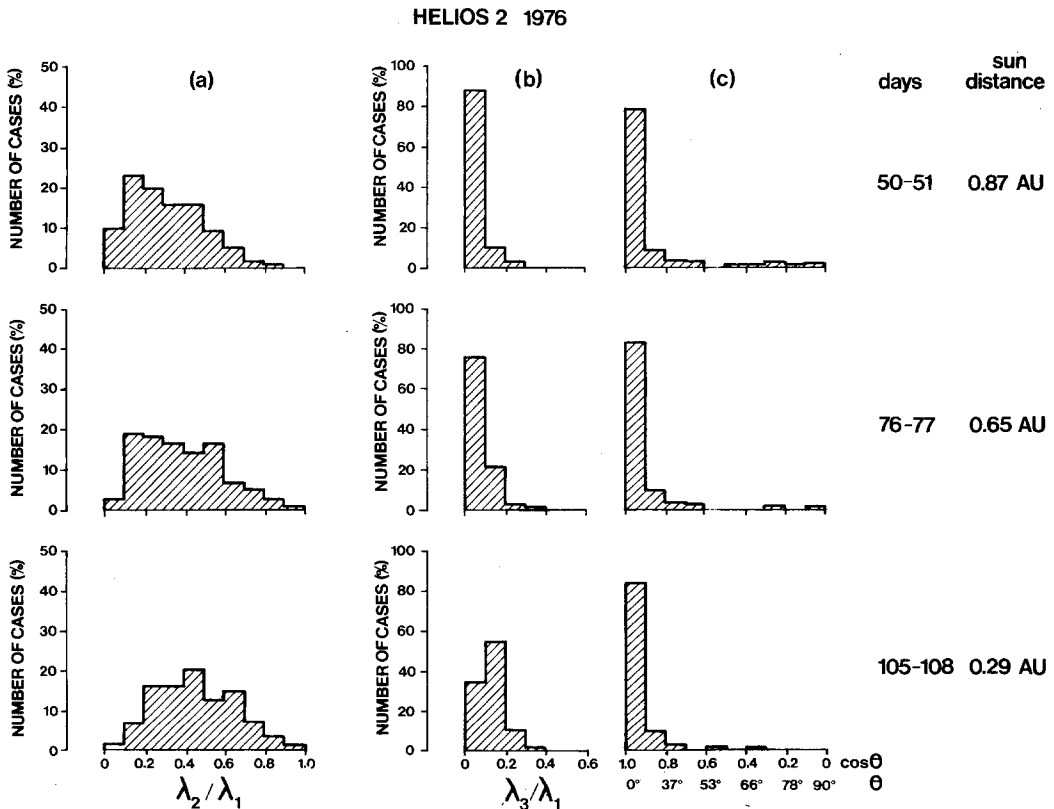


Fig. 2. Statistical distributions for the three stream encounters (see periods of Table I) of: (a) the ratio of the eigenvalues  $\lambda_2/\lambda_1$ ; (b) the ratio  $\lambda_3/\lambda_1$ ; (c) the angle  $\vartheta$  between the minimum variance direction and the average field vector. The analysis has been performed on a time basis of 22.5 min.

