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ASSOCIATED WITH HIGH SPEED STREAMS FROM
HELIX 2 OBSERVATIONS

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Statistical properties of MHD fluctuations associated with high speed streams from Helios 2 observations

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Abstract

Helios 2 magnetic data have been used to derive several statistical properties of MHD fluctuations associated with the trailing edge of a given stream observed in different solar rotations. Eigenvalues and eigenvectors of the variance matrix, total power and degree of compressibility of the fluctuations have been derived and discussed both as a function of distance from the Sun and as a function of the frequency range included in the sample. The results obtained add new information to the picture of MHD turbulence in the solar wind. In particular a dependence from frequency range of the radial gradients of various statistical quantities is obtained.

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 non homogeneous and expanding solar wind and their possible role in heating solar wind ions (for reviews of these works see Hollweg 1977, Barnes 1977).

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 non linear state

of MHD turbulence, have in fact stimulated recent theoretical developments on the subject (Dobrowolny et al., 1980b; Mangeney et al., 1981).

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. Variation 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. (1980) and Denskat and

Neubauer (1981). 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. A systematic investigation of power spectra for homogeneous sets of observations will be the object of a companion paper (Bavassano et al., 1981b).

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 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. A description of the instrumentation and data reduction is given by Scarce 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, (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. Fig. 1 gives the ecliptic projection of the spacecraft trajectory from day 20 to day 120, 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: 168s, 3m, 22.5m, 1h, 3h. We recall that Balcher and Davis (1971) give results referring to time basis of 168.75s, 22.5m and 3h 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 $\approx 8 \cdot 10^{-2}$ 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 1) varies from ≈ 0.10 to ≈ 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 Sect. 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 1 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 polarization properties of the fluctuations using the same sample of data (Bavassano et al., 1981a) has indicated that most of the observed fluctuations can be interpreted as a mixture of purely Alfvénic (perpendicular) modes and modes which also contain a fluctuating component parallel to the average magnetic field.

3. Variations with distance of statistical properties of MHD fluctuations

For the periods of Table 1 we have calculated eigenvalues ($\lambda_1, \lambda_2, \lambda_3$) and eigenvectors of the variance matrix. If we define $\lambda_1 \gg \lambda_2 \gg \lambda_3$, the eigenvector associated with λ_3 defines the minimum variance direction. This is well defined when $\lambda_3 \ll (\lambda_2, \lambda_1)$ and then the ratio $\lambda_2/\lambda_1 \ll 1$ 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 ϑ .

Fig. 2 gives the histograms of the ratios $\lambda_2/\lambda_1, \lambda_3/\lambda_1$ and the angle ϑ obtained for the three periods of observation of the stream listed in Table 1 and referring to a time basis of 22.5 minutes. The range of ϑ 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.

In Fig. 3 we have plotted, in a similar arrangement, the distribution of the quantities $\sigma_C^2/B^2, \sigma_B^2/B^2$ and σ_B^2/σ_C^2 , where σ_C^2 is the trace of the variance matrix (and hence represents the total power in magnetic fluctuations), σ_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 Figs 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 Sect. 1. It is $\lambda_3/\lambda_1 \ll 1$ ($\lambda_3/\lambda_1 \leq 0.1$) 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 \underline{B} (Dobrowolny et al., 1980a). Furthermore, the variations in field magnitude are very small with $\sigma_B^2/B^2 < 3 \cdot 10^{-3}$ in 90% of the 22.5 m intervals considered.

Comparing now histograms along each column in Figs. 2 and 3, we see that there are changes in the distributions for some of the parameters calculated. In particular, for the parameters λ_2/λ_1 , λ_3/λ_1 and σ_C^2/B^2 higher values become more frequent when the distance from the Sun decreases. This is better seen in Fig. 4 where we have plotted, for each of the parameters of Figs. 2 and 3, the average value at each stream encounter (distance from the Sun being on the horizontal axis). The various curves refer to the five different time basis used in the statistics (and the curve labelled 3 corresponds to the time basis , 22.5 m, of the histograms of Figs. 2 and 3).

There is a clearly increasing trend for the ratio λ_2/λ_1 upon approaching the Sun, which is found for all time basis (and therefore including different frequency ranges). The same trend applies for σ_C^2/B^2 except for curve 5 referring to the time basis of 3 hours and hence containing the lowest frequency fluctuations. The inverse trend applies for σ_B^2/B^2 which increases further away from the Sun.

