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Heliospheric magnetic field polarity inversions driven by radial velocity field structures

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[1] Magnetic field polarity inversions embedded in the predominantly unipolar fast solar wind have been observed by the Ulysses spacecraft at high latitudes. Such reversals have the nature of folded back field lines which we suggest are generated by the interaction of standard large amplitude, low frequency, Alfvénic turbulence with velocity shears in the fast solar wind. We present 2D magnetohydrodynamic simulations of a very low frequency and high amplitude Alfvén wave propagating away from the sun embedded in a velocity shear structure such as a microstream and show how reversals in the magnetic field lines are generated naturally on a time-scale consistent with their observation at Ulysses. The generated magnetic field and plasma signals are similar to those observed. We discuss the role turbulence-stream shear interactions might play in limiting differential velocities in the asymptotic high speed solar wind. **Citation:** Landi, S., P. Hellinger, and M. Velli (2006), Heliospheric magnetic field polarity inversions driven by radial velocity field structures, *Geophys. Res. Lett.*, *33*, L14101, doi:10.1029/2006GL026308.

1. Introduction

[2] During its recurring journeys out of the ecliptic around the Sun, the Ulysses mission has revealed that the high latitude fast solar wind is embedded with many different plasma and magnetic field structures, spanning a large interval of time scales - from several hours to days: pressure balance structures [*McComas et al.*, 1995], microstreams [*McComas et al.*, 1995; *Neugebauer et al.*, 1995], magnetic holes, radial magnetic field polarity inversions [*Balogh et al.*, 1999], as well as the ever present large scale Alfvén wave spectrum [*Smith et al.*, 1995] propagating away from the sun. At the same time, remote sensing observations show the solar corona appears to be finely structured even in coronal holes, where white light and EUV images reveal the presence of rays and plumes persisting out to about 30 solar radii, the largest distance observable using the LASCO-C3 coronograph aboard the SOHO spacecraft [*DeForest et al.*, 2001]. Although evidence for such coronal structures has been looked for in-situ there appears to be no unequivocally determined connection or correlation between fine-structures in coronal holes observed close to the sun and structures observed in the high latitude wind, probably because of the strong dynamical evolution occurring from the solar acceleration region outward.

[3] The fast solar wind carries magnetic field lines with a polarity which corresponds on average to the dominant polarity in the photospheric regions where the wind originates [*Balogh et al.*, 1995; *Forsyth et al.*, 1996]. However, high-latitude observations show a statistically significant number of cases where the magnetic field polarity is inverted. *Balogh et al.* [1999] have shown that, during these inversions, the velocity-magnetic field correlation in the Alfvénic turbulence spectrum corresponds to Alfvén waves that propagate sunward, an indication that the observed radial magnetic field inversion corresponds to a passage across a fold in a unipolar field, rather than a period of opposite polarity flux connecting all the way back to the sun. An analysis of the differential velocity between protons and alpha particles indicated that polarity inversions, observed both inside and outside pressure balanced structures, or PBS, are all similar and confirmed them to be switch-backs of magnetic field lines [cf. *Yamauchi et al.*, 2004b, Figure 1].

[4] *Yamauchi et al.* [2004a] suggested that the observed magnetic field polarity inversion could be produced at the sun by the eruption of macrospicule-size magnetic loops from the magnetic network. The erupting magnetic field loop could then become a magnetic field switch-back in the fast solar wind if reconnection with the open magnetic field line of the polar hole is not fully completed after the loop enters in the solar wind acceleration region. In the solar corona however the magnetic pressure largely exceeds the plasma pressure so that a magnetic field topology which contains switch-back field lines is hardly confined by the surrounding plasma pressure. The magnetic stress of this topology would then be free to expand on time scales comparable to the local characteristic Alfvén time and the polarity inversion should be suppressed well before it can be caught by the wind and advected up to Ulysses spacecraft. Recently, *Landi et al.* [2005a] have tested such ideas using 2.5D magnetohydrodynamic (MHD) simulations of a large amplitude Alfvén wave containing a region with a well defined polarity reversal in the magnetic field. The simulations showed that such bends in the field lines, as expected on dimensional grounds, do not survive over distances beyond few tens of thousands of kilometers, as the wave unfolds and field-lines straighten out. The conclusion is that the large-amplitude kinks in field lines required to explain the observations, if generated by reconnection at the sun, would dynamically evolve making them unlikely to survive out to the distance where they are observed by Ulysses, at least not for the smaller loops embedded in the coronal holes. We also suggested and carried out simulations of an alternative scenario for the formation of such structures, namely the interaction between a sheared velocity structure

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and a magnetic field containing a component across the shear. In that report, the transverse magnetic field was taken to be initially uniform in the simulation domain, so that it did not correspond to a wave-like feature propagating from the sun.

