OBSERVATIONS OF HYDROMAGNETIC TURBULENCE IN THE SOLAR WIND

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ABSTRACT

MHD turbulence is studied by analysing magnetic field and plasma observations from Helios-1 and -2 at minimum solar activity. The steady conditions in the plasma flows and the magnetic field sector structure in 1975/1976 facilitate an investigation of the radial evolution of the turbulence from 0.29 to 1AU. In high speed streams the fluctuations in the solar wind velocity v and the magnetic field b are highly correlated (the correlation coefficient almost being one), which indicates that the turbulence is mainly Alfvénic in high speed plasma. While some general fluctuation properties remain essentially unchanged from 0.29 to 1AU, power spectral analysis reveals a different frequency composition of the Alfvénic turbulence at different heliocentric distances. At 0.3AU much more 'high' frequency fluctuations (up to 1.2×10^{-2}Hz) contribute to the total power in the magnetic field and velocity fluctuations than at 1AU. The contributions of field magnitude fluctuations are found to be distance and frequency dependent. Magnetic field spectra with an extended frequency range up to 470Hz show certain frequency bands, where the steepness of the spectra is independent of the heliocentric distance.

INTRODUCTION

Since Solar Wind 4 in 1978 some progress has been made in the analysis of observations of the radial evolution of MHD-turbulence in the solar wind. Magnetic field and plasma data from 0.29 to 1AU are provided by the Helios-spacecraft, data outside 1AU are provided by the Voyager-spacecraft. This paper mainly treats the Helios observations from 0.29 to 1AU. A comprehensive review of theory and observations of hydromagnetic waves and turbulence in the solar wind, which does not yet include Helios and Voyager observations, is available from Barnes [1979].

To study the radial evolution of MHD-turbulence in the interplanetary plasma, we use proton plasma data from the Max-Planck-Institut at Katlenburg-Lindau and magnetic field data from the Technical University of Braunschweig. In this paper we mainly analyse fluctuations in high speed plasma streams, which are usually named Alfvénic fluctuations [Belcher and Davis, 1971] or Alfvénic turbulence. The time periods studied are the primary missions of Helios-1 and Helios-2 (December 74 to April 75 and January 76 to May 76).

To study the occurrence of Alfvénic turbulence we compute the correlation between $\underline{b}$ and $\underline{v}$ for heliocentric distances from 0.29 to 1AU, which is a necessary condition for Alfvén waves. For the calculations we choose the 'mean field' (MF) coordinate system defined such that the z-axis is taken along the average direction of the vector magnetic field, the x-axis is perpendicular to z and lies in the xz_{SE}-plane and y completes the right-handed orthogonal set. Considering a cor-

