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# Numerical simulations of large-scale solar wind fluctuations observed by Ulysses at high heliographic latitudes

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**Abstract.** An analysis of Ulysses plasma and magnetic field data from the high southern latitude pass revealed that at large spatial scales corresponding to wave frequencies below  $10^{-5}$  Hz in the spacecraft frame, there is a transition from highly Alfvénic turbulence in all three spatial components of the fields to fluctuations which are Alfvénic only in field components transverse to the radial direction with uncorrelated radial magnetic and velocity fields. We find that the general properties of the turbulence can be simulated using a spectral method solution of the magnetohydrodynamic (MHD) equations only when certain types of initial conditions are employed. These simulations place constraints on conditions in the solar atmosphere that can generate the observed fluctuations.

## Introduction

The high latitude southern pass of Ulysses has provided a unique opportunity to study turbulence in the solar wind when the magnetic field was predominantly radial and the solar wind speed was both high and relatively uniform. Many aspects of the high latitude fluctuations reflect expectations derived from Helios and Voyager studies in the ecliptic, primarily during solar minimum [Goldstein *et al.*, 1995b,c; Roberts, 1990; Roberts *et al.*, 1992]. Both Horbury *et al.* [1995] and Goldstein *et al.* [1995a] concluded that the evolution of interplanetary turbulence as deduced from Ulysses observations reflected primarily changes with heliocentric distance, rather than with heliolatitude.

One interesting aspect of the turbulence, most evident in the Ulysses data obtained near 2 AU during the high southern latitude pass (DOY 229–282, 1994) and also evident in 0.3 AU Helios data, is the way in which the degree of Alfvénicity changes across the frequency band. The magnetic and velocity field fluctuations for  $f > 10^{-5}$  Hz were highly correlated, implying that the fluctuations are highly Alfvénic. This feature of the solar wind fluctuations is seen often in the inner heliosphere, especially during times of reduced solar activity [Belcher and Davis, 1971; Matthaeus and Goldstein, 1982]. However, at lower frequencies the degree of Alfvénicity of both the Helios and Ulysses data decreased significantly. The decrease does not arise from a general lack of correlation of all components of the fields, but rather is due to a loss of correlation of only the radial components; the transverse components of the fields remain highly correlated.

This change in spectral characteristics near  $10^{-5}$  Hz is illustrated in Figure 1 (after Goldstein *et al.* [1995a]) where we have plotted

the normalized cross helicity ( $\sigma_c \equiv 2H_c/E$ , where  $H_c = (1/2) \langle \delta v \cdot \delta b \rangle$  and  $\delta b$  is in Alfvén speed units [Matthaeus and Goldstein, 1982]). The three curves in Figure 1a are  $\sigma_c(f)$ , formed from the ratio of the Fourier transforms of  $H_c$  and  $E$ , and  $\sigma_{cr}(f)$  and  $\sigma_{c\perp}(f)$  constructed from the ratio of the Fourier transforms of the radial and transverse components of  $H_c$  and  $E$ , respectively.

Above  $10^{-5}$  Hz the fluctuations are seen to be highly Alfvénic, with a normalized cross helicity that is  $\sim 0.9$ ; however, below  $10^{-5}$  Hz the degree of correlation of the radial components of fields decreases sharply and is essentially 0 below a few times  $10^{-6}$  Hz. In contrast, the transverse components of the field are still highly correlated, albeit at a level closer to 0.7–0.8. The analysis of Goldstein *et al.* [1995a] showed that by 4 AU the correlation in the transverse components had decreased below 0.5 in this frequency range. Thus, it would appear that the natural evolution of the turbulence is to reduce all components of the cross helicity with increasing distance, which is certainly consistent with previous analyses of Helios and Voyager data [Bavassano *et al.*, 1982; Grappin *et al.*, 1990; Roberts *et al.*, 1987a,b]. For this same data interval, we show the Alfvén ratio  $r_A = E/vB$  in Figure 1b. The Alfvén ratio  $r_{A\perp}$  (formed from the ratio of the perpendicular components of the kinetic and magnetic energy) in the frequency range  $10^{-5}$ – $10^{-6}$  Hz is near 1/2, typical of fully developed turbulence in the solar wind and characteristic of the value of  $r_A$  at higher frequencies. In contrast,  $r_A$  formed from the radial components of magnetic and kinetic energy is very large, reflecting the dominance of fluctuations in the radial component of the velocity at these scales.