[5] Here we report studies of the dynamic evolution of a system consisting of a transverse velocity shear, such as the ubiquitous micro-stream structure in the fast wind [*McComas et al.*, 1995; *Neugebauer et al.*, 1995], and a constant magnetic field magnitude Alfvén wave modeling the lowest frequency range of outwardly propagating Alfvénic turbulence. Shears in the radial speed have been previously invoked to explain deformations of the heliospheric current sheet [*Suess and Hildner*, 1985] and it has been previously suggested that they can have an important role in regulating the turbulence evolution in the solar wind [*Roberts et al.*, 1992]. Magnetic field fluctuations are observed over a broad frequency range, corresponding to a well-developed spectrum of outwardly propagating Alfvén waves in a well-defined interval. For periods less than some tenth of hours magnetic field and velocity field fluctuations are well correlated and the observed amplitudes of magnetic field fluctuations in this frequency regime are of the same order of the mean magnetic field $\delta b/b \sim 1$ [e.g., *Smith et al.*, 1995; *Neugebauer*, 2004].

[6] In the next section we detail the numerical model, then describe the results of the interaction between velocity shears and circularly polarized Alfvén waves. Finally, we discuss our main result, namely that the interaction of this so-called Alfvénic turbulence with fast solar wind velocity structures can lead to the polarity inversions observed in the fast wind and consistent with their observational signatures, and also suggest a mechanism of self-regulation between stream-shear amplitudes and the turbulence itself, explaining the quasi equi-partition of asymptotic micro-stream amplitude with the Alfvenic turbulent spectrum.

2. Numerical Model

[7] We consider the visco-resistive MHD equations for an isothermal plasma

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

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{c^2}{\rho}\nabla\rho + (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{R_\nu}\nabla^2 \mathbf{v} \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{R_\eta}\nabla^2 \mathbf{B} \tag{3}$$

Here $\mathbf{v}$ is the fluid velocity, $\mathbf{B}$ the magnetic field and ρ the density. $c^2 = R/\mu T$, with R the gas constant and $\mu = 1/2$ the mean atomic weight for a fully ionized plasma of electrons and protons, is the isothermal sound speed. These equations are expressed in dimensionless units, defining a characteristic length L, a characteristic density ρ_0 and a characteristic magnetic field strength B_0. The velocity field as well the isothermal sound speed are therefore expressed in units of the Alfvén speed $v_a = \sqrt{B_0^2/(4\pi\rho_0)}$ while the characteristic time scale is the Alfvén crossing time $t_a = L/v_a$. R_η and R_ν are the magnetic and kinetic Reynolds numbers, adapted to the resolution of the numerical grid. The equations (1), (2) and (3) are integrated in a rectangular box of dimensions $[-L_x, L_x] \times [-L_y, L_y]$.

[8] In the simulations we have assumed periodicity in one dimension (y) and spatial integration is performed by pseudo-spectral methods. In the x-direction the spatial integration is performed by the use of a fourth order compact difference scheme and boundary conditions are given by the method of the projected characteristics. Time integration is performed with a third-order Runge-Kutta method. Details of the code are described by *Landi et al.* [2005b].

3. Shear–Alfvén Wave Interaction

[9] Consider magnetic field perturbations belonging to the low-frequency range of so-called Alfvénic turbulence. These fluctuations are random and in general are not aligned with gradients in the radial velocity. To study how then the two interact we start with the simplest possible configuration with these ingredients, a very low-frequency magnetic field perturbation, embedded in a radial velocity field containing a shear, such as a region with higher speed.

