POWER SPECTRA OF THE INTERPLANETARY MAGNETIC FIELD NEAR THE EARTH

D. D. Childers and C. T. Russell

ABSTRACT

Power spectra of the interplanetary magnetic field measured by near-earth satellites upstream from the earth's bow shock are free from terrestrial contamination provided the field at the satellite does not intersect the bow shock. Considerable spectral enhancement for the range of frequencies 0.01 to 1.00 Hz, due to turbulence caused by the shock, may occur if the field observed at the satellite intersects the shock. This turbulence occurs frequently in both the morning and afternoon quadrants. In the frequency band from 0.07 to 1 Hz, this noise decreases in amplitude with radial distance from the shock with an attenuation length of 4 R_E.

INTRODUCTION

Since the first measurements of the interplanetary medium, power spectra of the interplanetary field have been calculated to characterize the nature of the fluctuations observed [*Coleman,* 1966, 1967, 1968; *Siscoe et al.*, 1968; *Sari and Ness,* 1969]. Not only was it hoped that the power spectrum would lead to insight into the physical processes occurring in the solar wind, but also that the power spectrum could be related to the diffusion of energetic particles from cosmic rays [*Jokipii,* 1966] to solar electrons [*Lin,* 1970]. For a 1-GeV cosmic ray, fluctuations at frequencies of the order of 10^{-4} Hz are important in the diffusion process, but for a 40-keV electron frequencies near 1 Hz are dominant. Thus, it is necessary to know the spectrum of the interplanetary magnetic fluctuations over a wide frequency range.

Clearly, earth-orbiting spacecraft that enter the magnetosheath and magnetosphere every few days are not capable of determining the spectrum below frequencies of the order of 10^{-4} Hz. Thus necessarily our knowledge of this low frequency portion of the interplanetary spectrum has come from deep space probes such as Mariner 2 [*Coleman,* 1966, 1967, 1968], Pioneer 6 [*Ness et al.*, 1966; *Sari and Ness,* 1969], and Mariner 4 [*Siscoe et al.*, 1968]. These spacecraft have also returned information up to frequencies from 10^{-2} to 10^{-1} Hz; because of the remoteness from the earth of these probes; however, their telemetry rates have not permitted an examination of the spectrum at higher frequencies.

Recent near-earth spacecraft, such as the OGO series, have had a much higher telemetry rate and thus can extend the spectrum to much higher frequencies. However, the interplanetary magnetic field beyond the earth's bow shock is not always free from the fluctuations associated with the interaction of the solar wind with the earth. To the extent that we are interested in examining the spectrum of waves in the interplanetary medium at 1 AU due to strictly solar wind related processes, these waves contaminate the interplanetary spectrum.

In this paper, we use data obtained in the near-earth interplanetary medium by the UCLA OGO-5 fluxgate magnetometer to show how the spectrum is altered by these so-called "upstream waves," and where this contamination is observed. A detailed description of this magnetometer has been given by *Aubry et al.* [1971], but a few relevant facts will be mentioned here. First, OGO-5 has an apogee of 24 R_E and thus at maximum is only 10 R_E from the earth's bow shock. Second, the

Dr. Childers is with the UCLA Department of Planetary and Space Science. Dr. Russell is with the UCLA Institute of Geophysics and Planetary Physics.

data are digitized to within ±1/16 γ, and the data used in this paper have a Nyquist frequency (1/2 the sampling frequency) of 3.47 Hz. This results in a digital noise level of ~3 × 10^{-4} γ^2/Hz, which is the limiting noise level for the data presented here.

We first compare OGO-5 spectra calculated both in the presence and absence of upstream waves with previous deep space measurements. We then show examples of the kinds of waves encountered in this region. Finally, we will present a map of the region of occurrence of these upstream waves and obtain an attenuation length for the higher frequency components of these waves.