## HELIOS 2 1976

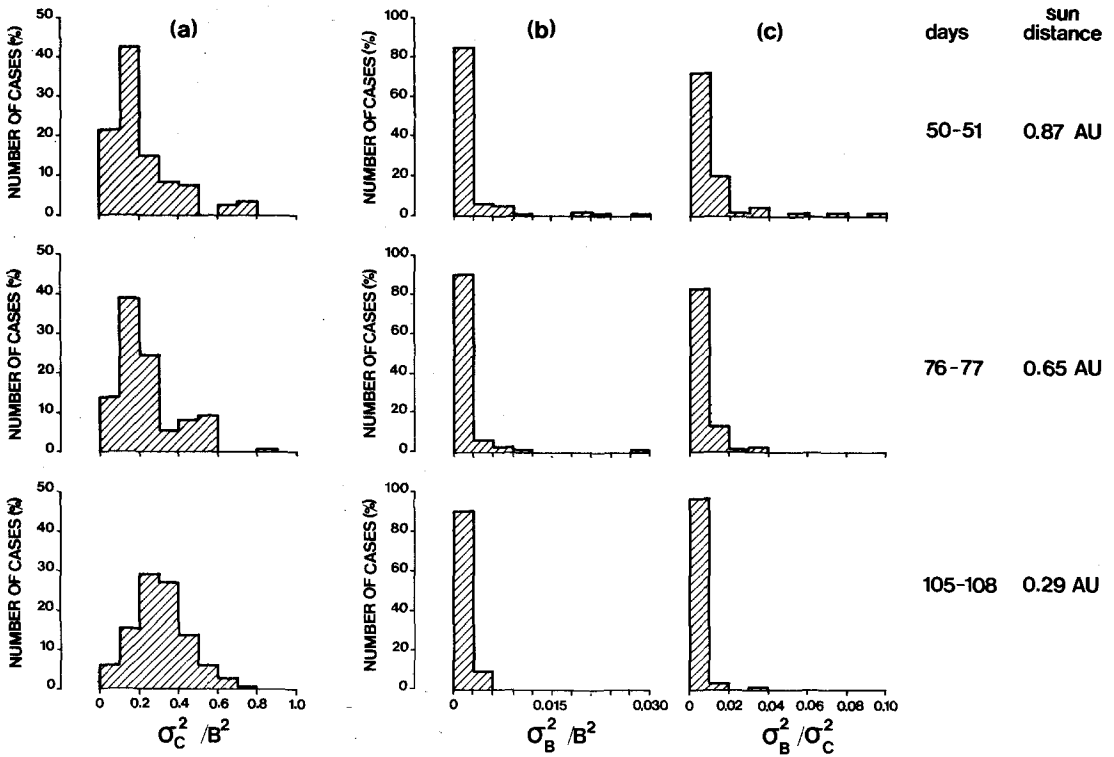


Fig. 3. Statistical distributions for the three stream encounters (see periods of Table I) of: (a) the ratio  $\sigma_C^2/B^2$ ,  $\sigma_C^2$  being the trace of the variance matrix and  $B$  the field magnitude; (b) the ratio  $\sigma_B^2/B^2$ ,  $\sigma_B^2$  being the variance in the field magnitude; (c) the ratio  $\sigma_B^2/\sigma_C^2$ . The analysis has been performed on a time basis of 22.5 min.

In Figure 3 we have plotted, in a similar arrangement, the distribution of the quantities  $\sigma_C^2/B^2$ ,  $\sigma_B^2/B^2$ , and  $\sigma_B^2/\sigma_C^2$ , where  $\sigma_C^2$  is the trace of the variance matrix (and hence represents the total power in magnetic fluctuations),  $\sigma_B^2$  is the variance in field magnitude (and hence gives a measure of the degree of compressibility of the fluctuations) and  $B$  is the average field magnitude.

By looking at the upper distributions of Figures 2 and 3, referring to a distance of 0.87 AU from the Sun, we remark, first of all, that the average values of the parameters which we infer are close to those obtained, for near-Earth observations, in most of the investigations recalled in Section 1. It is  $\lambda_3/\lambda_1 \ll 1$  ( $\lambda_3/\lambda_1 \lesssim 0.1$ ) so that the minimum variance direction is very well defined. This is almost aligned with the average magnetic field, which is a consequence of the small amount of power in components of the fluctuations parallel to  $B$  (Dobrowolny *et al.*, 1980a). Furthermore, the variations in field magnitude are very small with  $\sigma_B^2/B^2 < 3 \times 10^{-3}$  in  $\sim 90\%$  of the 22.5 min intervals considered.

