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# Nonlinear evolution of interplanetary Alfvénic fluctuations with convected structures

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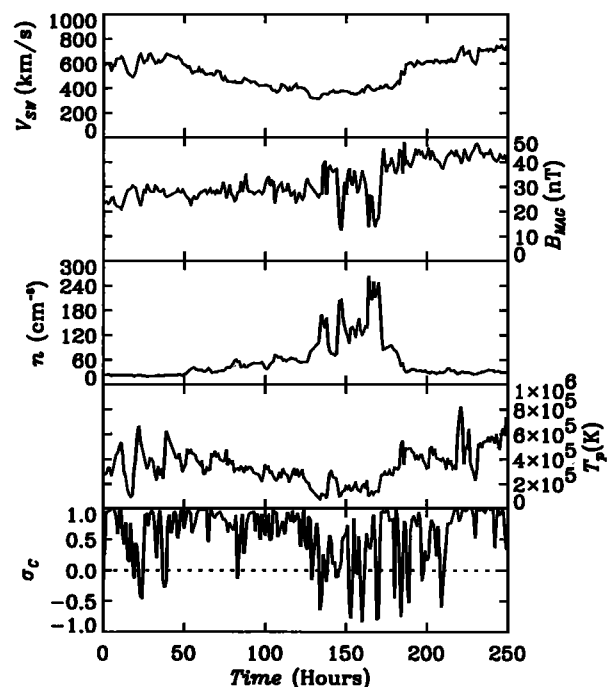
**Abstract.** At least at solar minimum, many regions in slow solar wind near the heliospheric current sheet have very low Alfvénicity. Motivated by recent suggestions that the interaction of the waves with the observed striated density, temperature, and magnetic field structures in the low Alfvénicity regions causes the decay of outward dominance, we have used two- and three-dimensional MHD codes to simulate such situations to determine the evolution. We find that outward propagating waves in the presence of structures become only slightly less Alfvénic (unlike observations), and that what were initially parallel propagating waves fairly rapidly become nearly isotropic with a self-similar spectrum typical of turbulence (similar to observations). These simulations suggest that the low Alfvénicity regions must arise from some other cause, such as “microstreams” that are eradicated as they decrease the Alfvénic correlations.

## Introduction

The discovery of the Alfvén mode in interplanetary fluctuations led directly and rapidly to the successful application of magnetohydrodynamics (MHD) to a number of space physics problems [Coleman, 1968; Belcher and Davis, 1971]. In particular, the ability to determine the direction of propagation of the waves using the sign of the correlation between velocity and magnetic field fluctuations has proven crucial in diagnosing the nature and dynamics of the fluctuations. It is now well established that fluctuations in regions of predominantly outward propagation originate near the Sun, below the Alfvénic critical point, and that nonlinear dynamical processes of some sort lead to the decline in the outward dominance [Roberts *et al.*, 1987a,b; see Goldstein *et al.*, 1995, for a recent review].

Regions that are not Alfvénic (with low velocity-magnetic field correlation) even near the Sun provide a different challenge. Belcher and Davis [1971] thought that the interaction regions between fast and slow wind would be the primary generator of nonAlfvénic fluctuations, but subsequent work has shown both that compression regions are not very different from the trailing edges of high speed streams on average [Roberts *et al.*, 1987a] and that the least Alfvénic regions at the closest distance that spacecraft have approached the Sun (Helios at 0.3 AU) are not typically interaction regions, but rather regions near the heliospheric current sheet, often

in slow flows, that are well removed from other flows (see Fig. 1, hours 125-175). These regions often have high densities and strong density fluctuations, but this does not imply that the regions are dynamically compressive; they are probably quasi-static pressure balance structures [e.g. Klein *et al.*, 1993a] that are primarily convected out from the Sun. Near the source region these striations are almost certainly those seen in coronal photographs [Koutchmy, 1988] and in radio scintillations they have been traced from the Sun by Woo [1995]. The solar origin is further confirmed by the anticorrelation of the density and temperature in the structures, observed by Klein *et al.* [1993a] (see Fig. 1); this implies a strong variation of the plasma entropy that would not be generated by compressive dynamical evolution. The correlation of low Alfvénicity with such structures suggests that the low Alfvénicity is due to a nonlinear interaction of the waves with the structures, and that other mechanisms such as velocity shear generation of inward correlations [e.g. Coleman, 1968, Roberts *et al.*, 1987b, 1991, 1992] are not required [Bruno and Bavassano, 1991, Klein *et al.*, 1993b]. These suggestions have motivated us to study the general interac-