While turbulence is an intrinsically thermodynamically irreversible process, which implies that one cannot, in principle, determine the initial conditions which produce a given observed turbulent state, nonetheless, it is possible to check the consistency of certain classes of initial conditions against the observations. That is the philosophy which we follow in this letter.

## Possible Interpretations

The fact that the transverse components of the fluctuating fields appear to be highly correlated at all frequencies above  $10^{-6}$  Hz, while the radial components only become correlated above  $10^{-5}$  Hz, suggests several possible interpretations, two of which we test here by numerical simulation. The assumption common to both of these interpretations is that the observations reflect some real aspect of the in situ state of the fluid. A third possibility, which we do not explore here, is that the observations reflect an aliasing effect that arises because of the Sun's rotation beneath the spacecraft (see Goldstein *et al.* [1995a]). The frequency range of interest is  $10^{-5}$ – $10^{-6}$  Hz, covers periods from many hours to several days. During such long time intervals, many magnetic flux tubes and/or velocity streams sweep past the spacecraft. Consequently, the temporal sig-

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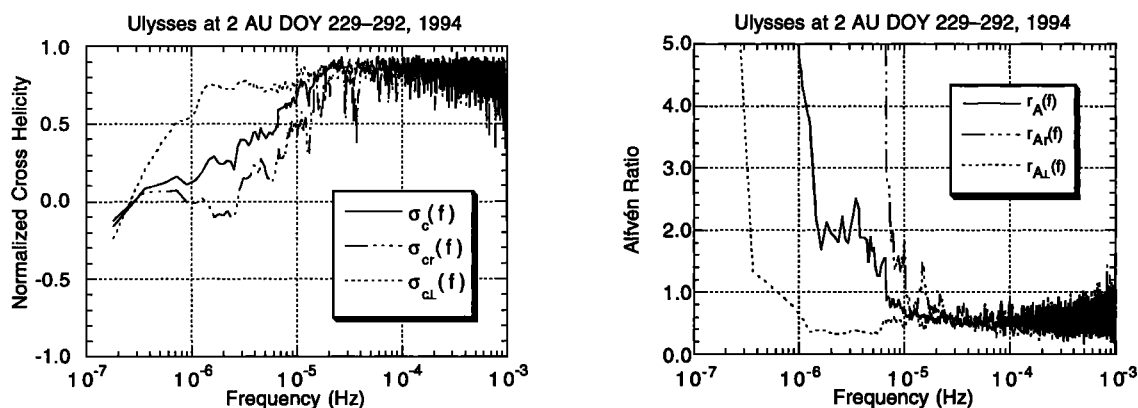


Figure 1. (a) The normalized cross helicity  $\sigma_c(f)$  calculated from the trace of the power spectral densities of  $z^\pm$  and the radial and transverse normalized cross helicities computed from the radial and transverse components of  $z^\pm$ , for the 2 AU Ulysses interval. (b) The spectrum of  $r_A(f)$  calculated as was  $\sigma_c(f)$  for the 2 AU Ulysses interval.

nal being received cannot be associated with structures originating at a single location in the solar corona. Thus, the spectral response seen in the  $10^{-5}$ – $10^{-6}$  Hz band may reflect under-sampling of higher frequency fluctuations. We have begun testing this hypothesis, as well, using simulated data, but we defer discussion of that work to a subsequent communication. In what follows below, we ignore the possible effects of solar rotation.

The first of the interpretations which we test here is to assume that the initial state for fluctuations is one in which transverse (quasi-planar) Alfvén waves are generated in the band  $10^{-6}$ – $10^{-5}$  Hz. Consistent with the observations, we also assume radially aligned velocity fluctuations at these scales; these are nonAlfvénic (and nearly nonmagnetic) and are expected to be the major driver of the subsequent evolution. We explore first whether these fluctuations interact to produce a Kolmogoroff inertial range spectrum ( $\sim k^{-5/3}$ ). We also wish to see whether  $\sigma_{cr}$  produced by the cascade becomes comparable to  $\sigma_{cl}$ , although  $\sigma_{cr}$  was initially close to 0. The goal is to examine the possibility that the initial fluctuations are only Alfvénic in the transverse components and that turbulent evolution “entrains” the radial component to be Alfvénic at high frequencies.

