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ON THE POLARIZATION STATE OF HYDROMAGNETIC FLUCTUATIONS IN THE SOLAR WIND

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ABSTRACT

From presently available observations one can infer that the Alfvénic turbulence measured in the solar wind, predominantly on trailing edges of high speed streams, is a mixture of modes with two different polarizations, namely, Alfvénic modes and modes which are the incompressible limit of slow magnetosonic waves. Using Helios 2 magnetic data and a variance analysis, we have separated parallel (to the mean field) and perpendicular components of the fluctuations and studied the possible correlation between such components which would be predicted as a consequence of the incompressible character of the turbulence. Correlations between eigenvalues of the variance matrix are also investigated and discussed.

1. INTRODUCTION

In a recent critical analysis of the present observations of almost incompressible Alfvénic fluctuations in the solar wind [Dobrowolny et al., 1980a], several noticeable properties of such fluctuations were pointed out. One of them, obtained by comparing observational results with the equations of incompressible magnetohydrodynamics, is that such fluctuations should be a mixture of modes with two different polarizations, namely, purely Alfvénic modes and modes which are the incompressible limit of slow magnetosonic waves.

Furthermore, by regarding the observed fluctuations as a turbulence (and not as simple waves), a model minimum variance matrix was constructed reproducing some observed statistical properties of the fluctuations under quite general assumptions on the distribution of wave vectors in the turbulence.

In this paper we use extensive sets of Helios 2 magnetic data, exhibiting 'pure' (i.e. almost incompressible) Alfvénic fluctuations in the trailing edges of several streams to study directly the polarization state of such turbulence through correlations between components of the fluctuations parallel and perpendicular to the background magnetic field. We also test same scaling relations between eigenvalues which are predicted by the turbulence model recalled above.

We start recalling in section 2 some main points in the theoretical analysis in [Dobrowolny et al., 1980a] on the nature of Alfvénic fluctuations, which lead to the tests on the data which are later presented.

In section 3 we present some results of the minimum variance analysis of Helios 2 magnetic data, referring to the trailing edges of several high speed streams. Such analysis evidences the presence of

Alfvénic fluctuations with statistical properties similar to those already obtained in various previous investigations [Belcher and Davis, 1971; Burlaga and Turner, 1976].

In section 4 we study the correlation between the component $\delta B_{\parallel}$ of the fluctuations parallel to the average magnetic field and the larger perpendicular component $\delta B_{\perp}$. We recall that, in a previous work [Sari and Valley, 1976] several phase and amplitude correlations between Fourier components of $\delta B_{\parallel}$ and $\delta B_{\perp}$ were presented (in, approximately, the frequency range 10^{-4} - 10^{-2} Hz). In this paper, the correlation is studied on the data themselves (at each instant of time within our resolution) and not between their Fourier components.
In the same section 4 we also investigate the correlation between different eigenvalues of the variance matrix.

Section 5 summarizes and discusses the conclusions of this work.

2. THEORETICAL CONSIDERATIONS ON THE NATURE OF INCOMPRESSIBLE MHD TURBULENCE IN THE SOLAR WIND

The Alfvénic turbulence associated with trailing edges of high speed streams in the solar wind [Coleman, 1968; Belcher and Davis, 1971; Burlaga and Turner, 1976] can, to a good approximation, be regarded as incompressible. This statement follows quite clearly from a comparison between the typical level of such fluctuations, $\delta B_r/|\langle\underline{B}\rangle| \sim 0.3 \div 0.4$, with the estimated level of fluctuations in the magnitude of $\underline{B}$, which is $\delta|\underline{B}|/|\langle\underline{B}\rangle| \sim 0.05 \div 0.06$ [Burlaga and Turner, 1976] and with the recent results on associated density fluctuations [Neugebauer et al., 1978], giving $\delta\rho/\rho \sim \delta|\underline{v}|/V_A$, where V_A is the Alfvénic speed in the average magnetic field $\langle\underline{B}\rangle$.

It has been shown in [Dobrowolny et al., 1980a] that the observed correlations between velocity and magnetic field fluctuations in regions of Alfvénic turbulence imply that such turbulence is in a very remarkable state characterized by <u>the absence of non linear interactions</u>. Physical arguments, based on the structure of the MHD equations, have been further given [Dobrowolny et al., 1980b], indicating that the tendency toward a state without non linear interactions may be a general property of the development of incompressible MHD turbulence and not a peculiar one of the solar wind turbulence.

If non linear interactions are absent, the fluctuations which are present can be expanded (whatever their amplitudes) as a linear Fourier series, i.e.

$$\delta\underline{B}(\underline{r},t) = \frac{8\pi^3}{V} \sum_{\underline{K}} \delta\underline{b}(\underline{K})\, e^{i(\underline{K}\cdot\underline{r} - \omega_{\underline{K}} t)} \qquad (1)$$

with $\omega_{\underline{K}} = \underline{K}\cdot\underline{V}_A$. On the other hand, the equation $\nabla\cdot\delta\underline{B}=0$, which must hold for each Fourier component, indicates that, for each $\underline{K}$, there are two independent polarization for the fluctuations $\delta\underline{b}(\underline{K})$ (with $\delta\underline{b} \perp \underline{K}$), i.e.