Comparing now histograms along each column in Figures 2 and 3, we see that there are changes in the distributions for some of the parameters calculated. In particular, for

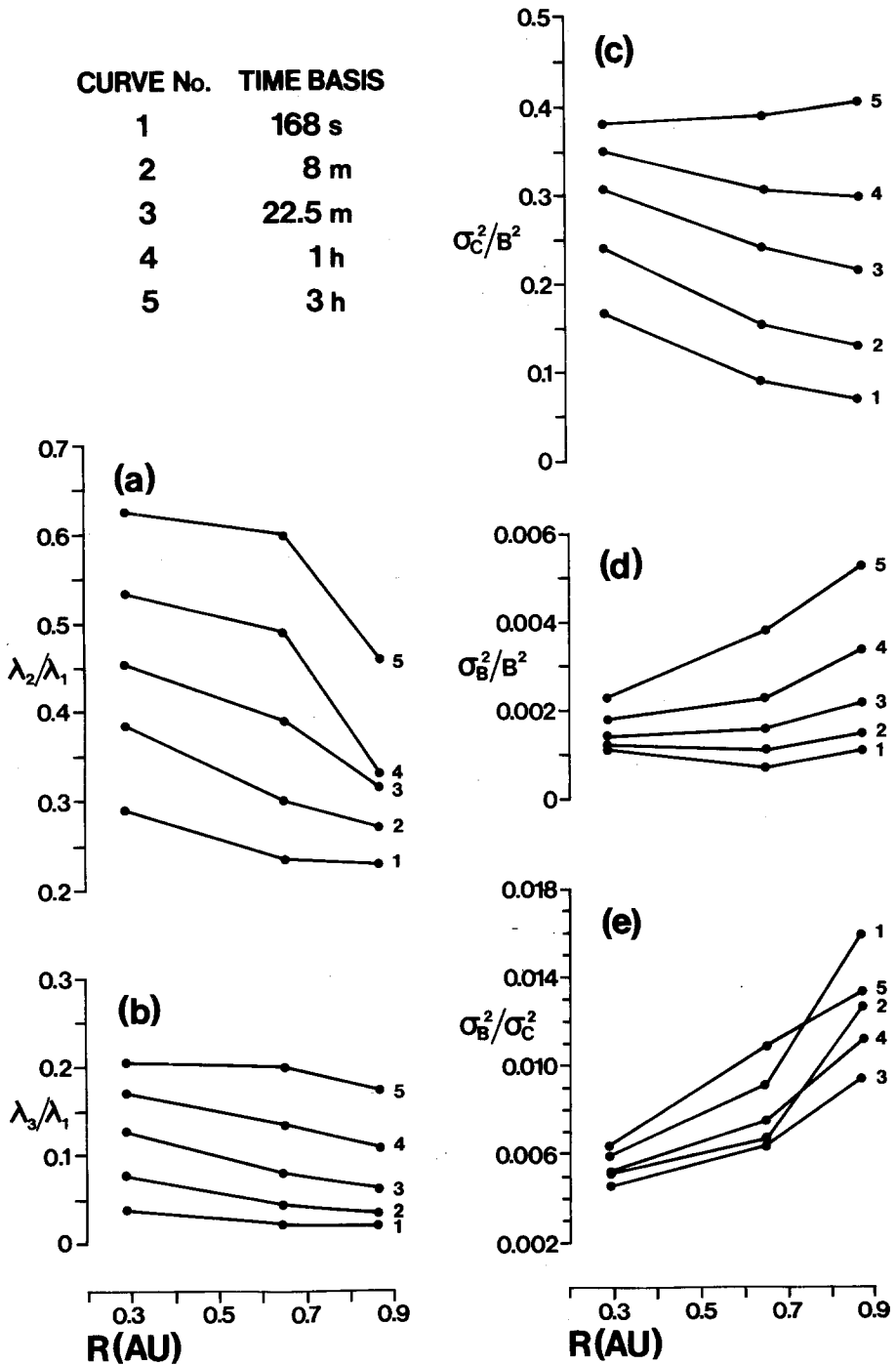


Fig. 4. Variation with the heliocentric distance of the average values, for each stream encounter, of  $\lambda_2/\lambda_1$  (a),  $\lambda_3/\lambda_1$  (b),  $\sigma_c^2/B^2$  (c),  $\sigma_B^2/B^2$  (d),  $\sigma_B^2/\sigma_c^2$  (e). The five curves in each panel refer to the different time bases used in the statistics.