**Figure 1.** Hour-averaged data from Helios 2 at 0.3 AU in 1976. Panels from top to bottom represent the solar wind speed, magnetic field magnitude, density, and temperature, and the Alfvénicity (+1 outward) at the 3-hour scale.

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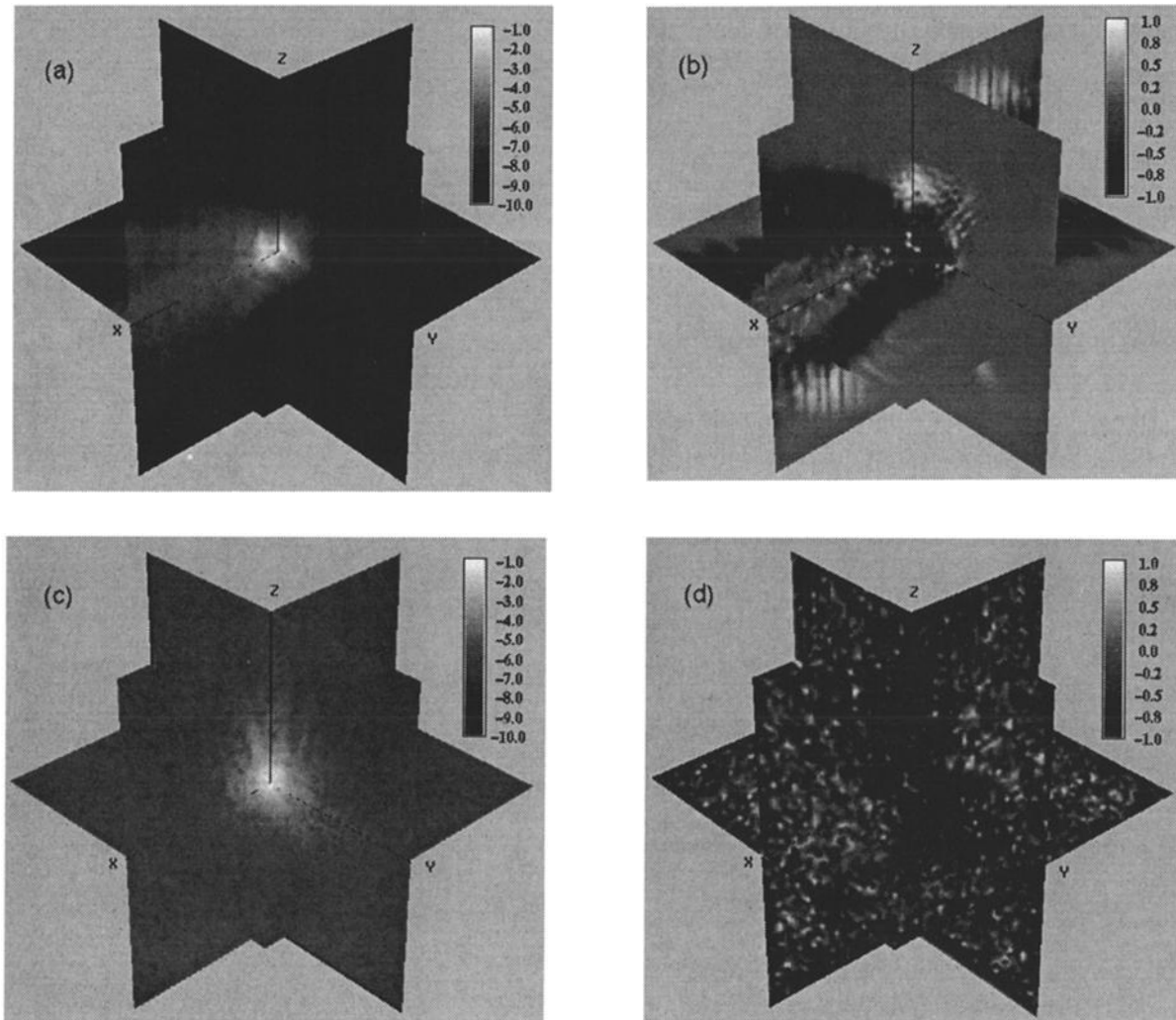
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tion of Alfvén waves with convected structures, starting with some simple but physically reasonable cases.