$$\begin{aligned}\delta\underline{b}(\underline{K}) &\equiv \delta\underline{b}_1(\underline{K}) + \delta\underline{b}_2(\underline{K}) \equiv \\ &\equiv \delta b_1(\underline{K})\ \hat{e}_1(\underline{K}) + \delta b_2(\underline{K})\ \hat{e}_2(\underline{K})\end{aligned} \tag{2}$$

with the two independent directions $\hat{e}_1$ and $\hat{e}_2$ given by

$$\begin{aligned}\hat{e}_1(\underline{K}) &= \frac{\underline{K} \times \langle\underline{B}\rangle}{|\underline{K} \times \langle\underline{B}\rangle|} \\ \hat{e}_2(\underline{K}) &= \frac{\underline{K}}{|\underline{K}|} \times \hat{e}_1(\underline{K})\end{aligned} \tag{3}$$

Clearly, the component $\delta\underline{b}_1(\underline{K})$ of the fluctuations parallel to $\hat{e}_1$ is entirely perpendicular to $\langle\underline{B}\rangle$ and, hence, in terms of proper modes of the incompressible plasma, is what is called properly an Alfvén wave, whereas the component $\delta\underline{b}_2(\underline{K})$, parallel to $\hat{e}_2$, has also a non zero projection $\delta b_{\parallel}$ parallel to $\langle\underline{B}\rangle$ and can therefore be said the incompressible limit of the slow magnetosonic mode [Ginzburg, 1970].

The existence of a component of fluctuations parallel to $\langle\underline{B}\rangle$ is, on the other hand, clearly indicated by the statistical analyses of the observations [Belcher and Davis, 1971; Chang and Nishida, 1973; Burlaga and Turner, 1976; Bavassano et al., 1978], through the method of minimum variance. Their results show that the minimum eigenvalues (λ_3) of the variance matrix (of eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$), although smaller than the other two ($\lambda_3 \ll (\lambda_1, \lambda_2)$), is however different from zero.

A second consequence of the absence of non linear interactions, if one adds to it the hypothesis of incompressibility (ρ=const), has been shown to be [Dobrowolny et al., 1980a] the constancy of the magnetic field magnitude

$$B^2 = \text{const} \tag{4}$$

Eqs. (2) and (4) imply in turn a precise relation between parallel and perpendicular components of the fluctuations, the power $\delta B_\perp^2$ in perpendicular fluctuations having a parabolic dependence from $\delta B_{/\!/}$. If we make the further hypothesis

$$|\delta B_{/\!/}|/\delta B_\perp < 1 \tag{5}$$

which is consistent with the observational evidence of a minimum eigenvalue (and will be seen to be most often verified on the data), we obtain from (4)

$$\frac{\delta B_{/\!/}}{|\langle \underline{B} \rangle|} = C - \frac{1}{2} \frac{\delta B_\perp^2}{|\langle \underline{B} \rangle|^2} \tag{6}$$

with C a constant given by

$$C \equiv \frac{1}{2} \left[\frac{B^2}{|\langle \underline{B} \rangle|^2} - 1\right] \tag{7}$$

In (6), $\delta B_{/\!/}$ refers obviously to the component at polarization $\hat{e}_2$ of the fluctuations, whereas the $\delta B_\perp^2$ on the right hand side includes both polarizations $\hat{e}_1$ and $\hat{e}_2$.

The presence of two polarizations in the fluctuations, expressed by (2) and (3), and the constancy of magnetic field magnitude (4) have consequences on the properties of the variance matrix characterizing such fluctuations.

In Dobrowolny et al. [1980a] a model calculation of such variance matrix was performed for a turbulence characterized by (2) and (4). For the simplest possible model of turbulence, i.e. a statistically homogeneous and normal turbulence (triple correlations all equal to zero), and using the further hypothesis

$$\delta b_{\parallel}/\delta b_{1} < 1 \qquad (8)$$

the results obtained give the following simple scaling relations between eigenvalues

$$\begin{aligned} \lambda_3 &= \lambda_1^2 \\ \lambda_2 &= \lambda_1 \end{aligned} \qquad (9)$$

the first of which can also be understood, in dimensional terms, from eq. (6), which in fact indicates that the power in parallel fluctuations can be expected to be proportional to the square of the power in perpendicular fluctuations.

3. MAGNETIC FIELD DATA ANALYSIS

The data analysis performed has used the magnetic field measurements of Helios 2. This spacecraft, launched on January 15, 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. During the primary mission of Helios 2 (January to April, 1976) we have selected, by visual inspection of hourly averages of the solar wind data of the Max Plank plasma experiment on Helios 2 (given to us by H. Rosenbauer and R. Schwenn; 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 observations of the stream begin on days 48 (February 17), 74 (March 14), and 103 (April 12) of 1976, at heliocentric distances of about 0.89, 0.68 and 0.31 AU respectively.

In the trailing edge of this stream we have performed, using 6 s averages of the magnetic field vector, a sistematic analysis of the eigenvalues and eigenvectors properties of the variance matrix of the magnetic field evaluated over time intervals of different duration, ranging from about 3 minutes to 3 hours.

In Figure 1 we present distributions of the ratios λ_2/λ_1, λ_3/λ_2, σ_B^2/λ_1, $\lambda_1 \geq \lambda_2 \geq \lambda_3$ being the eigenvalues of the variance matrix and σ_B^2 the variance of the field magnitude. Also shown is the histogram of the angle between minimum variance direction and average magnetic field. These results have been obtained for the two day period 50-51 within the trailing edge of the stream and using 22.5 minutes as a time basis for the statistics.