the parameters  $\lambda_2/\lambda_1$ ,  $\lambda_3/\lambda_1$  and  $\sigma_C^2/B^2$  higher values become more frequent when the distance from the Sun decreases. This is better seen in Figure 4 where we have plotted, for each of the parameters of Figures 2 and 3, the average value at each stream encounter. The various curves refer to the five different time bases used in the statistics.

There is a clearly increasing trend for the ratio  $\lambda_2/\lambda_1$  upon approaching the Sun for all time basis. The same trend applies for  $\sigma_C^2/B^2$ , except for curve 5 referring to the lowest frequency fluctuations. The inverse trend applies for  $\sigma_B^2/B^2$  which increases further away from the Sun. On the other hand, variations of  $\lambda_3/\lambda_1$  with distance are much less noticeable. If significant, these are in the sense of  $\lambda_3/\lambda_1$  slightly increasing upon approaching the Sun. This would imply, as the minimum variance direction is almost aligned with  $B$ , that the ratio between parallel and perpendicular fluctuations (with respect to the average field direction) has higher values upon approaching the Sun (see also Bavassano *et al.*, 1981).

The significance of the observed variations can be evaluated from Table II where we give, for each point of Figure 4, its value and the corresponding mean deviation. It can be seen that the variations are generally within deviations, however their degree of coherence is such that we must consider them as significant. This view is also supported by the histograms of Figures 2 and 3, showing that shifts in the distributions are really present.

It therefore seems possible to conclude that: (a) the degree of anisotropy of the fluctuations decreases (increasing  $\lambda_2/\lambda_1$ ) going towards the Sun; (b) the degree of compressibility decreases going towards the Sun; (c) the total power (normalized) in

TABLE II

Mean values and deviations, for each stream encounter, of  $\lambda_2/\lambda_1$ ,  $\lambda_3/\lambda_1$ ,  $\sigma_C^2/B^2$ ,  $\sigma_B^2/B^2$  and  $\sigma_B^2/\sigma_C^2$ .  
 $T_b$  indicates the time basis used in the variance matrix computations

$T_b$		168 s	8 min	22.5 min	1 hr	3 hr
		(1)	(2)	(3)	(4)	(5)
$\lambda_2/\lambda_1$	0.87	0.230 ± 0.149	0.271 ± 0.163	0.316 ± 0.155	0.327 ± 0.113	0.458 ± 0.166
	0.65	0.234 ± 0.139	0.299 ± 0.152	0.389 ± 0.163	0.489 ± 0.168	0.601 ± 0.101
	0.29	0.288 ± 0.150	0.384 ± 0.158	0.456 ± 0.160	0.533 ± 0.151	0.626 ± 0.135
$\lambda_3/\lambda_1$	0.87	0.022 ± 0.014	0.036 ± 0.023	0.063 ± 0.029	0.110 ± 0.044	0.176 ± 0.061
	0.65	0.023 ± 0.014	0.045 ± 0.025	0.081 ± 0.037	0.136 ± 0.047	0.199 ± 0.055
	0.29	0.038 ± 0.022	0.077 ± 0.037	0.126 ± 0.047	0.168 ± 0.044	0.204 ± 0.040
$\sigma_C^2/B^2$	0.87	0.071 ± 0.062	0.128 ± 0.090	0.214 ± 0.119	0.298 ± 0.111	0.407 ± 0.103
	0.65	0.090 ± 0.071	0.152 ± 0.091	0.239 ± 0.121	0.307 ± 0.091	0.392 ± 0.096
	0.29	0.166 ± 0.102	0.239 ± 0.111	0.307 ± 0.110	0.351 ± 0.099	0.382 ± 0.080
$\sigma_B^2/B^2$	0.87	0.0011 ± 0.0014	0.0015 ± 0.0017	0.0022 ± 0.0022	0.0034 ± 0.0026	0.0053 ± 0.0021
	0.65	0.0007 ± 0.0007	0.0011 ± 0.0011	0.0016 ± 0.0013	0.0023 ± 0.0015	0.0038 ± 0.0021
	0.29	0.0011 ± 0.0011	0.0012 ± 0.0010	0.0014 ± 0.0008	0.0018 ± 0.0008	0.0023 ± 0.0008
$\sigma_B^2/\sigma_C^2$	0.87	0.0161 ± 0.0165	0.0128 ± 0.0125	0.0095 ± 0.0074	0.0112 ± 0.0072	0.0134 ± 0.0051
	0.65	0.0092 ± 0.0084	0.0067 ± 0.0051	0.0064 ± 0.0043	0.0075 ± 0.0046	0.0109 ± 0.0065
	0.29	0.0059 ± 0.0046	0.0051 ± 0.0032	0.0045 ± 0.0021	0.0052 ± 0.0020	0.0064 ± 0.0026