COMPARISON OF OGO-5 AND MARINER 4 POWER SPECTRA

Figure 1 shows the power spectra of the radial components (in a heliocentric spherical coordinate system) of both typical quiet and disturbed magnetic fields for both the near-earth region upstream from the earth's bow shock (referred to below as the upstream region), observed with OGO-5, and the distant interplanetary region (but with a heliocentric distance of about 1.0 AU) observed on the Mariner 4 spacecraft. The Mariner spectra have been taken from *Siscoe et al.* [1968]; the flattening of the spectra at high frequencies is due to digitization noise. The interval of the OGO quiet spectrum is 2123 to 2223 UT, March 7, 1968. Above 0.07 Hz this spectrum has been computed from the digitally sampled data using 486 degrees of freedom per spectral estimate; the lower frequency portion has been computed from time-averaged data using 20 degrees of freedom per estimate. For this interval, OGO-5 was on the morning side of the sun-earth line at an average geocentric distance of 20.9 R_E and at a sun-earth-satellite (SES) angle of 63.1°. For the disturbed OGO spectrum the interval 0856 to 1035 UT, March 10, 1968, was used; again, OGO-5 was on the morning side, but at an average geocentric distance of 19.6 R_E and at an SES of 66.7°. The same techniques for computing the spectra as just outlined are employed, but the degrees of freedom per estimate are 40 and 810 for the low- and high-frequency parts of the spectrum, respectively.

A comparison of the two quiet spectra of figure 1 reveals that they agree rather well: They both exhibit, in general, roughly the same power law dependence on frequency in the region of frequency overlap, viz., $P(f) \propto f^{-1.5}$, and the power levels are similar. However, above 0.1 Hz, the OGO spectrum becomes steeper, obeying $P(f) \propto f^{-2}$. Closer inspection of this typical quiet OGO spectrum reveals that, for the overlapping frequencies, its power level actually is intermediate between the two Mariner spectra. The Mariner disturbed

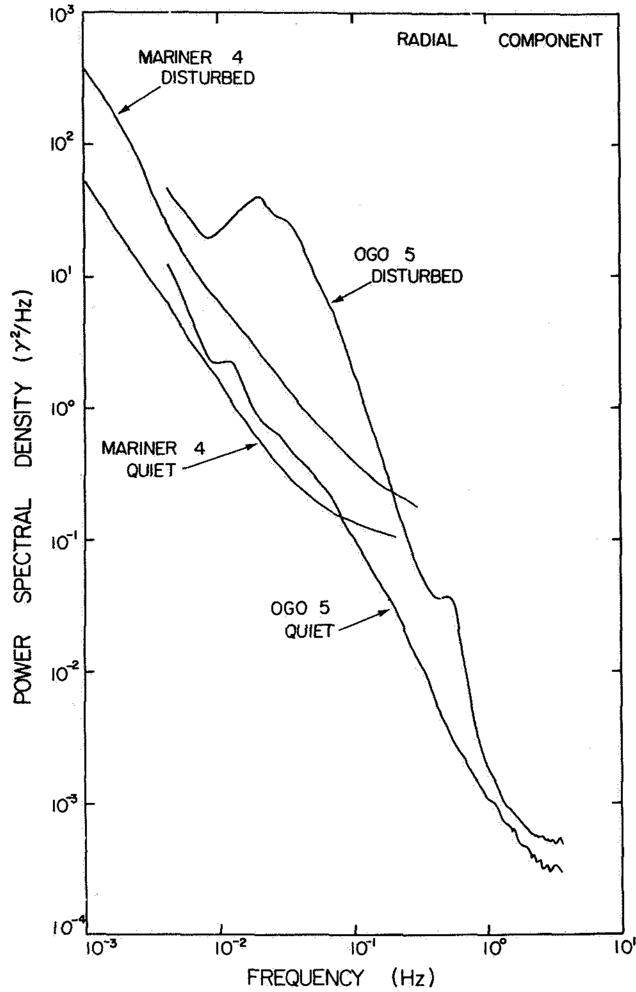

Figure 1. *Comparison of the power spectra of near-earth interplanetary fields, observed with OGO-5, with the spectra of interplanetary fields far from the earth, observed with Mariner 4 [Siscoe et al., 1968]. Spectra of the radial components, in a heliocentric spherical coordinate system, of both typical quiet and typical disturbed fields measured at both spacecraft are shown. The Mariner 4 spectra are taken from figure 2(a) of Siscoe et al. [1968]. The OGO-5 quiet spectrum was obtained from 2123 to 2223 UT, March 7, 1968, while the disturbed spectrum was obtained 0856 to 1035 UT, March 10, 1968.*