These results, and others which we do not report here, concerning eigenvalue distributions and distributions of the minimum variance direction over the other streams and with different time basis, give the typical statistical properties already obtained by several authors [Belcher and Davis, 1971; Chang, 1973; Burlaga and Turner, 1976; Bavassano et al., 1978] for almost incompressible Alfvénic turbulence in the solar wind.

A discussion of such statistical properties, in terms of the different frequency ranges for the fluctuations and as a function of distance from the sun, will be the object of a forthcoming paper [Bavassano et al., 1980].

The existence of correlations between parallel and perpendicular components of the fluctuations as well as of possible correlations between eigenvalues has been investigated for those periods, of each trailing edge, for which the Alfvénic characteristics were more evident. To have homogeneous sets of data, the duration of these periods was furthermore chosen so as to account for the rotational velocity of the sun as seen from Helios at the different times of the observations (as a consequence the periods chosen range from about 2 days to little less than 4 days). The periods investigated have been divided in intervals of 22.5 minutes and for each interval the average field has been evaluated, then the fluctuations of the individual measurements (6 s averages) around the mean have been resolved in terms of parallel and perpendicular components with respect to the average field direction. Eigenvalues of the variance matrix have also been computed for each interval.

4. RESULTS

A first aim of the present work is to present experimental evidence of the relation (6) between parallel and perpendicular fluctuations. This evidence does, on the one hand, prove the gross validity of condition (4) of constancy of the magnetic field and, on the other hand, indicate that the incompressible MHD turbulence observed is a mixture of modes with an Alfvénic and a slow magnetosonic wave polarization as indicated in (2) and (3).

To have a first insight about the relation between parallel and perpendicular fluctuations we may examine scatter plots of the variables

$$x = \frac{\delta B_{\perp}^2}{|\langle \underline{B} \rangle|^2} \quad , \qquad y = \frac{\delta B_{/\!/}}{|\langle \underline{B} \rangle|} \quad . \tag{10}$$

Some examples of them, for different intervals of 22.5 minutes, are given in Figure 2. If relation (6) is verified we should obtain points distributed along a straight line with a slope of -0.5. As it is seen the experimental data tend indeed to show such behaviour. The values of the correlation coefficient, given in the figure, strongly indicate the existence of a linear relation between x and y with an angular coefficient close to the value expected from (6).

The examples in Figure 2 are not particular ones but represent instead a quite typical situation. This is proved from Figure 3 where we give frequency distributions for the correlation coefficient R and for the quantities C_1 and C_o, which are the angular coefficient of the best fit straight line and its intercept with the y axis, respectively. The quantities R, C_1 and C_o are evaluated on the basis of 22.5

minutes intervals. For each parameter we show three different histograms, corresponding to the three selected periods of observation of the high velocity stream at different heliocentric distances. From the left and central panels it appears clearly that in the great majority of cases: a) the correlation coefficient is close to -1, indicating in fact a strong consistent tendency to a linear relation between x and y; b) the slope of the best fit straight line has a broad peak around -0.5, which is the value expected. These two properties remain practically unchanged when the distance from the sun varies. On the contrary the histograms in the right panel reveal a general increase in the values of $C_{\odot}$ approaching the sun. On account of (7), this can be taken as an indication of an increasing relative amplitude of the fluctuations when the sun distance decreases.

To gain some indications about the properties of the individual fluctuations we show in Figure 4 the overall frequency distributions for $\delta B_{\perp}/|\langle \underline{B} \rangle|$, $|\delta B_{\parallel}|/|\langle \underline{B} \rangle|$ and $|\delta B_{\parallel}|/\delta B_{\perp}$. These histograms are obtained from all the values of the parallel and perpendicular components of the fluctuations as evaluated, starting from 6 s averages, in the various 22.5 minutes intervals of the different periods analyzed. It can be seen that approaching the sun the relative amplitude of the fluctuations increases, as noted before, and that the parallel contribution to the fluctuating field becomes more important. One should keep in mind, however, that we are neglecting possible temporal variations in the turbulence associated with the high speed stream.

For a small but not negligeable portion of data points (see histogram of $|\delta B_{\parallel}|/\delta B_{\perp}$ in Figure 4) the condition $|\delta B_{\parallel}|/\delta B_{\perp} < 1$ is not well satisfied, which leads to a parabolic curve in the plane x-y. However, an examination of many examples of scatter plots shows that most of the experimental points fall in fact in a branch of the parabola where the linear approximation is good, so that the value of our linear correlation coefficient remains high. The few points for which the condition $|\delta B_{\parallel}|/\delta B_{\perp} < 1$ is not valid increase just slightly the slope of the best fit straight line, as it is seen both in Figure 2(c) and in the histogram of C_1 (Figure 3).

In conclusion we can say that in most of the analyzed time intervals there is a strong tendency to a linear relation between $\delta B_{\parallel}/|\langle \underline{B} \rangle|$ and $\delta B_{\perp}^2/|\langle \underline{B} \rangle|^2$ (correlation coefficient close to -1). Furthermore the slope of the best fit straight line has in general values near to that expected from relation (6). In other words the experimental data seem to prove the gross validity of the theoretical relationship.

As a second task in the paper we have investigated correlations between eigenvalues of the variance matrix, to test the degree to which the scaling relations(9), predicted by a model recalled in section 2, are verified.