[10] We choose $\hat{y}$ as the radial direction and we model the velocity shear using the following profile

$$\mathbf{v} = \delta u \exp\left[-\left(x^2/2\Delta^2\right)\right]\,\hat{y} \tag{4}$$

with Δ the half width of the stream and δu its amplitude. We assume a mean magnetic field $\mathbf{B_0}$ aligned with the velocity field and constant throughout the numerical domain, i.e., $\mathbf{B_0} = B_0\hat{y}$. The plasma density and temperature are assumed initially uniform.

[11] For the magnetic field perturbation we consider a circularly polarized Alfvén wave propagating along the mean magnetic field

$$\delta \mathbf{B}_\perp = \delta B\,[\cos(ky - \omega t)\,\hat{x} - \sin(ky - \omega t)\,\hat{z}] \tag{5}$$

where $\omega = v_a k$ is the phase speed and k the wave vector. The Alfvén wave is propagating in the direction of the background magnetic field so that $\delta \mathbf{v}_\perp = -v_a \delta \mathbf{B}_\perp / B_0$.

[12] Typical Alfvén speeds in the fast solar wind are few tens of kilometers per second while Ulysses observations have shown that fluctuations of the velocity field are of the order of 50 km/s [*McComas et al.*, 1995; *Neugebauer et al.*, 1995]. Moreover the largest period magnetic field fluctuations have amplitudes of the same order of the mean magnetic field [e.g., *Smith et al.*, 1995; *Neugebauer*, 2004]. In the simulations we have hence adopted $B_0 = 1$, $\delta b = 1$ and δu varying from 2 and 5 as representative values while the plasma β has been taken in the interval 2–5 compatible with the values usually observed in the high latitude fast streams observed by Ulysses [e.g., *McComas et al.*, 1995; *Yamauchi et al.*, 2004b]. The characteristic time scale of a polarity inversion is nearly one hour [*Balogh et al.*, 1999; *Yamauchi et al.*, 2004b], and a local Alfvén velocity of 10 Km/s [*Smith et al.*, 1995; *Goldstein et al.*, 1995a] implies that the typical length scale of our simulations is L = 36000 Km corresponding to the width