spectrum also has a power law exponent $\gamma \simeq 1.5$, where $P(f) \propto f^{-\gamma}$. Since the quiet OGO spectrum has the same power law exponent, at least up to 0.1 Hz, as do the two Mariner spectra, and since its power level lies within the range of the quiet and disturbed Mariner spectra which are characteristic of the interplanetary field far from the earth, it is evident that at times OGO-5 data can be used to extend our knowledge of the interplanetary spectrum.

However, when the near-earth field is disturbed, its spectrum can be quite different from the typical 1 AU interplanetary spectrum. Examining the two disturbed spectra reveals that the OGO spectrum is significantly enhanced in power over the Mariner spectrum for most of their common frequency range, $0.004 < f < 0.5$ Hz. This enhancement peaks around $f = 0.03$ Hz; below $f = 0.008$ Hz the OGO spectrum appears to fit onto the Mariner spectrum rather well. At frequencies above that of the low-frequency spectral peak, the OGO spectrum exhibits a power law exponent of $\gamma \gtrsim 3$, except, of course, that part of the spectrum around the peak at $f = 0.55$ Hz; on the other hand, the Mariner spectrum has $\gamma \simeq 1.5$. The low-frequency spectral peak is typical of disturbed OGO spectra, but, although the high frequency peak is a common feature of disturbed upstream fields, it does not always occur. The significance of both these spectral peaks will be discussed later.

From an examination of many such spectra we have found that the following characteristics distinguish disturbed upstream fields from distant interplanetary fields: (1) the upstream spectra are significantly enhanced over those of interplanetary fields for periods T ranging from the order of seconds to just over 100 sec; (2) this spectral power peaks at periods typically from 20–30 sec; and (3) at frequencies above the peak the power law exponent for the spectrum is $\gamma \gtrsim 3$, as compared to typical interplanetary values $\gamma \simeq 1.5$.

UPSTREAM WAVES

The power spectrum of disturbed upstream interplanetary fields shown in figure 1 was noted to have two spectral peaks. We first consider the low-frequency peak, which is a typical feature of disturbed fields observed near the earth. *Fairfield* [1969] has studied the properties of waves in the interplanetary field, in the 0.01 to 0.05-Hz frequency range, associated with the earth's bow shock. Figure 2 compares one of *Fairfield's* [1969] power spectra, computed from the IMP-4 (Explorer 34) magnetometer data, with the OGO-5 spectrum of the same disturbed interval shown in figure 1. Only the spectra of components transverse to the average field during their respective intervals are displayed. The two spectra agree very well. They both peak at $f \simeq 0.03$ Hz and have similar power law exponents for higher frequencies. This is to be expected, of course, because they were both obtained near the earth under similar conditions. Any significance in the higher power level for the OGO spectrum can be attributed to the fact that the IMP 4 is farther upstream.