fluctuations increases upon approaching the Sun (at least when the wave number range considered does not include fluctuations of periods above 1 hr).

A further important point, which is apparent from Figure 4 (and did not appear in any previous investigation) is that the radial gradients of the various quantities vary with the frequency range. This will be discussed in Section 5.

It is worth noticing that our results concerning the variation with distance of  $\sigma_C^2/B^2$  and  $\sigma_B^2/B^2$  can be compared with some of the results summarized in Behannon (1978), collecting different satellite data and containing also 1 hr and 3 hr variances. Our behaviour is confirmed for all data reported except for the 3 hr variances of Pioneer 10. These refer however to a quite different range of heliocentric distances than our results.

Finally, as shown in Figure 4, the relative importance of compressible components with respect to the total fluctuations (mostly incompressible) is seen to increase with distance from the Sun. This confirms a trend already remarked in the early work of Coleman (1968) and extends this finding to the range of heliocentric distances covered by the Helios mission.

#### 4. Variations with Frequency of Statistical Properties of MHD Fluctuations

From the curves of Figure 4 we can also evaluate, looking at a fixed heliocentric distance, the variations of the various parameters with frequency.

As seen in the figure there are, for each parameter, quite systematic variations with frequency range, for whose significance the comments given in the previous section apply. All the parameters plotted (with the exception of  $\sigma_B^2/\sigma_C^2$ ) increase upon extending the frequency range (towards low frequencies). For  $\sigma_C^2/B^2$  and  $\sigma_B^2/B^2$  this increase is quite obvious. Therefore the significant results we derive are: (a) the degree of anisotropy of the fluctuations decreases more and more when we include lower and lower frequencies; (b) the increase of  $\lambda_3/\lambda_1$  upon increasing the time basis implies that the ratio  $\delta B_{\parallel}/\delta B_{\perp}$  increases when lower frequencies are taken into account ( $\parallel$  and  $\perp$  refer to the average magnetic field direction).

As mentioned already, three different time bases were also taken in the work of Belcher and Davis (1971). As these authors considered in their analysis averages over the entire mission or over solar rotations, the regions of solar wind looked at are likely to have different characteristics with respect to those of our investigation, so that a direct comparison with our results is not strictly correct. Having precised this, we remark however that also Belcher and Davis results are indicative of an increase of the ratios between eigenvalues for lower frequencies, although their excursion is smaller than the one we obtain.

#### 5. Summary and Discussion

Using Helios-2 magnetic data, we have analyzed some statistical properties of MHD fluctuations associated with the trailing edge of a given stream observed in different solar rotations at different distances from the Sun. The homogeneity of the sample of data used

is a point of difference with respect to all previous investigations on properties of Alfvénic turbulence in the solar wind.

Eigenvalues and eigenvectors of the variance matrix, total power in the fluctuations and power in the fluctuations of field magnitude have been derived using 5 different time bases for the statistics. Thus a discussion of these statistical properties both as a function of distance from the Sun and as a function of the frequency range of the included fluctuations has become possible.