The second interpretation we test is motivated by *Heinemann and Olbert's* [1980] conclusion (also see *Jokipii and Kóta* [1989] and *Jokipii et al.* [1995]) that it is physically difficult for Alfvén waves to propagate in the solar wind at frequencies much below  $10^{-5}$  Hz. (This difficulty is removed if the observed fluctuations arise from an aliasing effect.) We assume in this scenario that the Alfvénic fluctuations are produced only above  $10^{-5}$  Hz, but that as the fluid is convected outward in the corona, long wavelength velocity structures cause the magnetic field to bend so that the spectrum below  $10^{-5}$  Hz includes significant power through coupling to higher frequencies. Because the higher frequency fluctuations are Alfvénic, the composite spectrum might then resemble the observations.

In the next section we outline the two numerical simulations designed to explore these two possible interpretations. This is followed in the last section with a discussion of the results and conclusions.

## Numerical Solution of the MHD Equations

To explore which classes of initial conditions might evolve to a state compatible with the observations, we used a high resolution pseudospectral method algorithm to solve the compressible MHD equations [Ghosh et al., 1993a,b]. Because we wish to have a sub-

stantial spectral range that is nearly dissipation-free, fairly high spatial resolution was required (256×256 modes), which precluded the use of a fully three-dimensional code, at least for these preliminary studies. Therefore, we restricted ourselves to two spatial dimensions, but did include all three components of the fluctuating magnetic and velocity fields. We refer to this as a 2 1/2-dimensional code. The equations solved describe fully compressible MHD, and we used a polytropic relationship between density and pressure, thus obviating the necessity of solving an explicit energy equation.

## Interaction of Transverse Alfvénic Fluctuations with Fluctuations in the Parallel Velocity

To investigate how a magnetofluid evolves if it contains an initial population of highly Alfvénic transverse fluctuations confined to a limited bandwidth in wave number and subjected to field aligned velocity shear, we superimposed transverse fluctuations onto a more energetic background of fluctuations in the radial component of the velocity (parallel to the mean magnetic field  $B_0$ ). There are two extreme ways in which such radial fluctuations can be created: First, they can be compressive fluctuations ( $\nabla \cdot \mathbf{u} \neq 0$ ); or second, they can be incompressive (solenoidal) fluctuations ( $\nabla \cdot \mathbf{u} = 0$ ). We found that only the incompressive initial state evolved to resemble the observations, suggesting that the observed variations in radial speed primarily reflect velocity shears; only the incompressive case is presented here.

To create the initial state described above, we first defined an isotropic spectrum of solenoidal velocity and magnetic field fluctuations in the band  $1 \leq k \leq 4$  such that the (modal) power spectrum for both  $E_V(k)$  and  $E_B(k)$  had a  $k^{-1}$  spectral shape. (Power spectra computed from both Ulysses and Helios have relatively flat spectra at small wave numbers [Goldstein et al., 1995a].) The total solenoidal energies had an Alfvén ratio  $r_A = E_V/E_B = 0.4$  with  $E_V + E_B = 0.5$ . The normalized cross helicity,  $\sigma_c = 2 H_c/E$ , was  $\sigma_c = 0.9$  and the magnetic helicity  $H_m = \langle \mathbf{A} \cdot \mathbf{b} \rangle$  was small ( $H_m = 0.1$ ). ( $\mathbf{A}$  is the vector potential in the Coulomb gauge [Matthaeus and Goldstein, 1982].) To create a spectrum with a minimum variance along the mean magnetic field, as observed, the distribution of fluctuations was then modified so that the ratio of transverse to parallel energies,  $E_\perp/E_\parallel$ , was 10, keeping the total solenoidal energy equal to 0.5. A background velocity structure (defined so that  $u_x = u_x(k_y)$ ) was constructed to fill the wave number band  $1 \leq k \leq 4$  with energy  $E_V = 0.5$ .