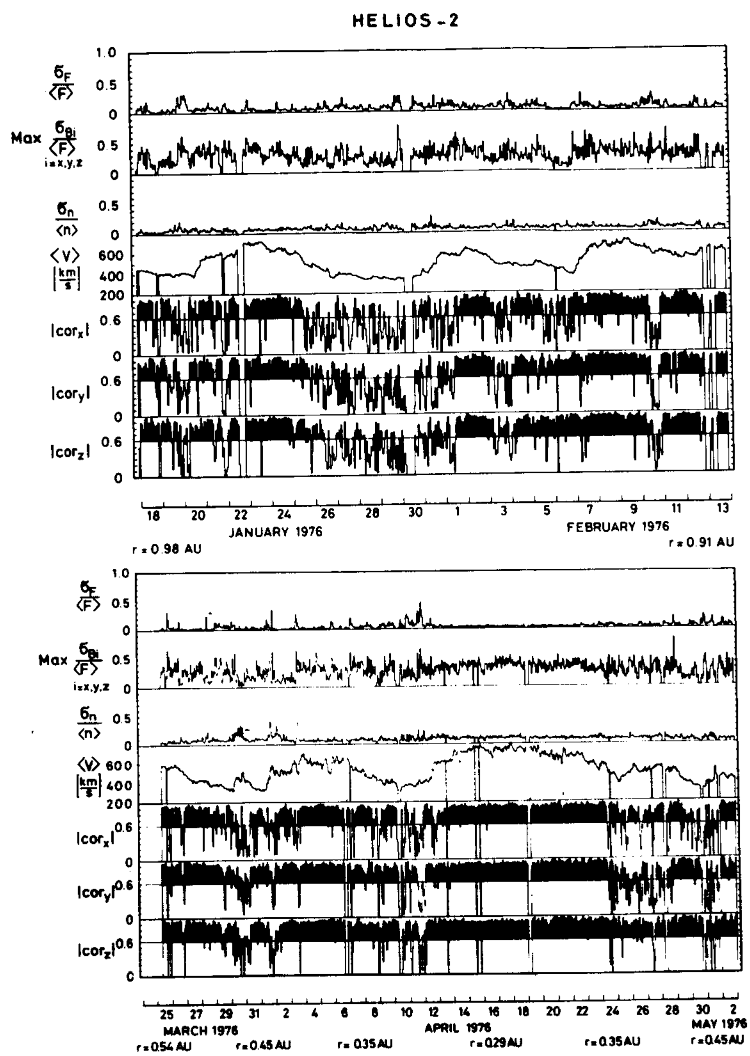

Figure 1. General properties of the Helios-2 fluctuations in relation to the speed profile between 0.98 and 0.91AU and between 0.29 and 0.54AU. The panels denote (from the top) normalized fluctuations in field magnitude, field components (given by the maximum value of the three components), proton density, average bulk speed, and the absolute values of the correlation coefficients between $\underline{b}$ and $\underline{v}$ (MF-coordinates). σ_F, σ_{Bi}, and σ_n are the one hours rms-values of F, Bi, and n, respectively.

relation to exist for correlation coefficients larger than |0.6| for the three components leads to a more than 75% occurrence of Alfvénic turbulence during one solar rotation at aphelion (figure 1a) and perihelion (figure 1b), respectively. The occurrence of Alfvénic turbulence is essentially restricted to high speed plasma streams. Within high speed streams the purest examples of Alfvénic turbulence (characterized by a high correlation between $\underline{v}$ and $\underline{b}$ and a low level of proton density and magnetic field magnitude fluctuations) occur in the centers and trailing edges. These results were already found by Belcher and Davis [1971] for fluctuations near 1AU and are now also found to hold for fluctuations at 0.3AU. At the leading edges of high speed streams there occurs a stronger amount of compressional fluctuation activity, which indicates a local generation mechanism.

Figure 1 shows that the correlation between $\underline{b}$ and $\underline{v}$ in high speed streams is often larger than |0.9|. The choice of |0.6| as a limit for correlated fluctuations was chosen due to results from earlier investigations [Burlaga and Turner, 1976; Denskat and Burlaga, 1977], where lower correlations have been found. These differences are presumably due to an increased accuracy of the plasma experiment on board of Helios. The highly correlated $\underline{v}$-$\underline{b}$ fluctuations indicate the almost pure Alfvénic character of the turbulence. However, there always is an additional compressive component present, which needs to be explained. These compressive fluctuations could be static structures convected by the solar wind or magnetoacoustic waves or both.

Together with the direction of the interplanetary magnetic field the sign of the $\underline{b}$-$\underline{v}$-correlation gives the propagation direction of the fluctuations. For the primary missions of Helios-1 and -2 all of the Alfvénic fluctuations in high speed plasma are found to propagate in the anti-solar direction. This clearly points to a generation of Alfvénic turbulence inside the Alfvén radius (10 to 20 solar radii).

Radial evolution of fluctuation amplitudes

The investigation of radial dependences of plasma and field parameters at solar activity minimum is facilitated by the magnetic field sector boundaries remaining stable over several solar rotations [Behannon et al., 1981] and the high speed streams occuring at the same solar longitudes at subsequent solar rotations [Marsch et al., 1982].

