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The Effect of Microstreams on Alfvénic Fluctuations in the Solar Wind

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Abstract. Even in nominally uniform solar wind flows, such as over the solar poles near solar minimum, the wind velocity exhibits fluctuations of order 40 km/s. We have shown previously that such variations will shear planar parallel propagating magnetic fluctuations leading to the generation of transverse wave vectors. Here we extend our previous two-dimensional magnetohydrodynamic (MHD) simulations to three dimensions and describe how, starting from an initial spectrum of circularly polarized Alfvén waves with radial wave vectors, such “microstreams” might produce fluctuations that could be described as “quasi-two-dimensional”. Our goal is to elucidate the origin of the “two-component” nature of the correlation function of magnetic fluctuations.

1. BACKGROUND

The earliest observations of plasma and magnetic fields in the solar wind revealed that fluctuations resembling outward propagating Alfvén waves were ubiquitous [1, 2, 3] (also see [4, 5]). There ensued a lengthy debate as to whether the highly Alfvénic nature of the fluctuations reflected a remnant of turbulence in the corona that was convected into the solar wind, or whether the solar wind was an evolving turbulent magnetofluid. The former interpretation was supported by the fact that pure Alfvén waves are exact solutions of the incompressible ideal equations of magnetohydrodynamics and, as such, do not undergo further evolution. However, the large velocity shears between fast and slow solar wind flows contain sufficient free energy to drive a turbulent cascade. Furthermore, log-log plots of the power spectra of magnetic fluctuations typically show an “inertial” range of nearly constant slope $\simeq -5/3$, which is characteristic of fully developed fluid turbulence. A resolution of the debate was offered [6] (see also the review [7]) where it was argued that the nearly pure outward propagating Alfvénic fluctuations did reflect coronal processes, but that the fluctuations were also stirred *in situ* by velocity shears that led to an evolution of the spectrum with heliocentric distance from a spectral index $\simeq -1$ near 0.3 AU to $\simeq -5/3$ at 1 AU, and beyond. The stirring by velocity shears also produced inward-propagating fluctuations which could then participate in a nonlinear cascade.

From single-spacecraft magnetic field data, one cannot easily characterize the symmetry properties of the solar wind fluctuations. A magnetofluid filled with par-

allel propagating transverse Alfvén waves would have slab symmetry, while fully developed fluid turbulence might be axisymmetric or, possibly, isotropic. That the solar wind was neither slab nor isotropic was suggested by [3, 8, 9]. Evidence for a two-component symmetry can be found in [10, 11, 12] (also see [13] and the review by Oughton in this volume). A common interpretation of those analyses is that solar wind fluctuations comprise two dominant populations: planar shear Alfvénic fluctuations propagating nearly parallel to the background magnetic field and a quasi-two-dimensional component with wave vectors predominately perpendicular to the background field. The nature and origin of this second component has yet to be determined. In the next section we review briefly some of its characteristics and discuss possible origins. Work presented in this volume by C. W. Smith suggests that the percentage of fluctuations with nearly perpendicular wave vectors, especially at high heliocentric latitudes, may be highly variable.

2. PROPERTIES OF THE NEARLY-PERPENDICULAR COMPONENT

Interest in the perpendicular wave number component of solar wind fluctuations is motivated by the possibility that they represent a true quasi-two-dimensional population. Quasi-two-dimensional fluctuations do not resonantly scatter energetic particles because $k_{\parallel} \simeq 0$. For the same reason, in a quasi-two-dimensional magnetofluid, the direction of minimum variance of magnetic fluctua-

tions should lie along \mathbf{B}_\odot , the local mean magnetic field. In addition, as shown in [14], two-dimensional fluctuations produce a stochastic diffusion of flux tubes that for particles magnetically tied to the local magnetic field will result in significant perpendicular diffusion.