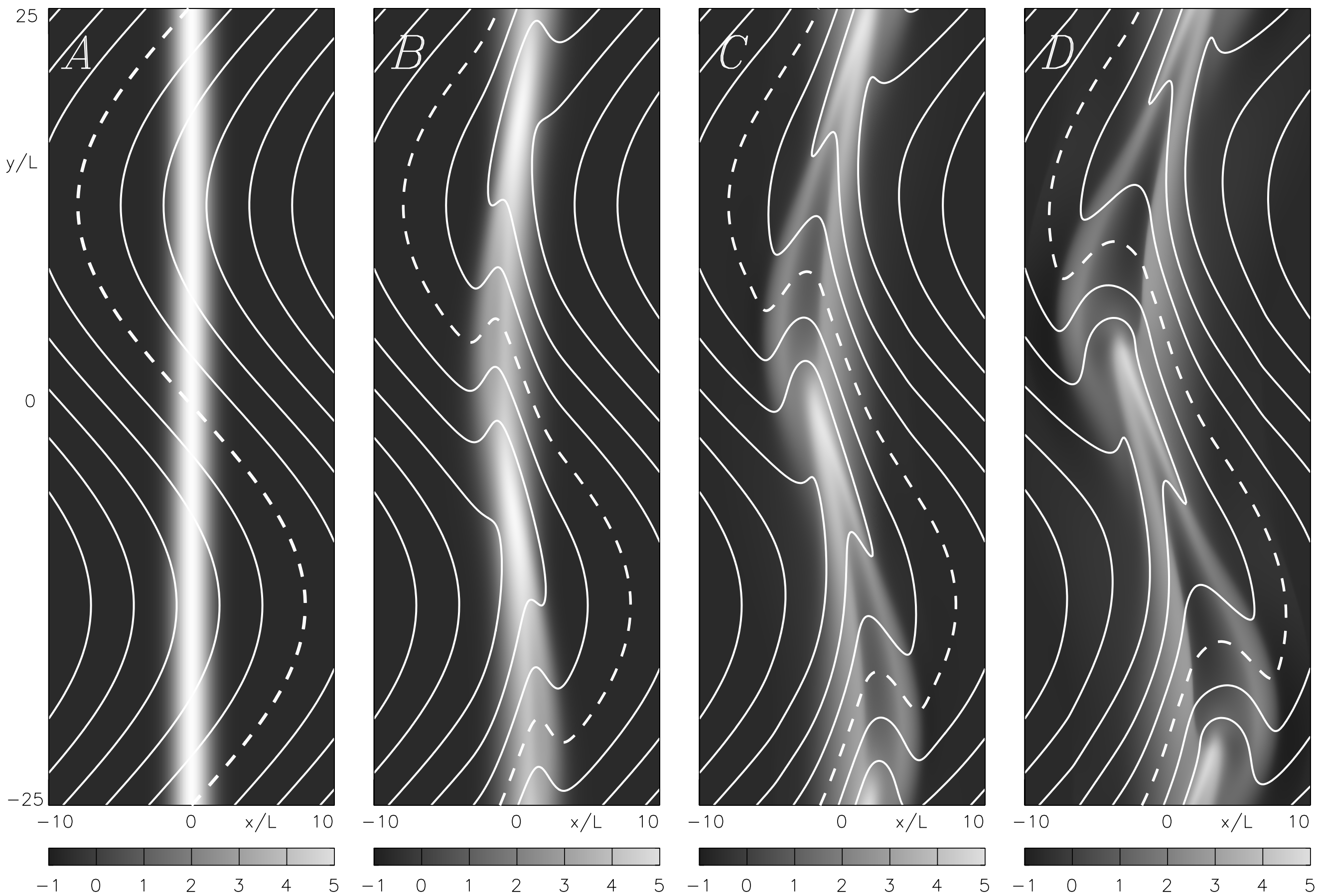

Figure 1. Magnetic field line (white lines) and shear time evolution for a simulation where a circularly polarized Alfvén wave is propagating along a uniform magnetic field directed along the shear. The magnetic field lines are stretched by the shear whose intensity is shown in gray scale. The reverse in the field line is emphasized by the dashed white line. Times are (a) t = 0 h, (b) 1 h, (c) 2 h, and (d) 3h.

of the velocity shear Δ. The lowest frequency range of the Alfvénic turbulence have characteristic period of few tenth of hours [e.g., *Smith et al.*, 1995]. For the circularly polarized Alfvén wave in the simulations here we have adopted wavelengths λ ranging from 10 L to 100 L, corresponding to periods of 10–100 hours.

[13] In Figure 1 the magnetic field lines and the intensity of the velocity shear are shown for different times for a simulation with $\delta u = 5$, $\beta = 5$ and $\lambda = 50$. The flow drags the magnetic field lines distorting them and a switch-back develops. The time scale for this to occur depends on the stream gradient and the initial transverse field, which must be stretched backward to create a radial component whose magnitude is of the same order of the initial radial field: $\delta t = 2B_0\Delta/\delta B\delta u$. With the values of the simulation shown in Figure 1 we obtain $\delta t = 0.4$ - in very good agreement with the time when the inversion occurs in the simulation.

[14] In Figure 2 we compare the magnetic field and plasma properties at two polarity reversals observed at Ulysses (from *Yamauchi et al.* [2004b]), with a virtual satellite in-situ crossing of our simulation box in $x = 4$ (for simplicity, we assume the virtual probe to cross in the cross-stream direction). The first row shows the radial velocity, the second the radial field, followed by the pressures and plasma β. In correspondence with the polarity inversion there is a drop in the magnetic pressure and an