To study the radial evolution of the fluctuation amplitudes, we calculated for one hour intervals the rms or standard deviations σ_F and $\sigma_{\underline{B}}$, where σ_F is the rms deviation of field magnitude fluctuations, and $\sigma_{\underline{B}}$ is the rms deviation of vector magnetic field fluctuations with contributions from both magnitude and directional fluctuations. The rms deviation $\sigma_{\underline{B}}$ is computed from the individual rms deviations according to

$$\sigma_{\underline{B}} = \sqrt{\sigma_{Bx}^2 + \sigma_{By}^2 + \sigma_{Bz}^2}\ .$$

Figure 2 shows $\sigma_{\underline{B}}/\langle F\rangle$ and $\sigma_F/\langle F\rangle$ for perihelion and aphelion time periods. Apparently there are no significant differences in the class of directional fluctuations. Since in the case of Helios-1 Musmann et al. [1977] found for the field magnitude F a distance dependence $F \sim r^{-1.6}$, these results are consistent with an $r^{-1.5}$ law for wave amplitudes predicted for Alfvén waves propagating outward without attenuation in a spherically symmetric solar wind [Whang, 1973; Belcher and Burchstedt, 1974]. However, these results are also consistent with satu-

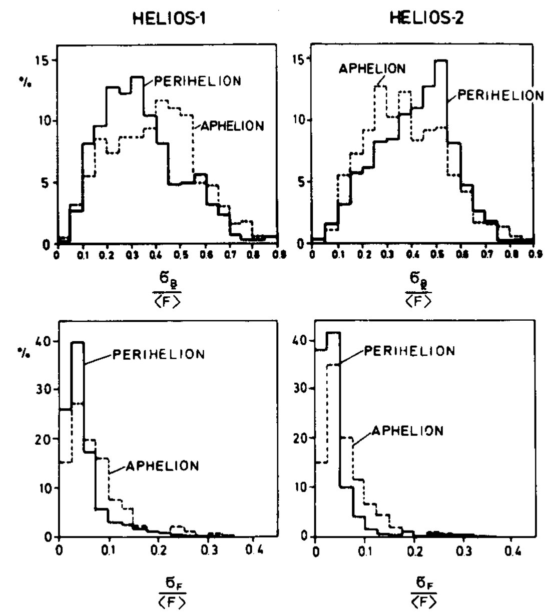

Figure 2. Distribution of normalized standard deviation of vector magnetic field fluctuations σ_B and magnetic field magnitude fluctuations σ_F normalized by the average field magnitude for one hour time intervals. The time periods for the calculations cover one solar rotation for the first aphelion and perihelion time periods of both spacecraft corresponding to distance intervals from 0.91 to 0.98AU and from 0.29 (0.31) to 0.54AU.

rated wave amplitudes, since $\sigma_B/\langle F \rangle$ never exceeds a value of 0.9. Burlaga et al. [1982] studied the evolution of fluctuation amplitudes with magnetic field data from Voyagers 1 and 2 at heliocentric distances from 1 to 5AU. They found a slight decrease in $\sigma_B/\langle F \rangle$ with increasing heliocentric distance. However, the variability was quite large and no distinction between unattenuated and saturated waves was possible.

The distributions $\sigma_F/\langle F \rangle$ in figure 2, which show that the field magnitude fluctuations are quite smaller in amplitude than the directional fluctuations, are broader for the aphelion periods than for the perihelion periods. This relative increase of $\sigma_F/\langle F \rangle$ with increasing heliocentric distance may point to a local generation of compressive fluctuations. Coleman et al. [1969] found the same results in Mariner 4 data between 1 and 1.5AU. However, Burlaga et al. [1982] found $\sigma_F/\langle F \rangle$ to remain almost constant from 1 to 5AU. There are two possible explanations for this discrepency. Firstly, $\sigma_F/\langle F \rangle$ may only increase with heliocentric distance out to ~ 1.5AU and remain approximately constant further out, where the constancy possibly is maintained by an equilibrium between generation and damping of compressive fluctuations. Secondly, the Helios-results shown were observed at minimum solar activity and may therefore be unique for these conditions.