In fact, cosmic rays appear to have scattering mean free paths that are longer than is expected from quasi-linear diffusion in slab-symmetry Alfvénic turbulence (see, *e.g.*, [15]). Furthermore, cosmic rays exhibit enhanced diffusion perpendicular to the background magnetic field (see, *e.g.*, [16]). Finally, the direction of minimum variance of interplanetary fluctuations tends to lie along \mathbf{B}_\odot [3, 17]. Thus, proof that quasi-two-dimensional fluctuations are the dominant mode of interplanetary fluctuations could provide a simple solution to three heretofore vexing problems in solar wind research.

2.1. Possible origins of the nearly-perpendicular wave number component

True quasi-two-dimensional turbulence arises in the limit of a strong DC magnetic field and incompressible flow [18, 19]. The solar wind, however, is not incompressible, which has motivated several generalizations of the Strauss and Montgomery theories. A *nearly incompressible* theory has been developed [20] and generalized ([21], also see [22], and Zank *et al.* and Bhattacharjee and Ng, these proceedings). That magnetic fluctuations become anisotropic when a strong magnetic field is present has been confirmed in a series of numerical simulations [23, 24, 25, 26]. The general lack of density and magnetic field magnitude fluctuations suggest that the k_\perp component does not arise from fast mode waves or from pressure-balance structures, which have $\delta\mathbf{b}$ parallel to \mathbf{B}_\odot . Other processes can generate perpendicular wave numbers, most notably the fact that parallel propagating planar Alfvén waves in sheared velocity fields experience phase mixing [25, 27, 28] that refracts the wave vectors toward the direction perpendicular to \mathbf{B}_\odot . Alternatively, the k_\perp component might arise in the solar atmosphere in regions of strong magnetic field, perhaps as a result of magnetic reconnection (see Chang, these proceedings, and [29]).

The two most likely origins of the k_\perp component, therefore, are a coronal source of true quasi-two-dimensional turbulence and/or phase mixing of planar Alfvénic fluctuations by velocity shears. Independent of any coronal source (*e.g.*, magnetic reconnection), fluctuations in solar wind velocity will shear the phase fronts of all planar waves. To explore how small velocity shears transform the two-dimensional correlation function of an initially nearly-planar Alfvénic wave

packet, we designed three-dimensional simulations that included small velocity-sheared flux tubes. The results are described in the next section.

3. SIMULATION OF THE EFFECT OF MICROSHEARS ON AN ALFVÉNIC WAVE PACKET

3.1. The MHD equations

The algorithm used to solve the compressible ideal equations of MHD is described in [30]. The code incorporates the rotation and tilt of the solar corona and allows for an influx of Alfvén waves, two-dimensional turbulence, and/or pressure balance structures. Only Alfvénic fluctuations are germane to this paper. Neither the heliospheric current sheet (HCS) nor gravity were included for this application.

The general MHD equations describe conservation of mass,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0, \quad (1)$$

conservation of momentum,

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\left(p + \frac{B^2}{8\pi} \right) \mathbf{I} + \rho \mathbf{v} \mathbf{v} - \frac{1}{4\pi} \mathbf{B} \mathbf{B} \right] = 0, \quad (2)$$

conservation of energy,

$$\frac{\partial}{\partial t} \left(\rho e + \frac{1}{2} \rho v^2 + \frac{B^2}{8\pi} \right) + \nabla \cdot \left[\left(\rho e + \frac{1}{2} \rho v^2 + p \right) \mathbf{v} - \frac{1}{4\pi} (\mathbf{v} \times \mathbf{B}) \times \mathbf{B} \right] = 0, \quad (3)$$

and Faraday's Law,

$$\frac{d\mathbf{B}}{dt} = -c \nabla \times \mathbf{E}, \quad (4)$$

where

$$\mathbf{E} = -\frac{1}{c} \mathbf{v} \times \mathbf{B}. \quad (5)$$

In addition, the internal energy, e , is related to the pressure, p , through the relation

$$p = (\gamma - 1) \rho e. \quad (6)$$

These equations were transformed to dimensionless units and solved. Here \mathbf{I} is the unit tensor with components δ_{ij} and γ is the ratio of specific heats, here taken to be 5/3 (see [31, 32]). The equations were solved on either a $304 \times 154 \times 154$ or 154^3 grid in r , θ , and φ spherical coordinates.