On the other hand, variations of λ_3/λ_1 with distance are much less

noticeable. If significant, these are in the sense of λ_3/λ_1 slightly increasing upon approaching the Sun which would imply (as the minimum variance direction is almost aligned with \mathbf{B}) that the ratio between parallel and perpendicular fluctuations has higher values upon approaching the Sun (see also Bavassano et al., 1981a).

We must now comment on the significance of the variations evidenced in Fig. 4. To this end, we have written, in Table 3, for each point reported in the various plots of Fig. 4, its value and the corresponding mean deviation.

We see that the variations resulting in Fig. 4 are actually within the range of these deviations. However, the variations with distance (and also those with respect to frequency range, see Sect. 4) resulting from Fig. 4, have such a degree of coherence (for example, in most cases, variations with distance are always in the same sense whatever the frequency range) that we are led to believe that such variations are significant.

This view is also supported by the histograms of Figs. 2 and 3 where we can see that the variations evidenced by the curves of Fig. 4 really correspond to consistent shifts in the distribution of the values for the various parameters.

It therefore seems possible to conclude that: a) the degree of anisotropy of the fluctuations decreases (increasing λ_2/λ_1) going towards the Sun; b) the degree of compressibility decreases going toward the Sun; c) the total power (normalized) in fluctuations increases upon approaching the Sun (at least when the wave number range considered does

not include fluctuations of periods above 1 hour).

A further important point, which is apparent from Fig. 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 Sect. 5.

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

Finally, as shown in Fig. 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 IMF fluctuations

In each of the plots of Fig. 4 the time basis increases (from 168 s to 3 h) going from curve 1 to curve 5. Hence the sample studied includes fluctuations of increasingly low frequency. The same Fig. 4, looking now at a fixed heliocentric distance, indicates the variations of the various parameters plotted with frequency range of the fluctuations.

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 increase upon extending the frequency range (towards low frequencies). For the powers σ_C^2/B^2 and σ_B^2/B^2 this increase is quite obvious. Therefore the significant results we derive from Fig. 4 are: a) the degree of anisotropy of the fluctuations decreases more and more when we include lower and lower frequencies (λ_2/λ_1 increasing upon increase of the time basis). Therefore, the higher frequency components of the fluctuations tend to be more anisotropic than the low frequency components. b) The ratio λ_3/λ_1 is also increasing upon increasing the time basis. This implies that the ratio $\int B_{||} / \int B_{\perp}$ increases when lower frequencies are taken into account ($||$ and \perp refer to the average magnetic field direction).

As mentioned already, three different time basis were also taken in the work of Balcher 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 dif-

ferent 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 main 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 basis 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 same anisotropy decreases upon increasing the time basis. Hence 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 h are included). As obvious, at fixed heliocentric distance, the to

tal 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 Fig. 4) is that the variation with distance of the various parameters depends from frequency range.

This is a main conclusion resulting from this investigation and not appreciated in previous studies of variation with distance, mostly concerned with wave amplitudes (see Barnes, 1977; Behannon, 1978; Villante, 1980). The available theory with which variations of the fluctuations with distance have been compared so far is the geometric optics approximation of wave propagation (see Barnes, 1977). However, our results on dependence from frequency of the various radial gradients cannot certainly be explained in this framework (as it does not contain, in principle, frequency effects) and one must resort to something else.

In the range of heliocentric distances considered WKB propagation would predict an increase in normalized wave power σ_C^2/B^2 with distance. This is just the opposite of the trend indicated by the curves in Fig. 4, with the exception of curve 5, referring to the 3 h basis, which is rather flat. A recent work of Villante (1980), referring to

1 h variances, concludes that the data are more consistent with $\sigma_c^2/B^2 =$ constant than the geometric optics indication.

Besides the disagreement with the geometric optics prediction, the radial gradients of σ_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 m, 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, 1977), 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. (1980) 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 1981; Bavassano et al. 1981b) indicate indeed a spectral index of the order of 1 at 0.3 AU but only for frequencies below $1.5 \cdot 10^{-2}$ 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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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

Table 1 - Periods used in the analysis.