Period range of the Alfvénic turbulence

To determine the period range of the Alfvénic turbulence we computed cross-spectra between $\underline{B}$ and $\underline{V}$. Figure 3 shows for one component auto power spectra, coherence and phase computed from data in high speed plasma near the first perihelion passage of Helios-2. These results are representative for spectra in high speed streams near perihelion. Coherence and phase between B_x and V_x show an almost perfect anticorrelation over a broad frequency range. At frequencies below 2.4×10^{-5} Hz the coherence is low, and therefore the fluctuations are not Alfvénic. These

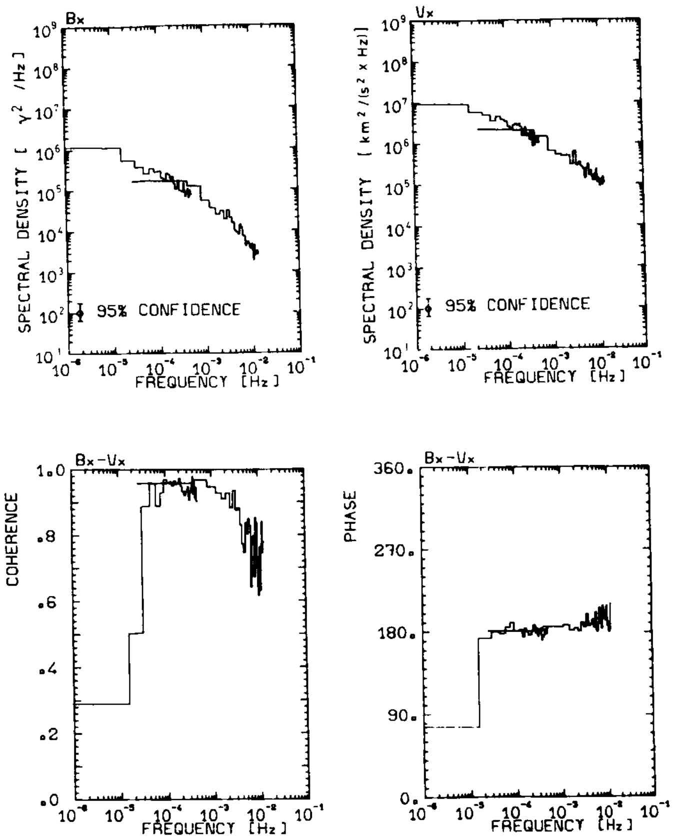

Figure 3. Power spectra B_x and V_x and coherence and phase between B_x and V_x for fluctuations in high speed plasma between 0.29 and 0.34 AU at the first perihelion passage of Helios-2. At low frequencies (10^{-6}Hz to 5 x 10^{-4}Hz) the spectra were computed from 1000s averages, in the higher frequency part (2.4 x 10^{-5}Hz to 1.2 x 10^{-2}Hz) from 40.5s averages.

fluctuations are apparently generated by larger-scale dynamical processes. The somewhat lower coherence above 3 x 10^{-3}Hz can at least in part be explained by the different kind of data which are correlated. The magnetic field data are averages over 40.5 sec, while the plasma experiment provides one data set each 40.5 sec, which is not necessarily the average value. A second reason may be a higher amount of compressive fluctuations at the higher frequencies. However, the coherence is still high up to 1.2 x 10^{-2}Hz and we consider the frequency range from 2.4 x 10^{-5}Hz to 1.2 x 10^{-2}Hz to contain Alfvénic turbulence. 1.2 x 10^{-2}Hz is certainly not the high frequency limit for Alfvénic turbulence, since from physical reasons we expect this limit at the proton gyrofrequency.