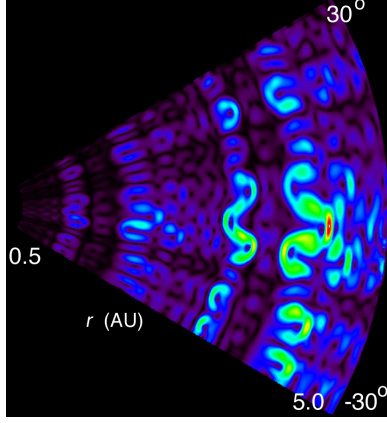


FIGURE 1. Magnitude of the vorticity, ω in the $r - \theta$ -plane from $r = 0.5 - 5.0$ AU from the $304 \times 154 \times 154$ run. The color scale is rainbow with minimum ω black and maximum ω white.

3.2. Microshears in high speed wind

We varied an otherwise steady fast wind by adding a superposition of 8×8 small amplitude modes ($\delta v/v_0 \sim 8\%$). We ran two cases; the first extended in radius from $0.5 - 5$ AU, while in the second case, the radial domain was restricted to $0.1 - 1$ AU. In both cases latitudinal and longitudinal range was $\pm 30^\circ$. A Parker spiral and associated changes in the flows were produced by moving the field across the input surface at a rate consistent with the 28-day solar rotation period. A packet of plane polarized Alfvén waves was introduced at the in-flow boundary, either 0.1 or 0.5 AU. The magnitude of the vorticity, $\omega = \nabla \times \mathbf{v}$, in the $r - \theta$ -plane at the end of the run, which extended to 5 AU, is shown in Figure 1, illustrating that significant evolution of the flow occurs by ~ 1 AU.

The microstreams in three dimensions are illustrated in Figure 2. The color contour at the in-flow boundary at 0.5 AU is the initial distribution of the velocity fluctuations; the contour in the $r - \theta$ -plane is the fluctuation in $\delta B_\perp = \sqrt{(\delta B_\theta^2 + \delta B_\phi^2)}$; and in the $r - \phi$ -plane, magnetic field lines are plotted in white along with a color contour of $|\mathbf{v}|$. The microstreams produce fluctuations in \mathbf{v} whose structure follows approximately that of the Parker spiral field. Not shown is that similar contour maps of δB_\perp also conform to the spiral field structure.

In Figure 3 illustrates the evolution of the magnetic fluctuations from plane-polarized waves to something reminiscent of the “Maltese cross” pattern [10]. Both panels are a collage of three color contours: The smallest in the lower lefthand corner is a color image of δB_\perp ; the alignment of these contours approximately follows that of the spiral field structure, *i.e.*, \mathbf{B}_0 is nearly parallel to r on the left and is closer to the ϕ -direction on the right. The abscissa of the radial ranges was $r = 0.1 - 0.43$ AU

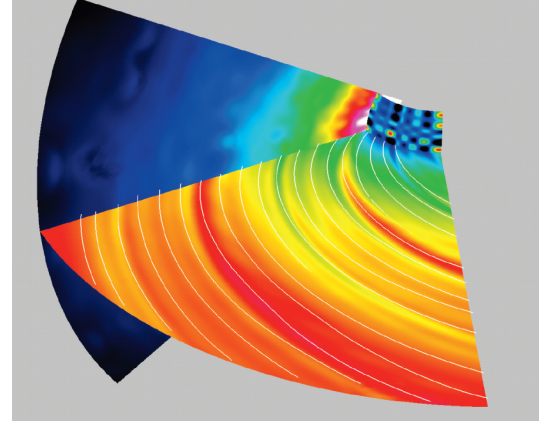


FIGURE 2. A three-dimensional view of the first simulation from the $304 \times 154 \times 154$ point run. r extends from $0.5 - 5.0$ AU. The color shading at the in-flow boundary shows the initial distribution of the velocity fluctuations (again using a rainbow color bar); the shading in the $r - \theta$ -plane is the fluctuation in δB_\perp ; and, in the $r - \phi$ -plane, magnetic field lines are shown in white along with a color shading of $|\mathbf{v}|$. The data are normalized so that the minimum value of the plotted quantity is black and the maximum value is white.