	T_b	168s	8m	22.5m	1h	3h
	R(AU)	(1)	(2)	(3)	(4)	(5)
λ_2/λ_1	0.87	0.230 \pm 0.149	0.271 \pm 0.163	0.316 \pm 0.155	0.327 \pm 0.113	0.458 \pm 0.166
	0.65	0.234 \pm 0.139	0.299 \pm 0.152	0.389 \pm 0.163	0.489 \pm 0.168	0.601 \pm 0.101
	0.29	0.288 \pm 0.150	0.384 \pm 0.153	0.456 \pm 0.160	0.533 \pm 0.151	0.626 \pm 0.135
λ_3/λ_1	0.87	0.022 \pm 0.014	0.036 \pm 0.023	0.063 \pm 0.029	0.110 \pm 0.044	0.176 \pm 0.061
	0.65	0.023 \pm 0.014	0.045 \pm 0.025	0.081 \pm 0.037	0.136 \pm 0.047	0.199 \pm 0.055
	0.29	0.038 \pm 0.022	0.077 \pm 0.037	0.126 \pm 0.047	0.168 \pm 0.044	0.204 \pm 0.040
σ_C^2/B^2	0.87	0.071 \pm 0.062	0.128 \pm 0.090	0.214 \pm 0.119	0.298 \pm 0.111	0.407 \pm 0.103
	0.65	0.090 \pm 0.071	0.152 \pm 0.091	0.239 \pm 0.121	0.307 \pm 0.091	0.392 \pm 0.096
	0.29	0.166 \pm 0.102	0.239 \pm 0.111	0.307 \pm 0.110	0.351 \pm 0.099	0.382 \pm 0.080
σ_B^2/B^2	0.87	0.0011 \pm 0.0014	0.0015 \pm 0.0017	0.0022 \pm 0.0022	0.0034 \pm 0.0026	0.0053 \pm 0.0021
	0.65	0.0007 \pm 0.0007	0.0011 \pm 0.0011	0.0016 \pm 0.0013	0.0023 \pm 0.0015	0.0038 \pm 0.0021
	0.29	0.0011 \pm 0.0011	0.0012 \pm 0.0010	0.0014 \pm 0.0008	0.0018 \pm 0.0008	0.0023 \pm 0.0008
σ_B^2/σ_C^2	0.87	0.0161 \pm 0.0165	0.0128 \pm 0.0125	0.0095 \pm 0.0074	0.0112 \pm 0.0072	0.0134 \pm 0.0051
	0.65	0.0092 \pm 0.0084	0.0067 \pm 0.0051	0.0064 \pm 0.0043	0.0075 \pm 0.0046	0.0109 \pm 0.0065
	0.29	0.0059 \pm 0.0046	0.0051 \pm 0.0032	0.0045 \pm 0.0021	0.0052 \pm 0.0020	0.0064 \pm 0.0026

Table 2 - Mean values and deviations, for each stream encounter, of λ_2/λ_1 , λ_3/λ_1 , σ_C^2/B^2 , σ_B^2/B^2 and σ_B^2/σ_C^2 .

T_b indicates the time basis used in the variance matrix computations.

Figure Captions

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

Fig. 2 - Statistical distributions for the three stream encounters (see periods of Table 1) of: (a) the ratio of the eigenvalues λ_2/λ_1 ; (b) the ratio λ_3/λ_1 ; (c) the angle θ between the minimum variance direction and the average field vector. The analysis has been performed on a time basis of 22.5 minutes.

Fig. 3 - Statistical distributions for the three stream encounters (see periods of Table 1) of: (a) the ratio σ_C^2/B^2 , σ_C^2 being the trace of the variance matrix and B the field magnitude; (b) the ratio σ_B^2/B^2 , σ_B^2 being the variance in the field magnitude; (c) the ratio σ_B^2/σ_C^2 . The analysis has been performed on a time basis of 22.5 minutes.

Fig. 4 - Variation with the heliocentric distance of the average values, for each stream encounter, of λ_2/λ_1 (a), λ_3/λ_1 (b), σ_C^2/B^2 (c), σ_B^2/B^2 (d), σ_B^2/σ_C^2 (e). The five curves in each panel refer to the different time basis used in the statistics.