To study this interaction, we have used compressible MHD simulations in both two and three dimensions (incompressible MHD runs give essentially similar results). The structures we are discussing are similar to what is called “two-dimensional turbulence.” The latter confines fluctuations to a plane perpendicular to the mean field  $\mathbf{B}_0$ . The wave vectors  $\mathbf{k}$  are perpendicular to the applied field as well, and thus the projection of the Alfvén speed along  $\mathbf{B}_0$  is zero. In our present case the fluctuations in the structures are field aligned rather than perpendicular to both  $\mathbf{B}_0$  and  $\mathbf{k}$ . Typical two-dimensional turbulence involves both magnetic and velocity fluctuations, whereas the structures we model are purely magnetic. There is no reason that there should not be field aligned velocity fluctuations near the Sun, and indeed these may be very important, but including them would just represent a return to well-studied velocity shear mechanisms.

## Equations and Initial Conditions

We solve the usual MHD equations with a polytropic relation between pressure and density. The numerical code is a pseudospectral predictor-corrector algorithm that has been discussed elsewhere [Ghosh *et al.*, 1993]. The three-dimensional (3-D) code uses a grid resolution of  $64^3$  and uses standard viscous ( $\nu$ ) and resistive ( $\mu$ ) dissipation coefficients set to give Reynolds’ numbers of about 500. The two and one-half dimensional ( $2\frac{1}{2}$ -D) code retains the three directional components of the vectors but restricts the spatial dependence to two variables. This permits expanding the grid resolution to  $256^2$ . For this case, we use bi-Laplacian forms of dissipation, replacing, for example,  $\nu$  in Fourier space by  $\nu_c(k) = \nu_0[1 + (k/k_{eq})^2]$ , where  $k$  is the wave number and  $\nu_0$  and  $k_{eq}$  are constants. We choose  $\nu_0 = 5 \times 10^{-6}$  and  $k_{eq} = 1$  to limit the dissipation to high wave numbers, leading to very low dissipation for most wave vectors and thus



**Figure 2.** Cuts along the coordinate planes in Fourier space of the simulated fields. (a) The logarithm of the total kinetic plus magnetic energy at  $T = 1$ . (b) The normalized cross helicity ( $\sigma_c$ ) at  $T = 1$  ( $-1$  initially). (c) The logarithm of the total kinetic plus magnetic energy at  $T = 4$ . (d) The normalized cross helicity ( $\sigma_c$ ) at  $T = 4$ .

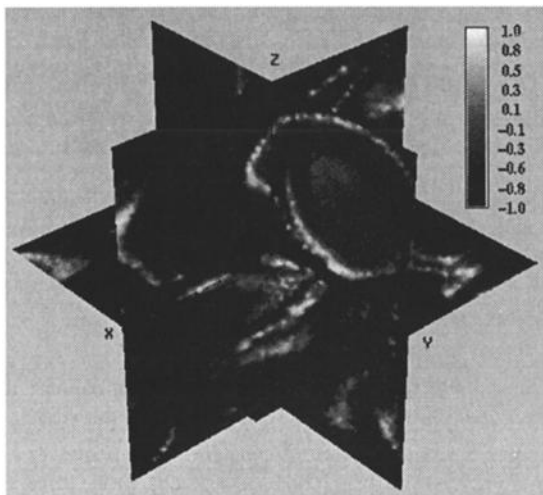
the possibility of recovering a true inertial (dissipation-free) range spectrum.