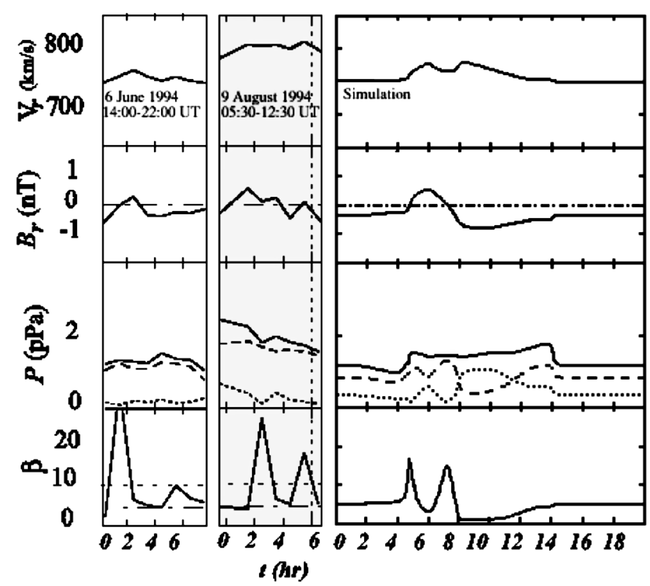

Figure 2. Comparison of radial polarity inversion periods in Ulysses data (from *Yamauchi et al.* [2004b, Figure 2]), and our simulations at time t = 2. From top to bottom, profiles of the radial velocity shear, radial component of the magnetic field, total (solid), thermal (dashed) and magnetic (dotted) pressures, and plasma β.

increase in the plasma pressure while the total pressure remains almost constant. In the simulation, the plasma β increases of roughly a factor 2–3 with respect to the adjacent regions, while the enhancement is larger in the data. Notice also the substructure forming in the profile of the radial velocity, a dip appearing at the center due to the drag arising from increased field line tension. Similar smaller scale radial velocity variations appear in the data.

4. Conclusion

[15] In the fast polar solar wind where the mean magnetic field is close to radial, low frequency Alfvénic turbulence causes the magnetic field to be unaligned with respect to the flow direction. In the presence of differential radial streaming (i.e., micro-streams or other radial velocity oscillations) the simulations show that switch-backs are a natural outcome. Our numerical simulations show how this interaction leads not only to the radial field inversions, but also to plasma pressure and density signals similar to those observed in the data, of which we have given two examples. The simulation therefore suggests that magnetic field polarity inversions could be produced in situ by the interaction of low frequency, high amplitude, transverse Alfvén waves with radial velocity field fluctuations.

[16] We have chosen initial conditions which are extremely simplified, but contain the minimal ingredients of the scenario we intended to outline. It is important to pursue the dynamical role of this interaction further, using more realistic initial conditions and higher dimensional simulations: the reason is that the interaction of Alfvénic turbulence with the velocity shears can play an important role in regulating the evolution of different sub-structures in the fast wind as well as the amplitude of the transverse turbulence itself. One could envisage the solar wind acceleration region consisting of jets with much greater velocity spreads, feeding via this mechanism into the transverse Alfvénic turbulence which at the same time would break the differential speeds. Saturation would naturally occur when the amplitude of the turbulence is of the same order of magnitude as the overall fluctuations in radial velocity observed at Ulysses. The effect of velocity shears in turbulence and wave evolution has been studied extensively in the past, showing that shear-wave interactions can be relevant in explaining some properties of the solar wind turbulence [e.g., *Roberts et al.*, 1992], as the cross-correlation decay with distance and the observed degree of wave energy equipartition, and it has been suggested that shears between streams tubes in a filamentary corona can generate fluctuations which regulate the shear gradient [see, e.g., *Goldstein et al.*, 1995b, and references therein].

[17] Although our scenario is able to reproduce polarity reversals which reproduce plasma density and pressure fluctuations analogous to those observed in same cases by Ulysses, it does not exclude additional possibilities. The lowest-frequency part of the Alfvénic turbulence spectrum, periods greater than half a day or so, contains the so called Jokipii and Kota regime [*Jokipii and Kota*, 1989], where, because of the solar wind expansion, the transverse magnetic field grows relative to the background radial field faster than the amplitude of the higher frequency turbulence. At some distance from the sun its amplitude could be of the same order of magnitude as the mean magnetic field. Some evidence of the observation of this regime has been reported by *Jokipii et al.* [1995] and *Smith et al.* [1997]. Shorter period, high amplitude Alfvén waves would propagate along the magnetic field lines kinked by the presence of such structures. In this case the global effect of large scale spatial structure and low frequency Alfvén waves could result in a strong change of the azimuth angle also creating a magnetic field polarity inversion.

[18] We have not mentioned the dynamics of waves and shears in the slower solar wind, because in this case large-scale CMEs and perturbations to the global magnetic field topology due to reconnection are very important ingredients, though there may be situations where the interaction of velocity shears, and shocks, with the turbulence, lead to anomalous field configurations. We leave the detailed investigation of these aspects to future work.

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