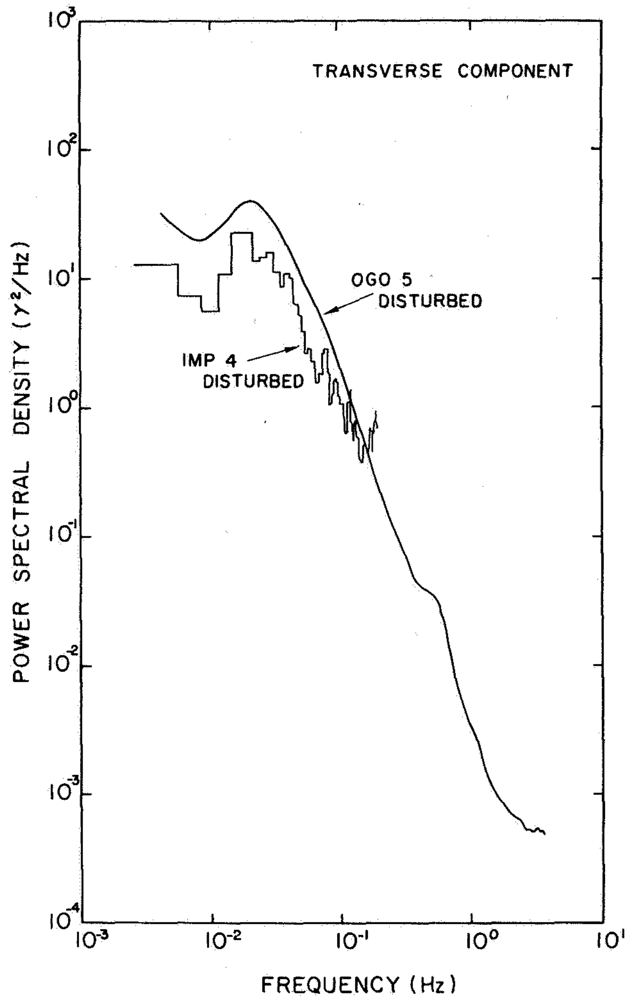

Figure 2. *Comparison of the power spectra of disturbed fields observed with OGO-5 with those observed with IMP 4 [Fairfield, 1969]. Shown are spectra for a component transverse to the average field direction in each case. The OGO-5 spectrum is for the same interval displayed in figure 1 (0856 to 1035 UT, March 10, 1968), while the IMP 4 spectrum is for the interval from 0102 to 0129 UT on July 3, 1967.*

Fairfield [1969] showed convincingly that these waves are associated with the earth's bow shock. Among other things, he found that these waves occur only when the interplanetary field observed at the satellite intersects the bow shock. More recently, these same conclusions have been reached by *Greenstadt et al.* [1970], who used simultaneous field observations of Vela 3A and Explorer 33 to study the occurrence properties of these upstream waves. Since it is improbable that hydromagnetic waves could travel to the position of the satellite against the solar wind flow velocity, and since particles reflected at the shock have been observed moving along field lines into the solar wind [see, for example, *Anderson,* 1968, 1969; *Asbridge et al.,* 1968; *Frank and Shope,* 1968], we attribute these waves to an unspecified instability of the reflected particles.

Before considering the high-frequency peaks, it is perhaps instructive to examine the spectra of all three components of the disturbed OGO fields. Figure 3 shows the spectra of all components in a heliocentric spherical coordinate system for the same interval, 0856 to 1035 UT, March 10, 1968, as shown in figures 1 and 2. Clearly, the spectra of the two transverse components of the field are similar to that of the radial component in almost every detail; however, the transverse spectra are seen to have more power than the radial spectrum. This feature, which was noted by *Siscoe et al.* [1968] to occur also for distant interplanetary fields, is rather typical of the disturbed upstream fields.