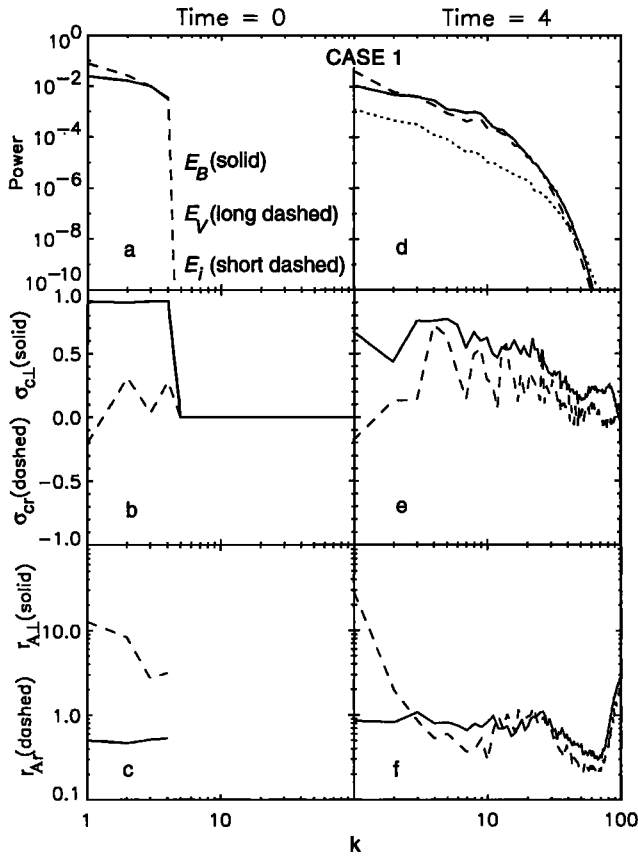


Figure 2. (a) The initial power spectrum of the magnetic and velocity fluctuations of the first scenario (case 1) discussed in the text. (b) The initial normalized cross helicity of the transverse (solid line) and parallel (dashed line) constructed from the magnetic field and velocity fluctuations for case 1. (c) The initial Alfvén ratio of the transverse (solid line) and parallel (dashed line) for case 1. Panels d, e, and f, show the evolution of the power spectra, normalized cross helicity, and Alfvén ratio, respectively, at 4 eddy-turn-over times. The dotted line in (d) is the spectrum of the internal energy.

The initial state then has the following characteristics (where  $r$  and  $\perp$  refer to parallel and perpendicular to the direction of  $\mathbf{B}_0 = B_0 \hat{x}$ ): The power spectrum was quite flat at low  $k$  and there was no power at  $k > 4$  (Fig. 2a);  $\sigma_{cr} = -0.001$ , and  $\sigma_{c\perp} = 0.9$ , so that the transverse fluctuations are Alfvénic (Fig. 2b); the Alfvén ratio is dominated by the fluctuations in the radial ( $r$ ) component of the velocity, so that  $r_{Ar}$  reaches values  $\sim 10$  and  $r_{A\perp} = 0.5$  (Fig. 2c). The state of the fluid at  $T = 4$  (where times are eddy-turn-over-times) is shown in Figures 2d,e and f. Magnetic and velocity fluctuations have cascaded to wave numbers above 4 and in the band  $4 < k < 20$  the transverse and radial components of normalized cross helicities are nearly equal and relatively large. Note that the somewhat lower values for the radial correlation are also present in the observations. In the range  $k < 5$ ,  $\sigma_{c\perp}$  is still quite large ( $\sim 0.7$ ) while  $\sigma_{cr}$  is small ( $\sim \pm 0.2$ ). Above  $k \approx 30$  the spectrum becomes dominated by dissipation.

In the band  $4 < k < 20$ , the transverse and radial components of  $r_A$  are also nearly equal and slightly below the equipartition value predicted by Kraichnan [1965], whereas in the range  $k < 5$ ,  $r_{A\perp}$  remains small ( $\sim 1$ ) while  $r_{Ar}$  is still large. This spectrum of the Alfvén ratio is similar to that shown in Figure 1b.

### Interaction of Long Wavelength Parallel Velocity Fluctuations with Shorter Wavelength Alfvénic Fluctuations

In the second simulation, the transverse fluctuations were assumed (for simplicity) to be parallel propagating transverse Alfvén waves in the spectral band  $5 \leq k \leq 15$  with a power spectrum of the form  $k^{-1}$ . The band below  $k = 5$  contained solenoidal velocity fluctuations ( $u_x(k_y)$ ) between  $1 \leq k \leq 5$  and no magnetic energy. The power spectrum of these velocity fluctuations was also  $k^{-1}$  (Fig. 3a). In the band between  $5 \leq k \leq 15$ , the  $r_{A\perp} = 1$  (Fig. 3b). The cross helicity in the band between  $k = 5$  and 15 defined so that  $\sigma_{c\perp} = 0.9$  and  $\sigma_{cr} = 0$ . By  $T = 4$  (Fig. 5d), the energy has cascaded out to larger  $k$ , and some magnetic energy has appeared at lower  $k$ . The cross helicity in the transverse components has also spread. Large values of  $\sigma_{c\perp}$  can now be found above  $k = 15$ , and the value of  $\sigma_{c\perp}$  below  $k = 5$  is now greater than zero, but still well below the value of 0.9 found at larger wave numbers (Fig. 3e). Significant evolution is also obvious in the Alfvén ratio. Below  $k = 5$ ,  $r_{A\perp}$  has reached a value of about 2, while  $r_{Ar}$  is still quite large (Fig. 3f). The overall tendency is for the evolution to resemble the Ulysses data, but only qualitatively. Quantitatively, in the wave number band below  $k = 5$ ,  $\sigma_{c\perp}$  is too small and  $r_{A\perp}$  is too large.