Figure 5 shows an example of scatter plots of λ_1-λ_2 and λ_1^2-λ_3 (all eigenvalues being conveniently normalized), with superposed the best fit straight lines and the computed correlation coefficients. The Figure refers to the days 76 and 77, when the spacecraft is observing the trailing edge of the stream at a distance of $\sim$0.65 AU from the sun.

Similar plots have also been produced from the other data sets utilized so far (at different distances from the sun), taking overall periods of different length and, as already mentioned, with a time basis different from 22.5 minutes for the statistics.

In general, the results obtained are very similar to the ones presented in Figure 5 and the values of the correlation coefficient reported there ($R = 0.67$ for the λ_1-λ_2 correlation and $R = 0.59$ for the λ_3-λ_1^2 correlation) can be said to be typical.

Although these values for the correlation coefficient are significant, we see that the scaling relations (9) appear to be verified in a much poorer way than relation (6) between parallel and perpendicular components of the fluctuations at individual data points.

5. CONCLUSIONS

From the results presented in section 4 we can draw the conclusion that the relation (6) between parallel and perpendicular components of the MHD fluctuations, observed in trailing edges of high speed streams, appear to be extremely well verified on an extensive set of data. We must stress that, although (6) is a consequence of the constancy of magnetic field magnitude (4), the test which has been done is more general than a test of constancy of $|\underline{B}|$. As it should appear clearly from the discussion in section 2, it is also a test on the polarization state of the observed MHD turbulence which, in this way, is in fact demonstrated to be a mixture of purely Alfvénic (perpendicular) modes and modes which are the incompressible limit of slow magnetosonic waves. The problem of how such a state is reached, starting, for example, from an initial production of both compressible and incompressible MHD fluctuations in the solar corona, is a different one and quite open at present.

As far as the correlations between the eigenvalues of the variance matrix are concerned, they, in general, tend to reproduce the scalings (9), predicted by a model calculation. However, the correlation coefficients obtained, although significant, are not as high as those of the $\delta B_{\parallel} - \delta B_{\perp}^2$ correlation between individual data points. As the scaling $\lambda_3 \propto \lambda_1^2$ follows, in a dimensional way, from the same relation (6) between $\delta B_{\parallel}$ and $\delta B_{\perp}^2$ which turns out so well tested with the data, we must ask ourselves which can be the reasons of the poorer correlation found between eigenvalues. There may be indeed two such reasons, both related to the special hypotheses of the model calculation in Dobrowolny et al. [1980a].

The first one is the hypothesis (8) $\delta b_2/\delta b_1 < 1$ used in the calculations. Although the parallel component $\delta B_{\parallel}$ of the fluctuations at polarization $\hat{e}_2$ is indicated by the analysis (see Figure 4) as smaller, in the majority of cases, than the perpendicular component $\delta B_{\perp}$, the perpendicular fluctuations come from two contributions, at the polarizations $\hat{e}_1$ and $\hat{e}_2$, and there is no way to separate these from the data, so that we do not know a typical value for $\delta b_{2\perp}/\delta b_{1\perp}$ and the hypothesis used ($\delta b_2/\delta b_1 < 1$) may be wrong. On the other hand, the results of Dobrowolny et al. [1980a] would certainly change if one was able to repeat an analogous calculation by maintaining $\delta b_2/ \delta b_1 \sim 1$.

A second important point is that the calculation leading to (9) was assuming normal distributions for the turbulent fluctuations. Whereas this was done for the sake of having a tractable example, there is no reason to expect the real MHD turbulence to verify such an hypothesis and, in general, by analogy with developed hydrodynamic turbulence, which is essentially not normal [Orszag, 1970], we would expect also in MHD turbulence triple correlations between fluctuating quantities to be different from zero. Going to the scheme of the calculations in Dobrowolny et al. [1980a], one becomes easily convinced that, in the presence of triple correlations, the scaling (9) between eigenvalues will no longer hold true but would be replaced by more complicated relations.

Thus the fact that the testing of (9) with the experimental data, presented in this paper, has not given such high correlation coefficients as the testing of the single point relation (6), may also reflect the deviation from normality of the MHD turbulence in the solar wind.