The most significant results obtained can be summarized as follows:

- The degree of anisotropy of the fluctuations (in the plane perpendicular to the minimum variance direction) decreases upon going towards the Sun for all frequency ranges considered. At fixed heliocentric distance the higher frequency fluctuations appear to be more anisotropic than the lower frequency components.

- The total (normalized) power in MHD fluctuations increases upon approaching the Sun (for all frequency ranges except when periods above 1 hr are included). As obvious, at fixed heliocentric distance, the total power increases as lower and lower frequencies are included in the sample.

- The degree of compressibility (variance of field magnitude normalized to  $B^2$ ) in the fluctuations generally decreases going towards the Sun.

Although, for clarity of exposition, we have discussed separately the variations with distance (for given frequency range) and, viceversa, the variations with frequency range (at fixed heliocentric distance), an important point we obtain (and clearly seen in Figure 4) is that the variation with distance of the various parameters depends from frequency range.

This is in fact the most significant conclusion resulting from this investigation and not appreciated in previous studies of variation with distance, mostly concerned with wave amplitudes (see Barnes, 1979; Behannon, 1978; Villante, 1980). These frequency variations of the radial gradients cannot be explained by the WKB theory of wave propagation (see Barnes, 1979).

Referring in particular to the normalized wave power  $\sigma_C^2/B^2$ , WKB propagation theory, in the range of heliocentric distances considered, would predict an increase in such power with distance. This is just the opposite of the trend indicated by the curves in Figure 4, with the exception of curve 5 referring to the 3 hr basis. A recent work of Villante (1980), referring to 1 hr variances, concludes that the data are more consistent with  $\sigma_C^2/B^2 = \text{constant}$  than the geometric optics indication.

Besides the disagreement with the geometric optics prediction, the radial gradients of  $\sigma_C^2/B^2$  that we have obtained increase when we restrict the sample to higher frequencies (i.e., decreasing the time basis). However, for curves 1, 2, 3, i.e., for samples including periods roughly below 20 min, the gradients seem to remain the same.

To explain this type of behaviour, it seems necessary to invoke some damping mechanism on the waves. The damping should increase with frequency. This is indeed a feature of all damping mechanisms we can think of, both collisional and collisionless. However, as it is commonly quoted in the literature (see Barnes, 1979), damping mechanisms on Alfvénic waves are quite ineffective.

Variations with frequency of the radial gradient of our parameters could also in principle be due to various non linear effects operating differently in different spectral regions. However, if we remain in the framework of incompressible MHD turbulence and solar origin of the waves, the times of non linear cascade of the modes along the spectrum (Dobrowolny *et al.*, 1980b) are much shorter than the convection time up to our minimum distance of 0.3 AU from the Sun, for the wavelengths we have included in our samples. This implies that the turbulence is there in a state with no (or very small) non linear interactions. Results by Denskat *et al.* (1981) on correlation between velocity and magnetic field fluctuations indicate that indeed the modes are essentially outwardly propagating (and hence without non linear interactions as these require Alfvénic waves in the two directions).

Thus there does not seem to be at the moment a simple explanation of the observational results concerning the variation with frequency of the radial gradients of various parameters and some further theoretical study of the properties of Alfvénic turbulence is necessary.

Finally, the turbulence is not strictly incompressible and compressibility (although remaining small) is relatively more important away from the Sun.

A possibility of having compressible components of the fluctuations is given by the parametric instability of Alfvénic waves. For incoherent Alfvén waves (Cohen and Dewar, 1974), this depends from the index of the wave power spectrum (which should be  $< 1$ ). Recent studies of power spectra in the range of Helios heliocentric distances (Denskat and Neubauer, 1982; Bavassano *et al.*, 1982) indicate indeed a spectral index of the order of 1 at 0.3 AU but only for frequencies below  $\sim 10^{-2}$  Hz. However, the time scales of the parametric process, as discussed by Cohen and Dewar for the expanding solar wind, appear to be quite marginal.

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