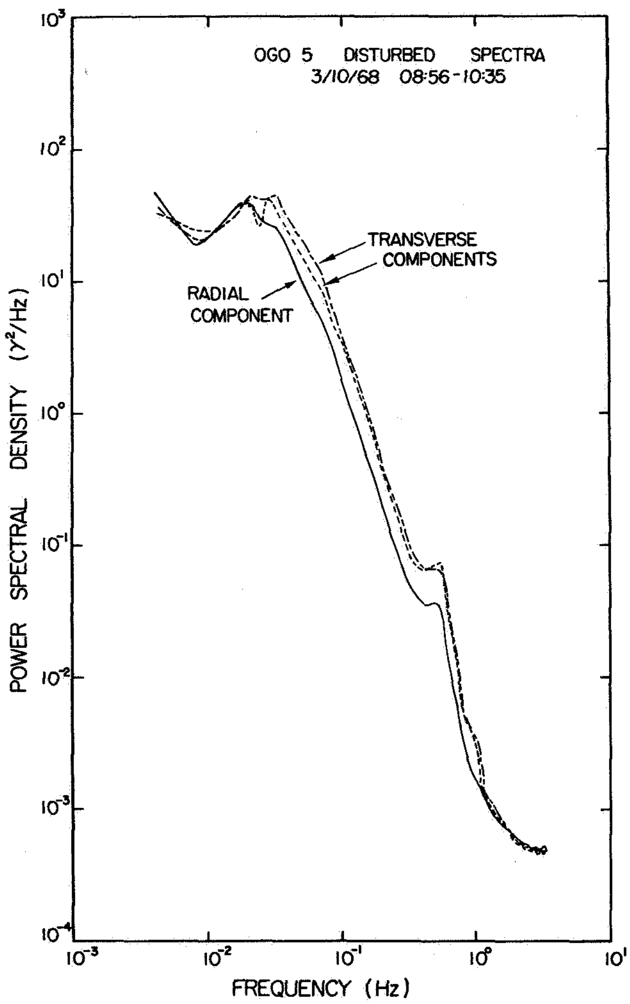

Figure 3. *OGO-5 power spectra of all three vector components for the period 0856 to 1035 UT March 10, 1968. Spectra are for the radial and transverse components in a heliocentric spherical coordinate system. The solid line represents the radial component, the uniformly dashed line the azimuthal component, and the other dashed trace the northward component.*

The spectral peak at $f = 0.55$ Hz occurs on all three spectra; the cross-spectral coherences at $f = 0.55$ Hz are very large among all three components, with the largest coherence being 91 percent for the two transverse components. For these particular spectra, these peaks at $f = 0.55$ Hz are caused by the occurrence of several discrete wave packets of a class that has been analyzed in some detail by *Russell et al.* [1971]. Some of these packets for this interval are illustrated in figure 4. Note

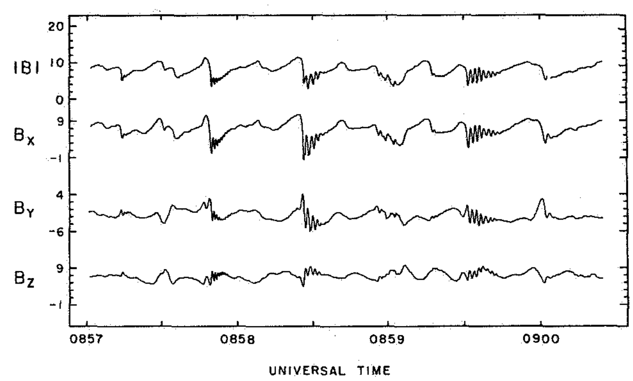

Figure 4. *Discrete wave packets occurring in association with irregular low-frequency waves on March 10, 1968, while the satellite was at 19.1 R_E and at a sun-earth-satellite angle of 67.5°.*

that low-frequency fluctuations of the type discussed earlier occur here along with these high frequency wave packets. *Russell et al.* [1971] have found that the discrete wave packets are more likely to occur when the lower frequency turbulence is present, which explains in part why the high-frequency (0.1 to 1.0 Hz) spectral peaks are rather common features of disturbed upstream fields. Often high-frequency spectral peaks occur in upstream spectra which are due, not to discrete wave packets, but rather to continuous waveforms as illustrated in figure 5. These waves, too, are associated with the occurrence of the low-frequency turbulence, of which another example is shown superposed on the high frequency fluctuations in figure 5. However, we emphasize that, although these higher frequency spectral peaks are very common among disturbed upstream spectra, they do not occur all the time.