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FIGURE CAPTIONS

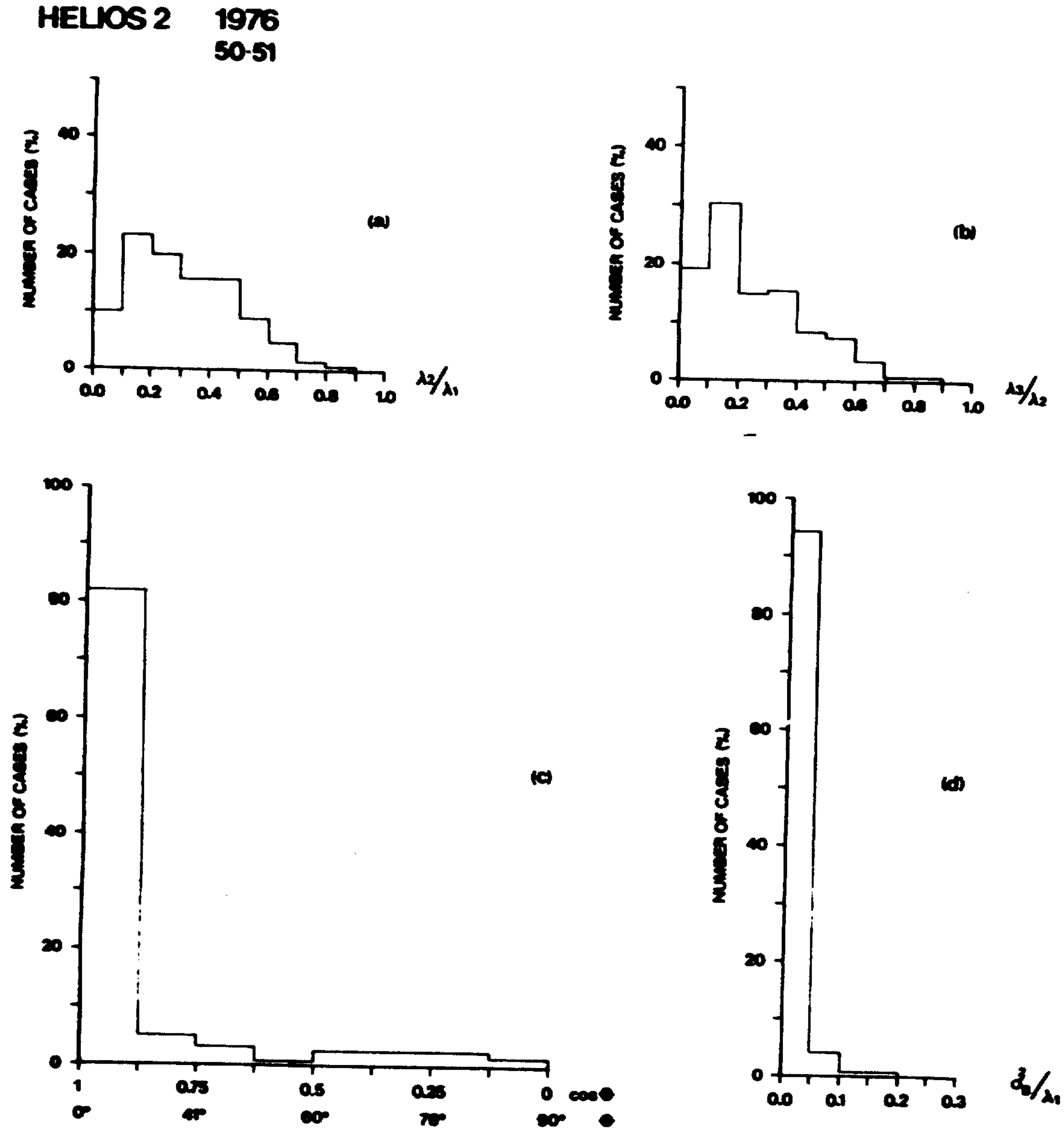
Figure 1. Statistical distributions for the two day period 50-51 of: (a) the ratio of the eigenvalues λ_2/λ_1; (b) the ratio λ_3/λ_2; (c) the angle θ between the minimum variance direction and the average field vector (the range of θ being divided in equal increments of $\cos\theta$ to correct for solid angle effect); (d) the ratio σ_B^2/λ_1 of the variance of the field magnitude to the largest eigenvalue.
The analysis has been performed on a time basis of 22.5 minutes.

Figure 2. Examples of scatter plot of the variables $x=\delta B_\perp^2/|\langle \underline{B}\rangle|^2$ and $y=\delta B_\parallel/|\langle \underline{B}\rangle|$ for different intervals of 22.5 minutes. In each plot we give the initial time of the interval, the best fit straight line and the value of the correlation coefficient R.

Figure 3. Statistical distributions of: (a) the correlation coefficient R; (b) the slope of the best fit straight line; (c) the intercept of this line with the y axis. The three different histograms for each parameter refer to the three successive observations of the trailing edge of the stream.