We use the modal “Alfvénicity” (normalized cross helicity) as an important diagnostic. It is given by

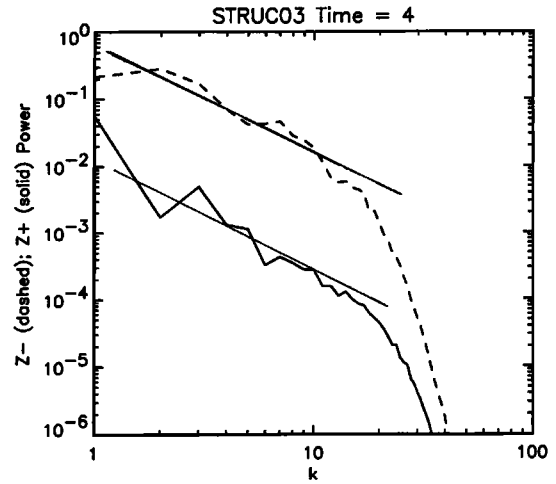
$$\sigma_{c,k} = 2(\mathbf{u}_k \cdot \mathbf{B}_k) / (\mathbf{u}_k \cdot \mathbf{u}_k + \mathbf{B}_k \cdot \mathbf{B}_k) \quad (1)$$

where the Fourier components of velocity and magnetic field are given by  $\mathbf{u}_k$  and  $\mathbf{B}_k$ , with  $\mathbf{B}$  in Alfvén speed units. This gives a measure of the degree to which the fluctuations are Alfvénic at each wave number, with  $-1 \leq \sigma_{c,k} \leq +1$ .

The initial conditions for the 3-D compressible run consist of a magnetic structure formed from the superposition of two fluctuations at wave vectors  $(k_x, k_y, k_z) = (0, 0, 1)$  and  $(0, 1, 0)$  of the  $\delta B_x$  component. The mean magnetic field is  $\mathbf{B}_0 = B_0 \hat{x}$  and  $B_0 = 1.0$ . The magnetic configuration thus consists of essentially four “flux tubes” in the quadrants of the  $y - z$  plane, one with a strong mean field, one with a weak field, and two intermediate. Pressure variations due to the magnetic structure are balanced by a (non-propagating) density variation, in accord with observations (see Fig. 1). Three randomly-phased field-aligned Alfvén waves are added to the magnetic/density structure. Their wave vectors are parallel to the unit mean magnetic field with  $k_x = 1$  to 3. The velocity and magnetic vectors of the waves are orthogonal to the mean magnetic field direction. The Alfvénicity of each wave is initially  $\sigma_{c,k} = -1$ . (Note the minus sign is for propagation along the field, opposite to the convention chosen in Fig. 1.) The fluctuation amplitudes of the waves are equal, giving the energy in each wave as  $(\delta \mathbf{u} \cdot \delta \mathbf{u} + \delta \mathbf{B} \cdot \delta \mathbf{B})/2 = 1/2$ , and the total energy in the structures is  $(\delta \mathbf{B} \cdot \delta \mathbf{B})/2 = 1/4$ . Hence, discounting the relatively small amount of energy in density fluctuations, the total fluctuating energy is  $E = 1.75$ . The fields thus chosen are similar to the interplanetary fields near 0.3 AU (Fig. 1), and in particular  $\delta|B|$  is a substantial fraction of  $|B|$ . The cases we discuss here are generalizations of previous 2-D incompressible simulations carried out for other purposes [see *Malara et al.*, 1992 and references therein].



**Figure 3.** Coordinate plane cuts in physical space showing the spatial structure of  $\sigma_c$  at  $T = 4$ .



**Figure 4.** Spectra of  $z^+$  (“outward”; dashed) and  $z^-$  (“inward”; solid) fluctuations at  $T = 4$  in a 2-1/2-D simulation with structures and waves. The straight lines have a slope of  $-5/3$ .

## Results and Discussion

It is a priori possible that the low Alfvénicity seen at 0.3 AU is due to initial conditions that were dominated by structures. The overall value of  $\sigma_c$  for the idealized waves and structures of our simulations is  $E_w / (E_w + E_s)$  where the subscripts refer to waves ( $w$ ) and structures ( $s$ ). For a typically observed value of  $\sigma_c = 0.2$  ( $-0.2$  for the simulations), this implies  $E_s / E_w = 4$ , a value that seems unrealistically large. Moreover, the observations show large oscillations in  $\sigma_c$  including many negative values that this model cannot produce. Finally, it is only in the limit of exactly transverse wave vectors that the structures are truly nonpropagating, and thus the selection of outward propagation might be expected to apply to much of this population as well. Although it is still possible that variations on the above conditions would yield plausible conditions consistent with the observations, here we focus on the possibility of dynamical evolution as the cause the destruction of the correlated state.