and $r = 4 - 5$ AU for the left and right panels, respectively. The ordinate spans the ϕ domain of $\pm 30^\circ$. The next larger color image is the two-dimensional correlation function of δB_θ and δB_ϕ , also shown in the same rectangular $r - \phi$ representation and computed over the same radial ranges. The largest contour is the sum of the two-dimensional power spectra of δB_θ and δB_ϕ . The abscissa and ordinate are k_r and k_ϕ , respectively.

The two-dimensional correlation function at small radial distance is aligned nearly perpendicular to the wave vector of the fluctuations, as expected of radial wave vectors. Close to $r = 5$ AU the contours are nearly parallel to fluctuating magnetic field structures; furthermore, the shape of the correlation function (particularly, the *green* level), is reminiscent of that from ISEE-3 [10]. Although the two-dimensional power spectrum taken between $\sim 4 - 5$ AU still contains some power in wave vectors parallel to the spiral field direction, the power in the perpendicular direction dominates. Thus, the small velocity shears deform the distribution of initially parallel-propagating plane-polarized Alfvén waves so that by several AU the correlation function contains substantial power nearly perpendicular to the direction of the background magnetic field. The interval analyzed by [10] was a mixture of fast and slow wind from near the ecliptic plane, while the simulation parameters chosen above are closer to those encountered by Ulysses at high latitudes. However, C. W. Smith (these proceedings) has presented evidence that the two-component model of solar wind fluctuations also fits periods of Ulysses data.

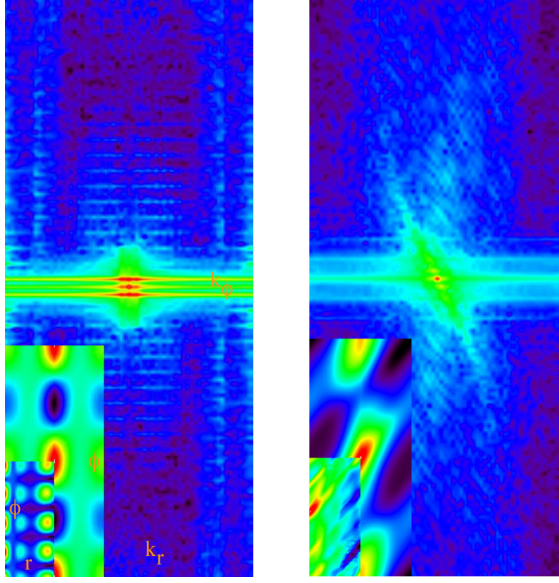


FIGURE 3. B_{\perp} , two-dimensional correlation function, and two-dimensional power spectrum (see text). The lefthand panel covers $r = 0.1 - 0.43$ AU with $\phi \pm 30^\circ$. The righthand panel covers $r = 4 - 5$ AU and the same range in ϕ . The data are normalized and a rainbow color bar is used.

4. SUMMARY

The shearing of Alfvénic fluctuations by even small velocity shears similar to those observed by Ulysses at high heliographic latitudes can yield nearly perpendicular wave vectors. Such distributions of wave vectors, while similar to that deduced from ISEE-3 data, are not truly quasi-two-dimensional in that $\delta\mathbf{B}$, $\delta\mathbf{k}$, and \mathbf{B}_0 are not mutually perpendicular. (Note that $\mathbf{B}_0 \parallel \hat{\phi}$ and much of the spectral power in δB_{\perp} comes from B_{ϕ} .) We conclude that the effect of microstreams must be included in any explanation of the observed anisotropies in solar wind fluctuations and that the solar wind may not contain a dominant, truly quasi-two-dimensional, component.

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