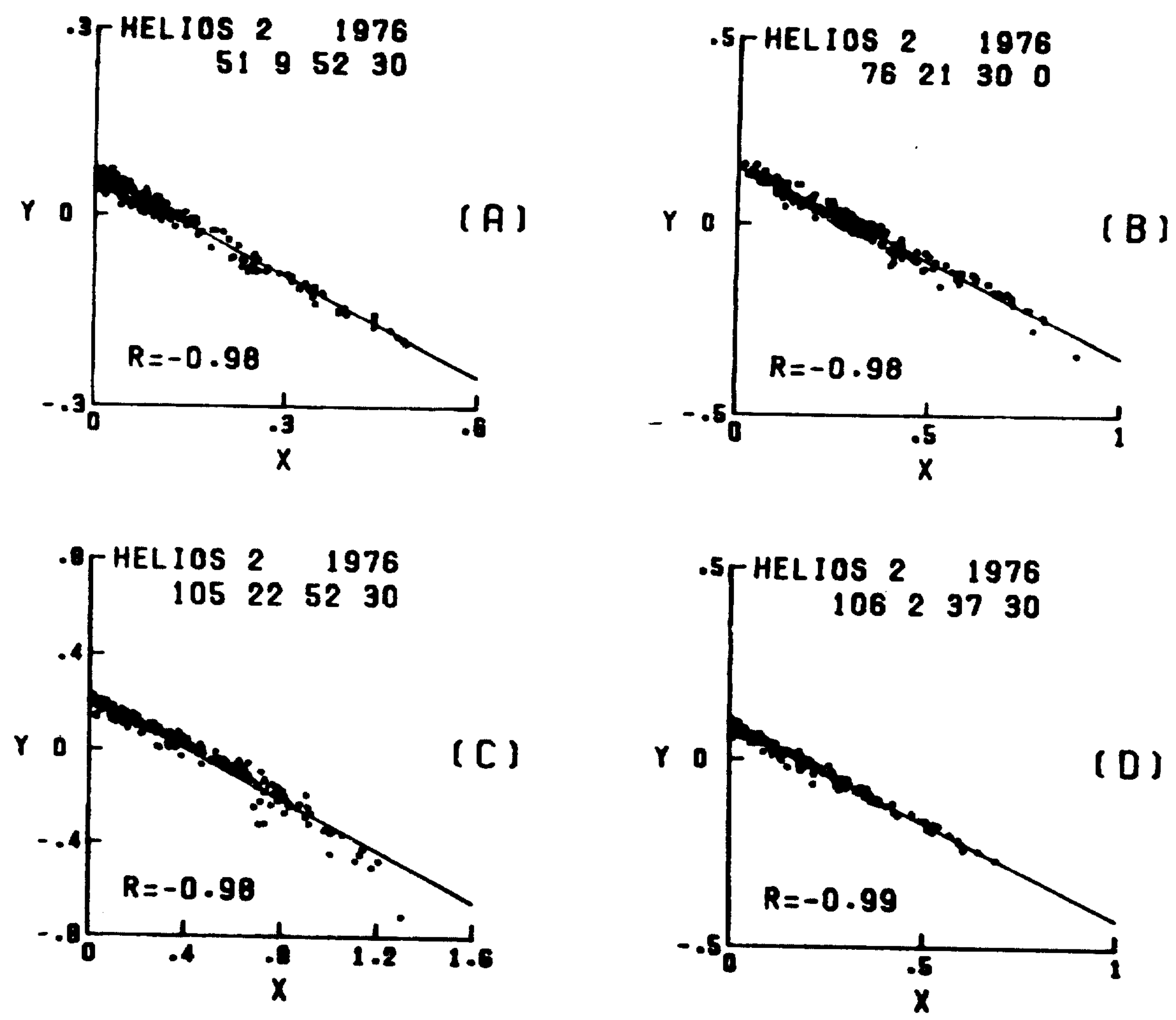
Figure 4. Statistical distributions of: (a) $\delta B_\perp/|\langle \underline{B}\rangle|$; (b) $|\delta B_\parallel|/|\langle \underline{B}\rangle|$; (c) $|\delta B_\parallel|/\delta B_\perp$. The three histograms for each parameter refer to the three successive observations of the trailing edge of the stream.

Figure 5. Scatter plots of A_1-A_2 and A_1^2-A_3 (A_1, A_2 and A_3 being the variance eigenvalues λ_1, λ_2 and λ_3 normalized to the average field magnitude) on a time basis of 22.5 minutes for the two day period 76-77. In each plot the best fit straight line and the value of the correlation coefficient R are also given.



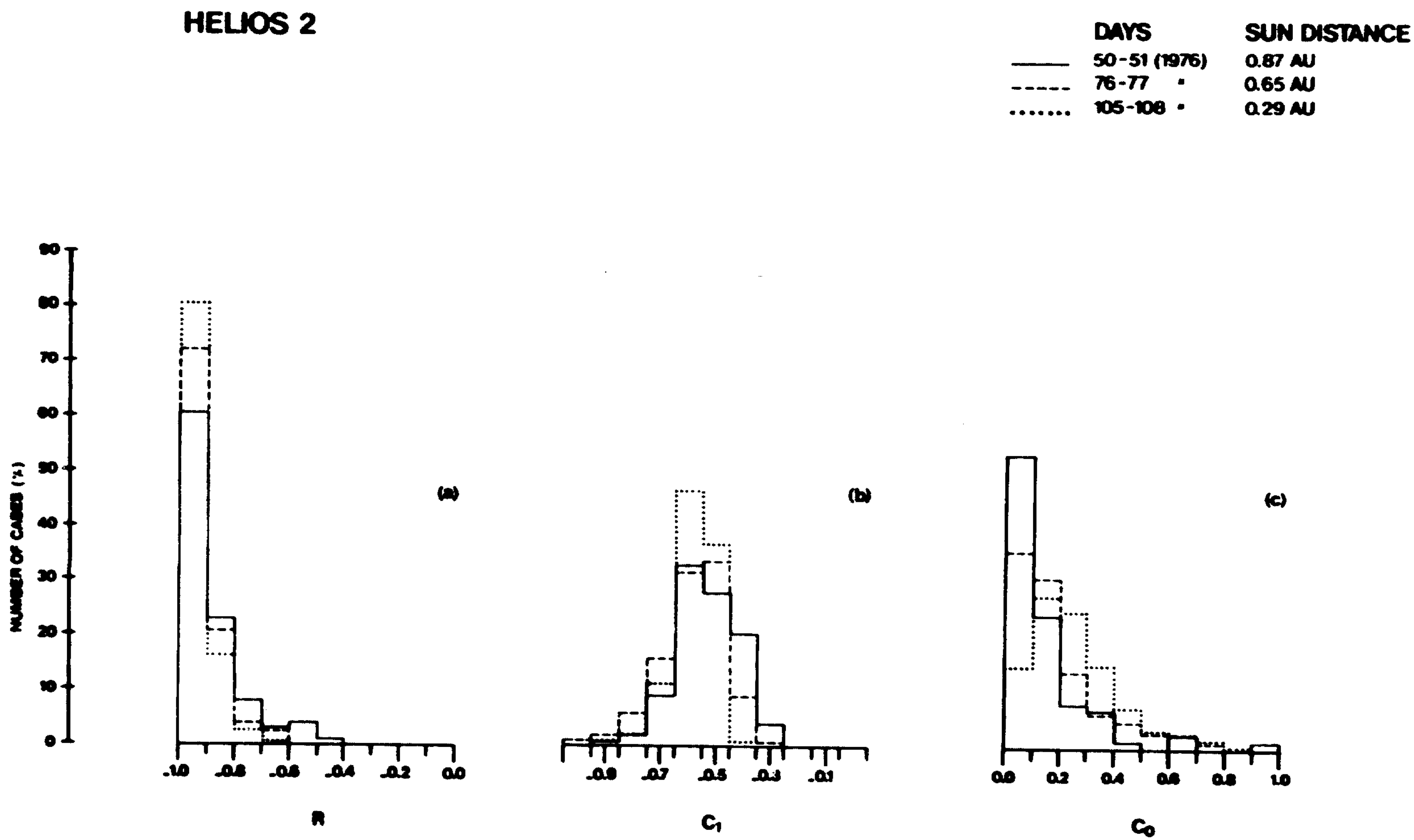
HELIOS 2 1976
50-51
NUMBER OF CASES (%)
(a)
λ_2/λ_1
(b)
λ_3/λ_2
(c)
cos Θ
Θ
(d)
$\tilde{\sigma}_B^2/\lambda_1$