The coherences between $\underline{B}$ and $\underline{V}$ were computed for all data in high speed streams during the primary missions of the Helios spacecraft. At all heliocentric distances the results are quite similar, and we find no systematic variation. This may be surprising with respect to the low frequency limit, since the maximum Doppler shift at perihelion is 4 to 5 and at aphelion 8 to 9. However, one must consider that the resolution of the procedure in determining this lower frequency limit is quite poor (details may be found in Denskat and Neubauer [1982]).

Magnetic field power spectra from 0.29 to 1AU

For the primary missions of Helios-1 and -2 we computed power spectra of the interplanetary magnetic field in the frequency range containing Alfvénic turbulence (2.4×10^{-5}Hz to 1.2×10^{-2}Hz). Due to a larger number of data gaps from Helios-1, more spectra could be computed from the Helios-2 data. Only these were used for further analysis. Figure 4 shows examples of magnetic field power spectra at different distances from the sun. These spectra are quite representative for the locality where the data have been taken (both spectra were computed from data in high speed plasma streams). The power spectral density increases as the sun is aproached, in addition the slope of the power spectral density as a function of frequency changes significantly. The spectra are considerably flatter at 0.29AU than at 0.97AU with clear differences between the spectra for the field components and the field magnitude. For the components the major flattening at 0.29AU occurs below, say 2×10^{-3}Hz. Assuming a power law dependence for the spectral density P with $P \sim f^{-\alpha}$ the avarage best fit exponent α (determined by a least square method) varies between 1.59 and 1.69 at 0.97AU and between 0.87 and 1.15 at 0.29AU. The uncertainties are estimated with $\pm$ 0.12. Since at 0.29AU the power law fit $P \sim f^{-\alpha}$ does not seem to be the best possibility of representing the frequency dependence of the spectral densities, we made an additional exponential fit with $P \sim e^{-\beta f}$. However, for most of the distance range the power law fit was superior.

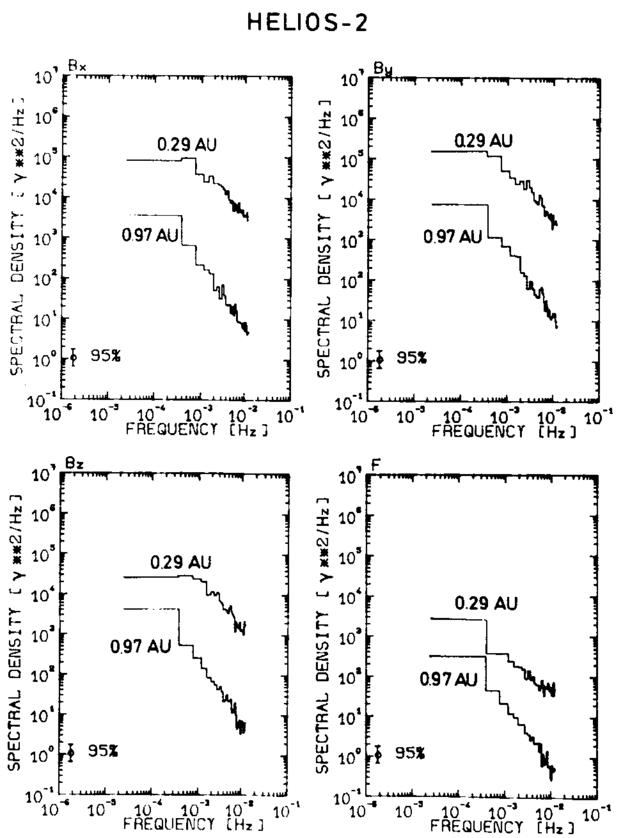

Figure 4. Magnetic field power spectra (vector components in MF-coordinates and magnitude) at different heliocentric distances from data in high speed plasma streams.