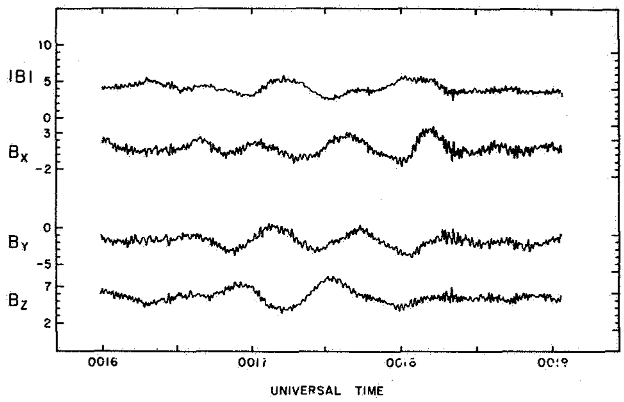

Figure 5. *Continual high frequency waves simultaneous with quasi-sinusoidal low-frequency waves on March 8, 1968, while the satellite was at 21.9 R_E and at a sun-earth-satellite angle of 61.3°.*

SPATIAL PROPERTIES OF THE UPSTREAM TURBULENCE

On the average, the interplanetary field lies along the Parker spiral angle, and field lines upstream from the bow shock on the afternoon side of the earth do not intersect the bow shock. Thus, upstream waves usually are not present in this region. Deviations from the spiral angle occur frequently enough, however, that even here upstream waves are seldom entirely absent for periods of more than 5 hr (at the OGO-5 orbit). Thus far, the data shown have been obtained entirely on the morning side of the earth. Figure 6 shows power spectra obtained on the afternoon side of the earth while OGO-5 was at a geocentric distance of 19.9 R_E and a SES of 59.3°. We see that, when waves are observed in this region, the spectra are the same as on the morning side as shown in figure 3.

The major difference between the morning and afternoon sides of the upstream region is not in the spectral character of the waves but in their frequency of occurrence. This becomes evident when we attempt to map the average amplitude of the turbulence upstream from the shock. We decided to construct such a map from the amplitudes in the frequency range from 0.07 to approximately 1 Hz, because this quantity was available as a minutely average from the regular OGO-5 data processing. Although this frequency range does not include the spectral peak at ~0.03 Hz, it is thought that the average behavior of the turbulence can be obtained from the amplitudes at slightly higher frequencies.

To make this map, we used data from the first 1-1/2 years of OGO-5 operation containing over 1200 hr in the interplanetary medium. Only data for times during

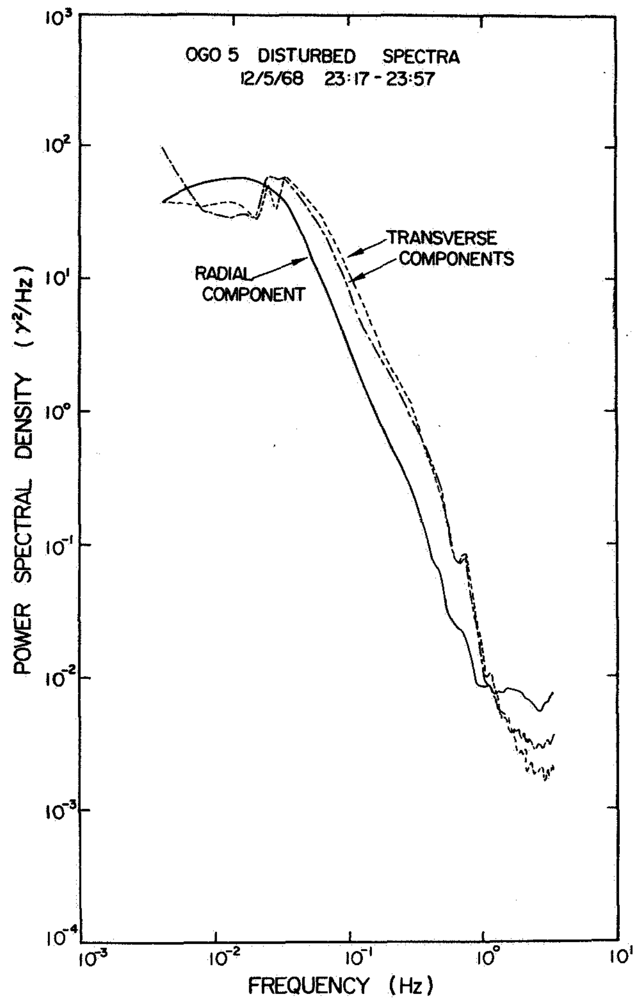

Figure 6. *OGO-5 power spectra of disturbed upstream fields observed on the afternoon side of the sun-earth line for the interval 2317 to 2357 UT on December 5, 1968. The spectra are shown in the heliocentric coordinate system described in figure 3.*