FIG. 1



HELIOS 2 1976
51 9 52 30
(A)
R=-0.98
Y
X
HELIOS 2 1976
76 21 30 0
(B)
R=-0.98
HELIOS 2 1976
105 22 52 30
(C)
R=-0.98
HELIOS 2 1976
106 2 37 30
(D)
R=-0.99

FIG. 2



HELIOS 2
DAYS
SUN DISTANCE
50-51 (1976)
0.87 AU
76-77 "
0.65 AU
105-108 "
0.29 AU
NUMBER OF CASES (%)
(a)
(b)
(c)
R
C_1
C_0

FIG. 3

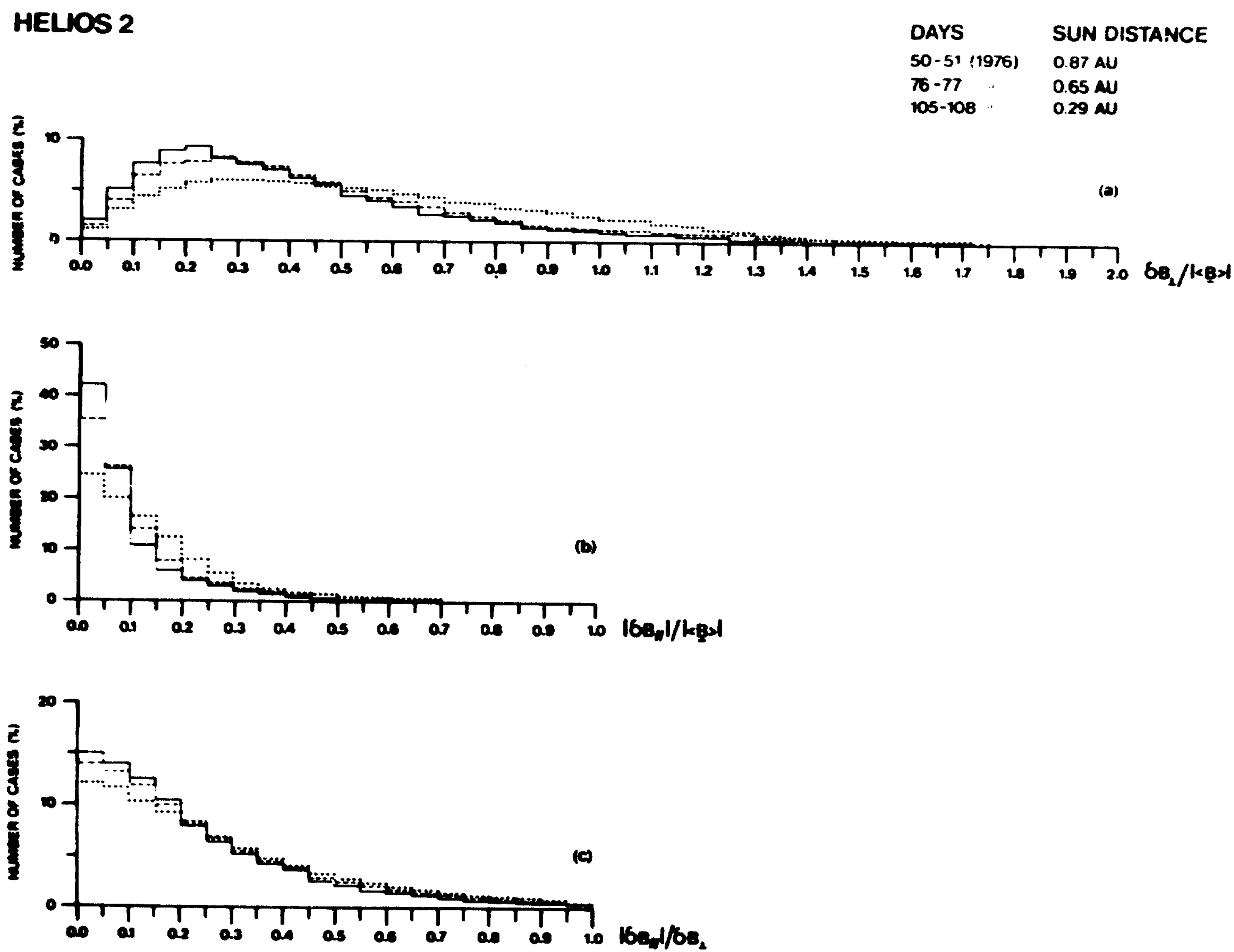

HELIOS 2
DAYS
SUN DISTANCE
50-51 (1976)