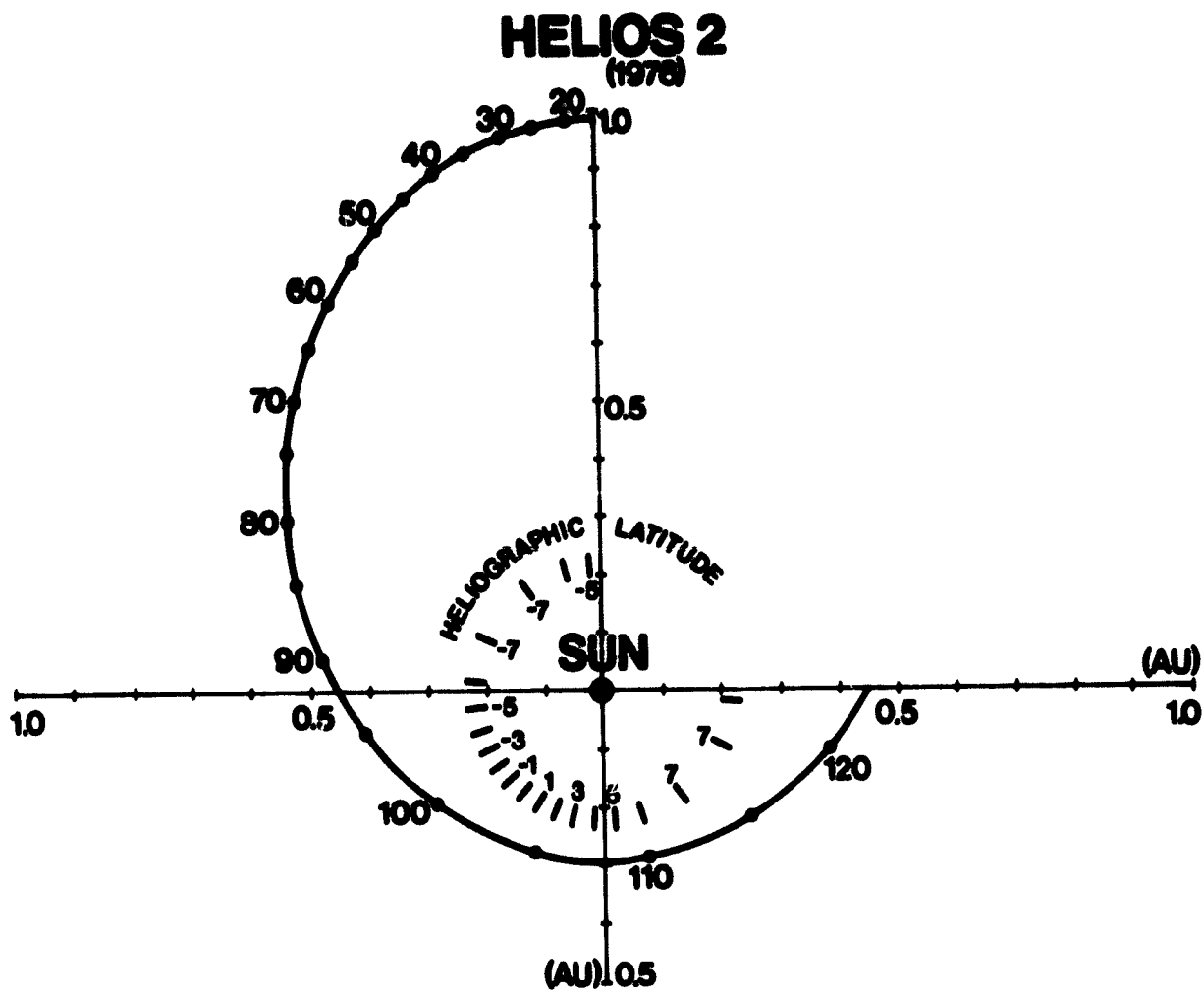


FIGURE 1

HELIOS 2 1976