Figure 2 shows the spectral evolution of the normalized cross helicity and total energy at an early and a late time in the coordinate planes of the Fourier space of the simulation. (The initial waves are near the origin, at the base of the “cone” in Fig. 2b.) The waves are refracted by the varying Alfvén speed due to the structures, leading to a turning and increasing of amplitude of the wave vectors. Perpendicular structures are also modified, and in late times the Alfvénic dominance, which remains in the original parallel propagating wave modes, is seen to become nearly isotropic, although the original nonAlfvénic structure mode (barely distinguishable near the origin in Fig. 2d) is still largely nonAlfvénic. The spatial structure of the cross helicity at late times is shown in Fig. 3 that shows the dominance of the original sense ( $-1$ ) of correlation between the velocity and magnetic field over most of the volume.

In two dimensions it is possible to use enough modes to obtain spectral information, and Fig. 4 shows the omnidirectional power spectrum of the “outward” and “inward” waves

( $z^\pm = v \pm b$ ) for a  $256^2$  compressible run, illustrating the appearance of a Kolmogoroff-like power law despite the highly structured initial conditions. It also shows that the initially dominant ( $z^-$ ) waves remain so, even at small scales created by the cascade.

Thus we find that simple structures are not sufficient to decrease the Alfvénicity of the fluctuations as observed and that parallel propagating Alfvénic power rapidly produces transverse Alfvénic power in the presence of structures leading ultimately to a self-similar spectrum. These results are limited at this point first in that the conditions modeled are idealized representations of suggested mechanisms, and second in that the effects of expansion are not included. Including more general cases of quasi-two-dimensional turbulence as “structures” will lead to significant departures from the above cases. Expansion may well slow spectral transfer in general [Grappin *et al.*, 1993] and introduce anisotropies and reflections at large scales. Nevertheless, unless the structures component of the fluctuations is very strong, at least some more complex version of the waves-plus-structures view is needed to explain low cross helicity regions near 0.3 AU. Moreover, it seems unrealistic to model the fluctuations in any interestingly variable region of the solar wind as waves-plus-structures, especially with these components remaining readily distinguishable throughout the evolution, in that, even without the turning of the spiral field, wave vectors are refracted and largely isotropized.

The dynamical evolution of structures and waves is reminiscent of more general turbulence simulations. The present simulations develop an inertial range (consistent with observations) and tend toward isotropy, although not completely. Also, we have generally found [Roberts *et al.*, 1992] that when the energy-containing scales of the simulation are dominated by highly Alfvénic fluctuations, the smaller scales generally are too. The energy-containing scales must have low cross helicity to produce an inertial range that behaves in the way observed by spacecraft, with a general decline toward zero Alfvénicity. The requirement of small cross helicity in the energy containing scales may explain, for example, the difficulty Marsch and Tu [1993] have in obtaining solutions that do other than yield greater Alfvénicity with increasing heliocentric distance.

Our simulations leave unanswered the question of the reason for low cross helicity regions near 0.3 AU. One possibility, suggested by observations, is that the proximity of the current sheet is important. Structured regions are not uniformly nonAlfvénic (see Fig. 1), and the regions in which the radial field becomes small tend to be associated with lower Alfvénicity, consistent with the simulations of Roberts *et al.* [1991]. Finally we suggest that the striated density structure observed near 0.3 AU is accompanied by strong striations in velocity (“microstreams”) that are eradicated in the process of destroying the Alfvénic correlation. Such velocity variations would be a natural consequence of the highly variable solar atmospheric base conditions that are also the origin of the density and associated variations, and such microstreams have recently been reported in remote sensing observations by Woo [1995]. The disappearance of the Alfvénicity could

occur by turbulent viscosity without initially destroying the flux tubes themselves.

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