0.87 AU
76-77
0.65 AU
105-108
0.29 AU
NUMBER OF CASES (%)
(a)
$\delta B_\perp/|\langle \underline{B} \rangle|$
(b)
$|\delta B_\parallel|/|\langle \underline{B} \rangle|$
(c)
$|\delta B_\parallel|/\delta B_\perp$

FIG. 4

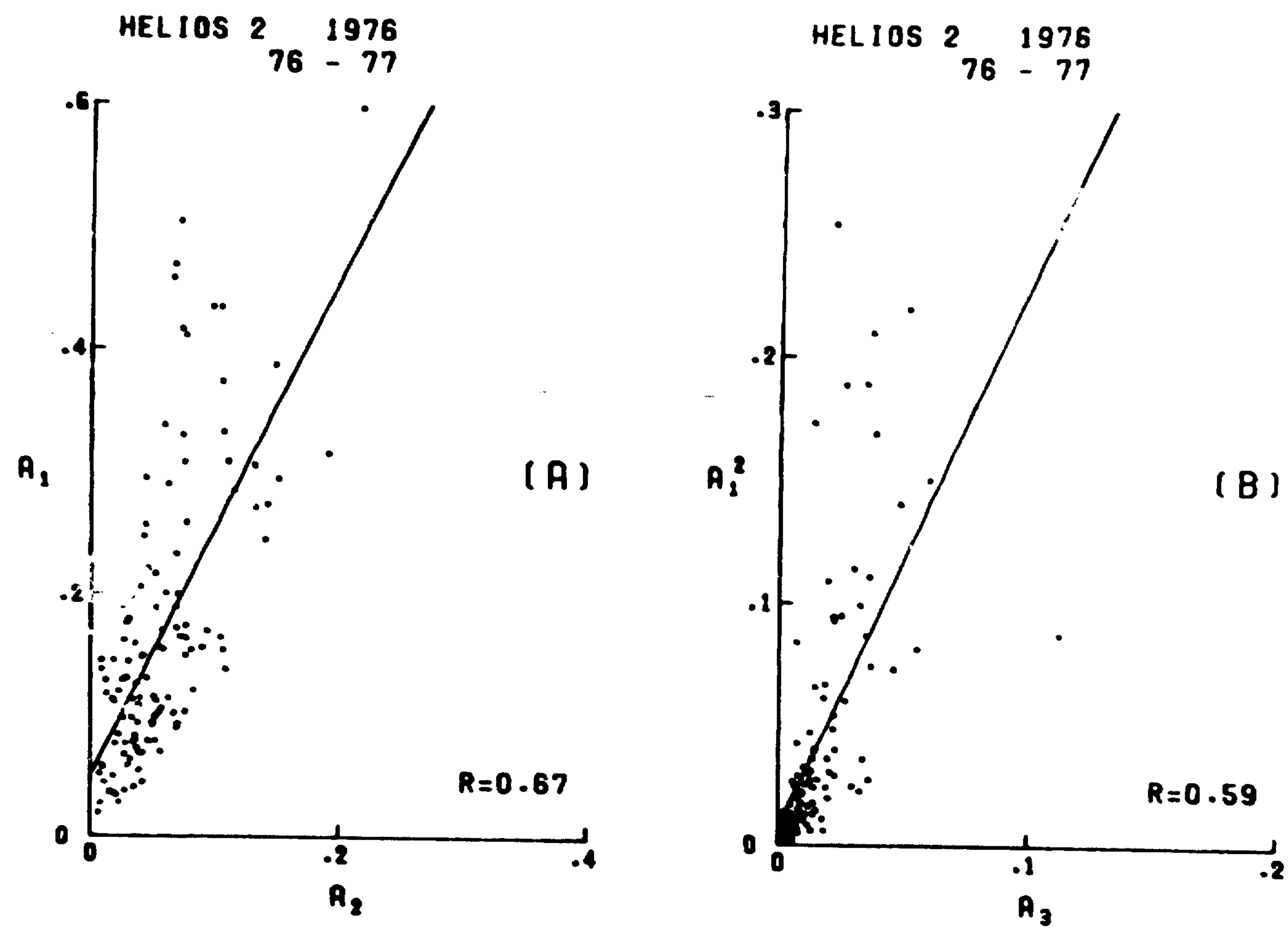

HELIOS 2 1976
76 - 77
.6
.4
.2
0
A_1
(A)
R=0.67
0
.2
.4
A_2
HELIOS 2 1976
76 - 77
.3
.2
.1
0
A_1^2
(B)
R=0.59
0
.1
.2
A_3

FIG. 5