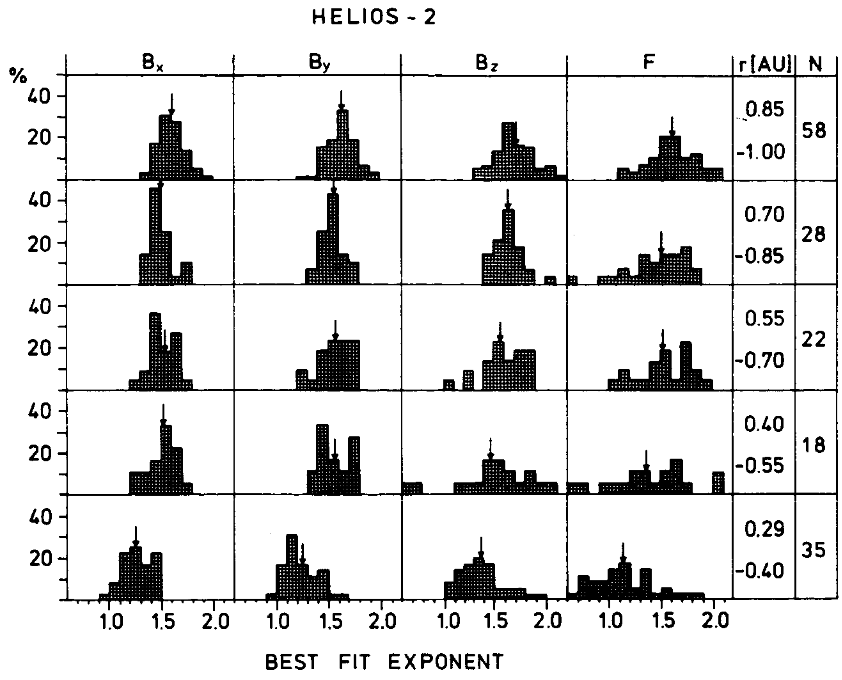

Figure 5. Distributions of best fit exponents α of magnetic field power spectra P (assumption $P \sim f^{-\alpha}$) for 5 heliocentric distance ranges. N gives the number of spectra computed in each distance interval, arrows mark the mean values of the distributions.

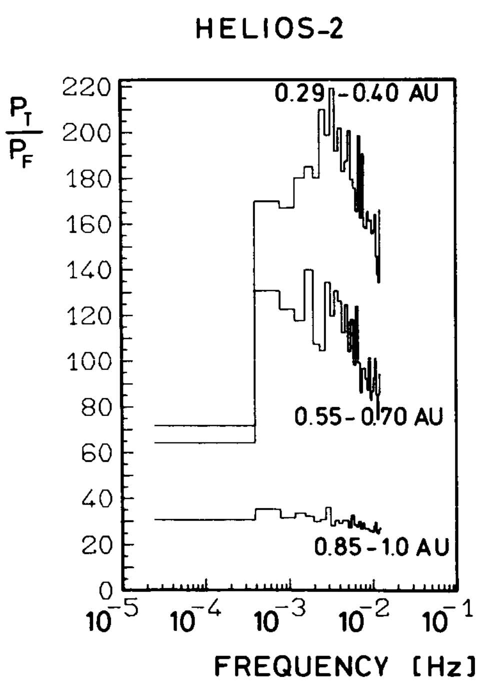

Figure 6. Average ratio P_T/P_F (P_T is the trace of the power spectral matrix; P_F is the power of the fluctuations in F) for three distance ranges as a function of frequency. The number of spectra averaged may be taken from figure 5.

Figures 5 and 6 give general information about the radial dependences of the steepness of the magnetic field spectra and about the different contribution of field magnitude fluctuations to the total power at different heliocentric distances for the Helios-2 primary mission. In figure 5 the spectral exponents generally show a large variability, but a systematic change only inside 0.4AU. This means that the very flat spectra at frequencies below 2×10^{-3}Hz occur only inside 0.4AU. Further out the spectra become increasingly steeper in this frequency range leading to spectra with a constant steepness from 2.4×10^{-5}Hz to 1.2×10^{-2}Hz.