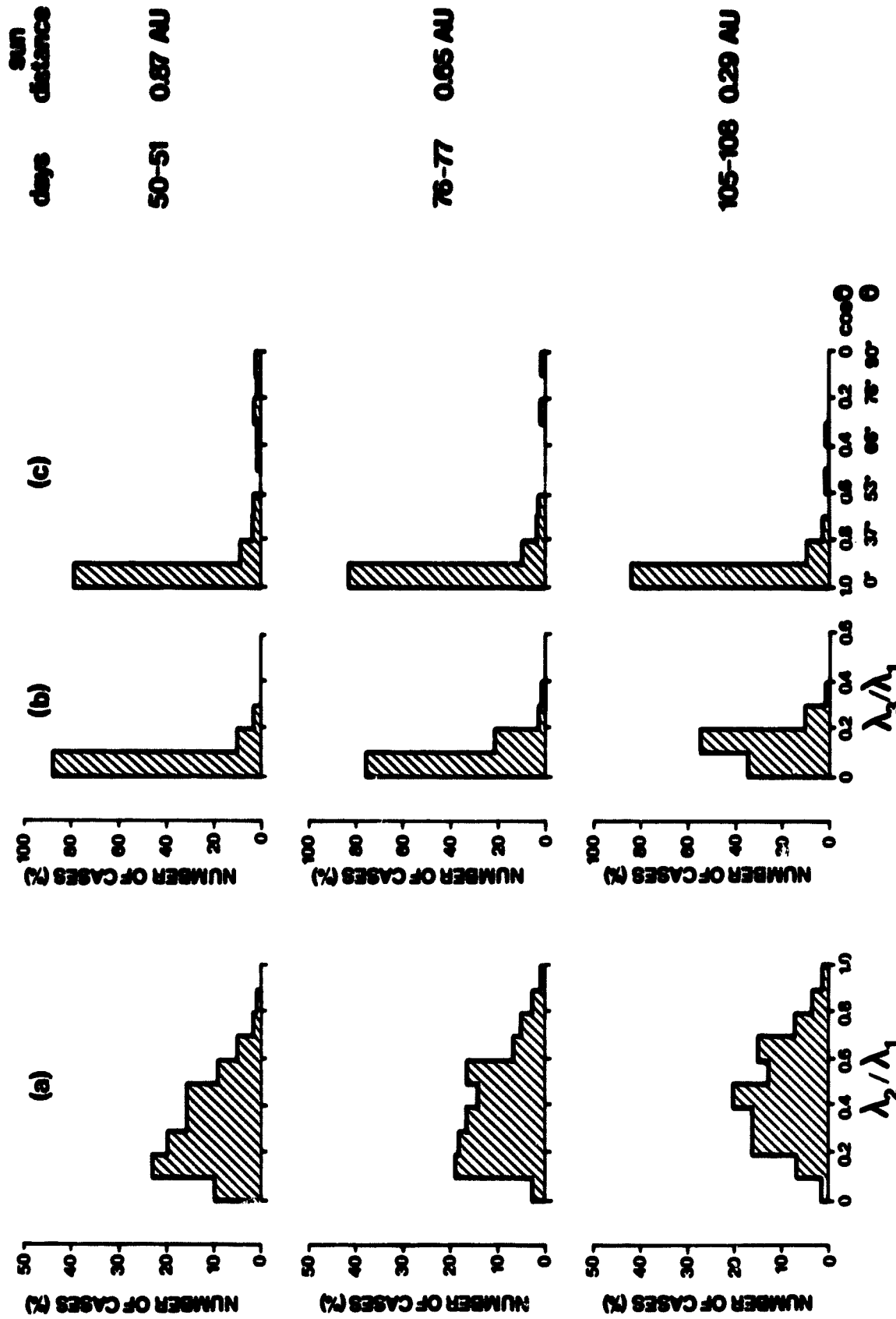


FIGURE 2

HELIOS 2 1976

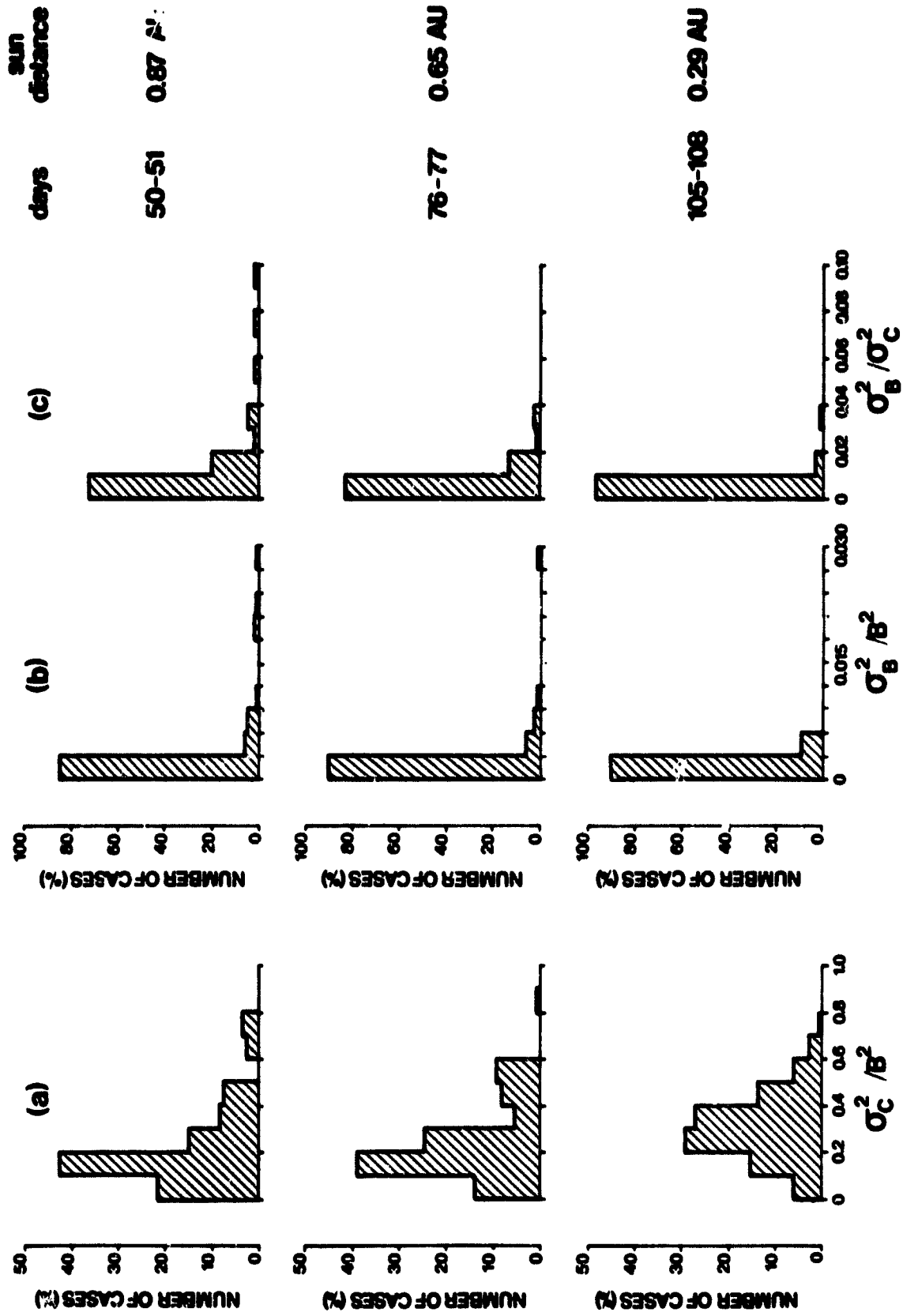