which the satellite was within 40° azimuth of the solar magnetospheric (GSM) equatorial plane were used. The azimuthal angle is defined here in a geocentric spherical coordinate system that used the solar direction (GSM X axis) as the polar axis; the GSM Y axis, which is perpendicular to both the GSM X axis and the earth's magnetic dipole axis and points generally oppositely to the earth's orbital motion, is the reference axis for this azimuthal angle.

Figure 7 shows the results of this mapping. The vertical axis represents the geocentric distance, in earth radii, along the solar direction of observation point, while the horizontal axis is of the distance perpendicular to this direction; the outer curve represents the OGO-5

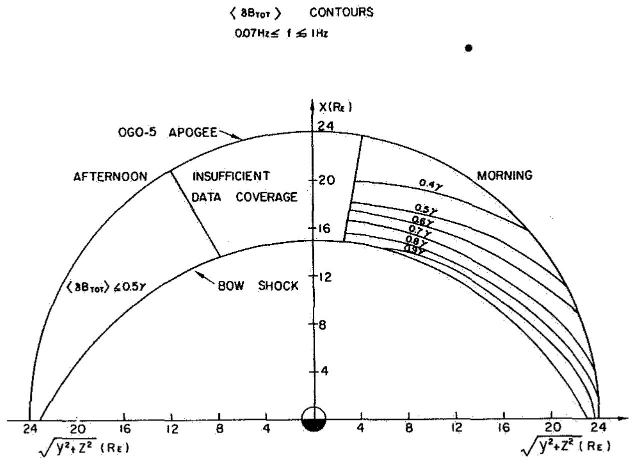

Figure 7. *A contour map of the average rms amplitudes of magnetic field turbulence, in the frequency range $0.07 \leqslant f \lesssim 1$ Hz, observed upstream of the average position of the earth's bow shock (inner curve). The outer curve represents the OGO-5 apogee at 24 R_E.*

apogee, at 24 R_E, while the inner curve is of the average bow shock position (no aberration of the shock position is assumed). On the afternoon side no contours are shown, since within our statistical accuracy no unambiguous spatial dependence of wave rms amplitudes was found. However, we were able to conclude from our data that the average rms field amplitude in this region is about 0.5 γ or less, and thus the region is marked. No data coverage is available near the subsolar point (the X axis) from the OGO-5 orbit.

In the morning region, however, there is an unambiguous spatial dependence of the average wave amplitudes. The contours of the average amplitudes range from 0.4 γ up to 0.9 γ, and these contours roughly parallel the shock front. Furthermore, the amplitude is greatest near the shock and decreases with increasing distance from the shock. This further illustrates that the source of the energy for these waves comes from some process in the earth's bow shock.