We have no final explanation for these observations yet. There are several possibilities to explain this radial evolution of power spectral densities of magnetic field fluctuations. The reason may be a frequency dependent damping (at high frequencies) or a frequency dependent generation of magnetic field fluctuations (at low frequencies). Also possible is an inverse energy cascade in wave number space leading to this evolution of the spectra.

Figure 6 shows that the radial evolution of field magnitude fluctuations is quite different from the evolution of fluctuations in the field components. The ratio P_T/P_F varies with heliocentric distance and with frequency. At 1AU we find a non-frequency dependent behaviour of P_T/P_F, but inside 0.70AU this ratio is clearly frequency dependent. Obviously, the compressive magnetic field fluctuations become increasingly more powerful relative to the directional fluctuations with increasing heliocentric distance. In addition, this radial evolution is frequency dependent.

Parker [1982] studied spectral properties of the magnetic component of hydromagnetic fluctuations near 4 and 5AU from Pioneer-10 and -11 data. In a frequency range similar to our study he found magnetic field power spectra with smaller amplitudes than the ones found from the Helios-data at 1AU, but with very similar slopes. Apparently, the magnetic field power spectra of hydromagnetic fluctuations do not evolve further outside 1AU apart from a general amplitude decrease with increasing heliocentric distance.

Some years ago Coleman [1968] tried to explain the extremely structureless power spectra of magnetic field fluctuations in high speed plasma with the presence of an energy cascade in wave number space. In this context it is interesting to analyse magnetic field fluctuations in a frequency range extended well above the proton gyrofrequency. With the search coil magnetometer on board of Helios we are able to study magnetic field fluctuations with frequencies up to 2.2 kHz.

Figure 7 gives two examples of magnetic field spectra in high speed plasma streams from 2.4×10^{-5}Hz up to 470 Hz at 0.30AU and up to 100 Hz at 0.98AU. The power spectral densities in the frequency range of Alfvénic turbulence show the behaviour presented before. In the higher frequency range up to 2 Hz the power spectral density decreases with increasing heliocentric distance, but the steepness of the spectra remains unchanged. This is a typical feature of directional magnetic field fluctuations in this frequency range at all heliocentric distances analysed. Above 2 Hz there is a drop in spectral density together with a major change in spectral slope at the higher frequencies, where P is proportional to about f^{-3} as found by Beinroth and Neubauer [1981].