FIGURE 3

CURVE No.	TIME BASIS
1	168 s
2	8 m
3	22.5 m
4	1 h
5	3 h

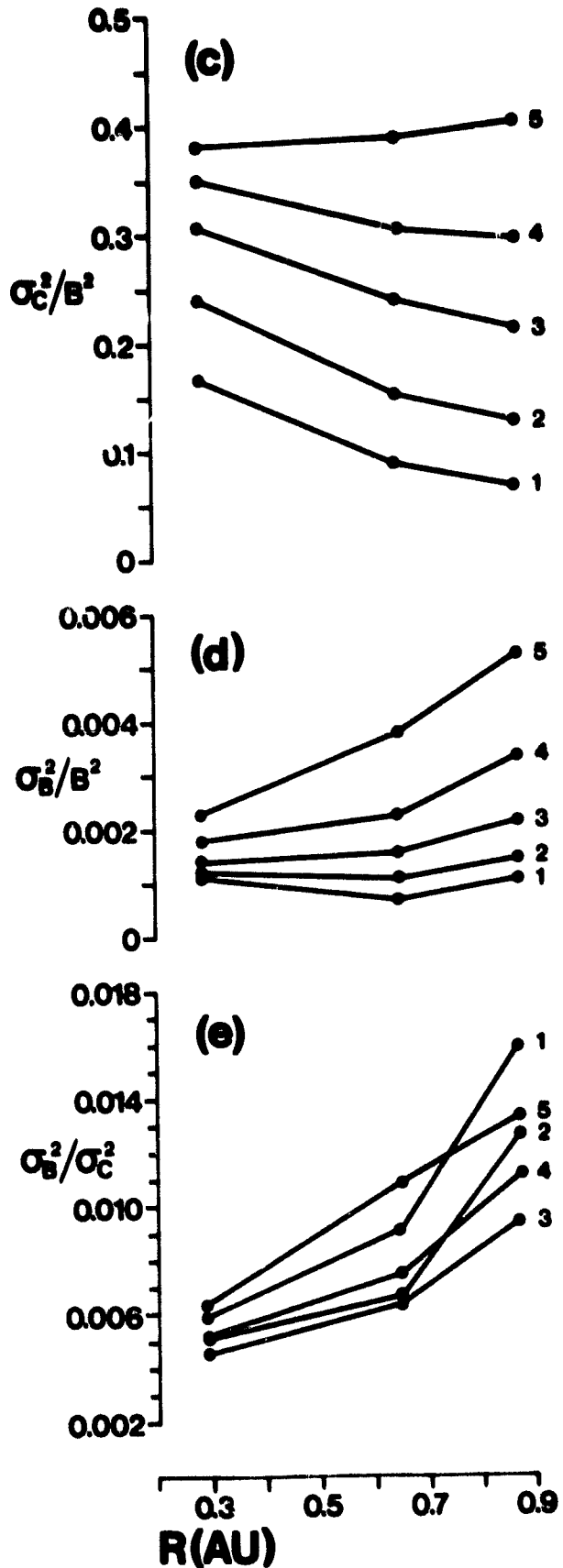
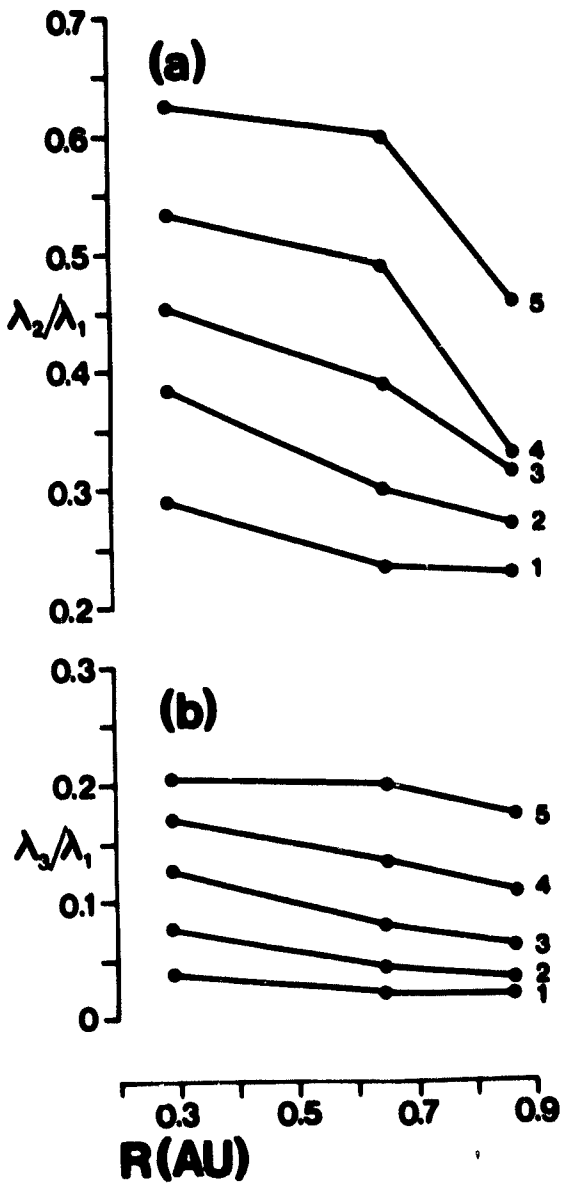


FIGURE 4