To examine the significance of these contours, it was recalled that *Fairfield* [1969] reported that the occurrence of the lower frequency waves ($0.01 < f < 0.05$ Hz) at the IMP 4 is consistent with the concept of a source at the shock transmitting information–waves or, most probably, particles–along interplanetary field lines threading the shock to the satellite position, where this information is then responsible in some way for the observed fluctuations. He measured the propagation velocity of such information along field lines to be about 2.7 times the solar wind velocity. We can apply this result to our contours of wave fields in a slightly higher frequency range, as shown in figure 8. As illustrated in the inset, we assume a typical spiral field angle of 45° to the X axis; the information streams out along the field at a velocity of 2.7 V_{SW}. In the shock frame the solar wind velocity adds to this, resulting in a velocity direction in this frame of 25.5° to the negative Y axis (or, equivalently, 64.5° to the solar direction). Lines of this direction are shown sketched across the region containing the 0.5 γ and 0.8 γ contours. We also make three further assumptions: (1) the contours will be assumed to be axially symmetric about the X axis (on the morning side only); (2) the shock will be assumed to be uniformly distributed with information radiators, hence the equispaced lines; and (3) any turbulence generated upstream of a particular contour by this or any other shock-associated mechanism and convected past the contour will be ignored. We then find that the distances from the average shock position to the two contours along these information lines, over the region in which both contours are connected by the lines, to be remarkably constant. The mean distance along these information lines for the 0.8 γ contour is 1.6 R_E, and for 0.5 γ contour it is 5.6 R_E. Since the power ratio of the wave fields represented by these contours is roughly *e*, we therefore find that the attenuation length of the turbulence field, for frequencies 0.07 to the order of

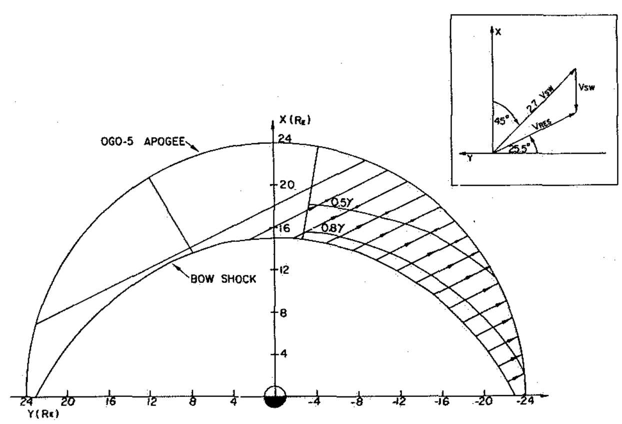

Figure 8. *In the inset it is shown schematically that information propagating upstream along the interplanetary field, at a typical spiral field angle of 45° to the sun-earth line (X axis), with a velocity of 2.7 V_{SW} appears in the shock frame to propagate at a resultant angle of 25.5° to the Y axis. The rest of the figure is a reproduction of the 0.8-γ and 0.5-γ contours from figure 7, along with information lines at 25.5° to the Y axis superposed. The distances from the shock position to the 0.8-γ and 0.5-γ contours are 1.6 R_E and 5.6 R_E, respectively.*

1 Hz, is approximately 4 R_E. This is to be contrasted with *Fairfield's* [1969] estimate of an attenuation length of approximately 15 R_E for the turbulence at lower frequencies of 0.01 to 0.05 Hz.

SUMMARY

We have shown that it is possible to calculate power spectra of the interplanetary magnetic field, free of any evident terrestrial contamination from data obtained by spacecraft such as OGO-5, which probe the interplanetary medium in the vicinity of the earth's bow shock. However, to avoid terrestrial contamination of the spectra, the measurements must be performed for times during which the field line threading the satellite does not intersect the bow shock.

When the observed field at the satellite does intersect the shock, then the power spectra may be substantially enhanced at frequencies from about 0.01 to 1 Hz, with a peak in power occurring at frequencies from 0.01 to 0.05 Hz. This spectral enhancement is a consequence of turbulence generated by some shock-associated process, probably by particles reflected at the bow shock and traveling against the solar wind along field lines. Because of deviations of the interplanetary field from its average spiral angle, these upstream effects are observed often in the afternoon upstream region, as well as in the morning hemisphere. In the afternoon quadrant at the OGO-5 orbit, the effect of these deviations is such as to make periods of greater than five hours duration during which these upstream waves are absent very rare.

From our OGO-5 data, we estimate the attenuation length of the high frequency components, from 0.07 to about 1 Hz, of the shock-associated turbulence to be about 4 R_E. However, low-frequency shock-associated waves have been observed as far as 46 R_E from the average bow shock position [*Fairfield,* 1969]. Therefore, power spectra of the interplanetary field can be contaminated by terrestrial effects at considerable distances upstream from the bow shock.

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