### Discussion and Conclusions

Data from Ulysses at high heliolatitude and Helios in the ecliptic both illustrate a curious property of Alfvénic solar wind. Below  $10^{-5}$  Hz the Alfvénic nature of the fluctuating magnetic and velocity fields changes. Whereas at higher frequencies all three vector components of the magnetic and velocity fluctuations are highly correlated, now it is only the transverse components that are—the

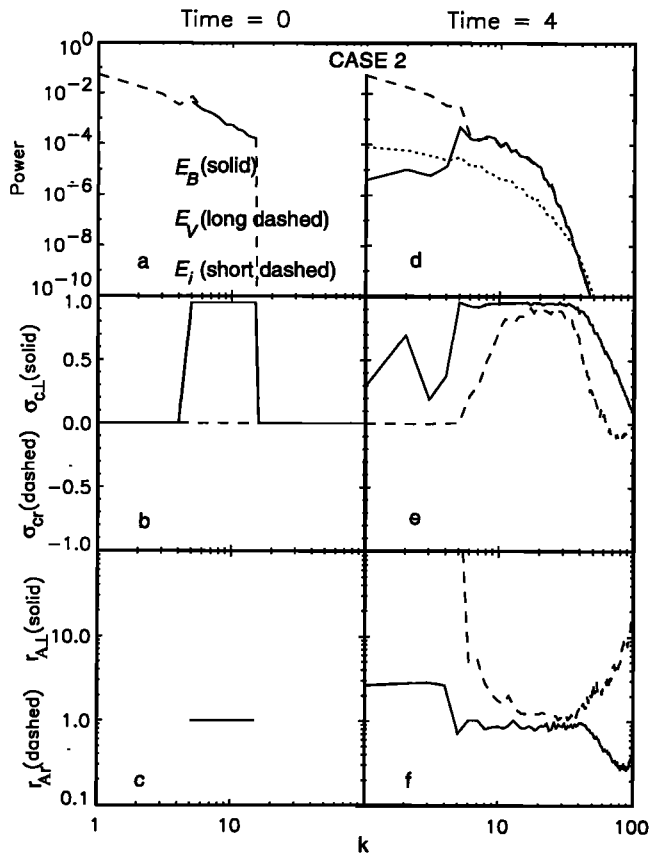


Figure 3. Similar to Figure 2, but for the second scenario (case 2).

Alfvén waves have become planar. While some aspects of this apparent change may reflect an aliasing that is unavoidable at these relatively small distances (0.3 – 2 AU) and low frequencies, it may also reflect a properties of the sources of the waves in the corona. It appears from our numerical simulations that plane waves generated at higher frequencies cannot couple sufficiently rapidly to lower frequencies to result in the observations (*cf.* Fig. 3). While the tendency of the evolution is correct, it appears to be quantitatively inadequate. To some extent this is a consequence of restricting the simulation to only four eddy-turn-over times, but from earlier work [Roberts *et al.*, 1992], we feel that there will be at most this much time available. In contrast, if the fluctuations are generated at these low frequencies as transverse Alfvén waves, then, as shown in Figure 2, there appears to be ample time for couplings to higher frequencies to produce the spectra that characterize the solar wind at larger heliocentric distances—*viz.*, a power spectrum that is near equipartition (*i.e.*,  $r_A \sim 1$  and highly Alfvénic). The problems in this case are that the  $f^{-1}$  spectrum cannot be produced by a simple cascade, and the degree of Alfvénicity demonstrated is not as high as the  $\approx 0.8$  observed (the values in Fig. 2e are  $\sim 0.6$  for  $\sigma_{\perp}$  and somewhat less for  $\sigma_{\parallel}$ ). The results shown in Figure 2d,e, and f suggest that one may be able to get the high  $\sigma_{\perp}$  values (but not the spectrum) using higher resolution (and/or better functional forms for the dissipation coefficients [Siregar *et al.*, 1995]). Nonetheless, these simulations suggest to us possible characteristics for the source spectrum of interplanetary fluctuations that will motivate further modeling and study.

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