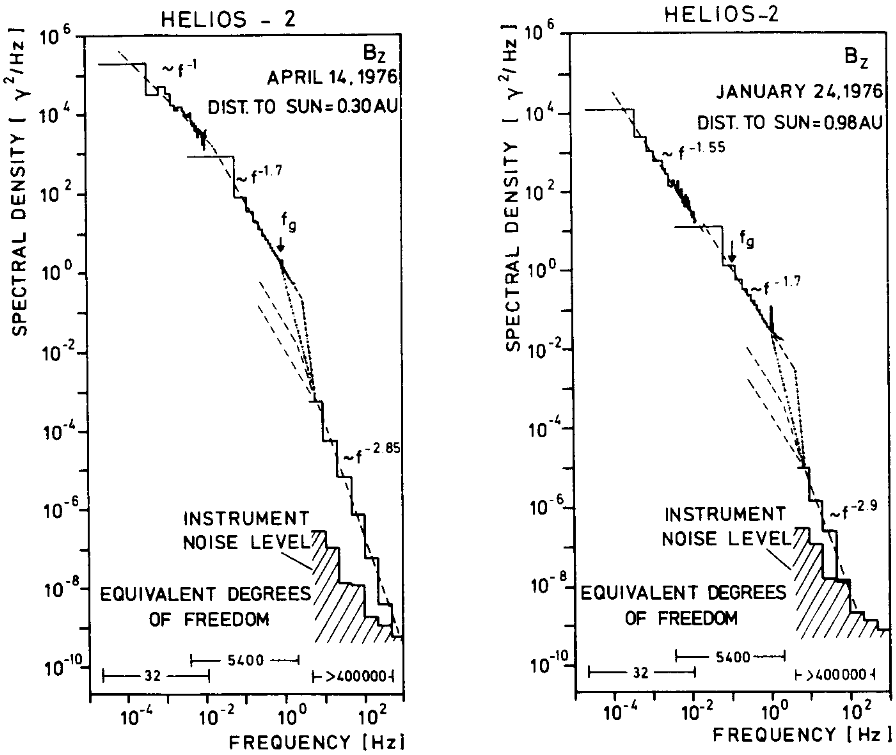

Figure 7. Power spectra of B_z at 0.30 and 0.98AU. Up to 2 Hz spectra are computed from fluxgate-magnetometer-data. The spectra above 4.7 Hz were measured with the search-coil-magnetometer. The spectral enhancement at 1 Hz is due to the spin of the spacecraft, which could not be removed totally from the data.

To interpret the radial evolution of magnetic field power spectra in this wide frequency range, one must consider the different wave modes possible at particular frequencies. The linear theory of wave propagation in a hot collisionless magnetoplasma described by the Vlasov-Maxwell set of equations (e.g. Montgomery and Tidman, 1964) yields an infinite number of wave modes most of which are strongly damped. At low frequencies below the dominant ion cyclotron frequency there are three important wave modes: the Alfvén wave and the fast and slow magnetoacoustic waves (e.g. Barnes, 1979). As the frequency approaches the He^{++} and the proton cyclotron frequencies the Alfvén waves are severly damped by ion cyclotron damping. Hence we expect an appreciable drop in power spectral density which is somewhat stretched out in frequency due to the Doppler-shift. The remaining power spectral densities at high frequencies than represent the continuation of the magnetoacoustic wave mode at the low frequencies usually called 'whistler' mode above the proton gyrofrequency. We therefore attribute the drop in spectral density between $\lesssim$ 2 Hz and 4.7 Hz to the damping of the Alfvén portion of the spectrum, which close to the ion gyro frequencies are generally refered to as ion cyclotron waves. Possible variations of the total spectral densities across the gap are indicated by dotted lines. The possible contributions of the magnetoacoustic component is indicated by dashed lines.

Conclusion

The Helios-observations between 0.29 and 1AU show that the occurrence of Alfvénic turbulence is essentially restricted to the high speed plasma streams independent of heliocentric distance. The fluctuation amplitudes of Alfvénic turbulence normalized by the average magnetic field magnitude show no systematic heliocentric distance dependence indicating that the fluctuation amplitudes may be in a saturated state. This is different for normalized field magnitude fluctuations, which become larger with increasing heliocentric distance.

The period range of Alfvénic turbulence is found to be between at least 81s (lower limit owing to the resolution of the plasma experiment) and approximately 12 hours (in the spacecraft frame).

Power spectra of the interplanetary magnetic field show a clear distance dependence. Up to 0.4AU the spectral slope is extremely flat at low frequencies up to $\sim 2 \times 10^{-3}$) and becomes increasingly steeper with increasing frequency. Further out in the solar wind the spectral slope up to 1.2×10^{-2}Hz is well represented by a power law with $P \sim f^{-1.6}$ on average. The reason for this behaviour may be frequency dependent damping (at the high frequencies) or frequency dependent generation (at the low frequencies) of the magnetic fluctuations. Another possibility is an inverse energy cascade in wave number space. Magnetic field power spectra extended up to 470 Hz show an increasing steepness of the spectra with increasing frequency. Spectra from 2×10^{-3}Hz up to the proton gyrofrequency are well represented by a power law $P \sim f^{-1.7}$ independent of heliocentric distance and the spectra above the proton gyrofrequency are well represented by a power law $P \sim f^{-3}$ independent of distance as well.

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