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Model for vortex turbulence with discontinuities in the solar wind

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Abstract. A model of vortex with embedded discontinuities in plasma flow is developed in the framework of ideal MHD in a low β plasma. Vortex structures are considered as a result of 2-D evolution of nonlinear shear Alfvén waves in the heliosphere. Physical properties of the solutions and vector fields are analyzed and the observational aspects of the model are discussed. The ratio of normal components to the discontinuity B_r/V_r can be close to -2. The alignment between velocity and magnetic field vectors takes place. Spacecraft crossing such vortices will typically observe a pair of discontinuities, but with dissimilar properties. Occurrence rate for different discontinuity types is estimated and agrees with observations in high-speed solar wind stream. Discontinuity crossing provides a backward rotation of magnetic field vector and can be observed as part of a backward arc. The Ulysses magnetometer data obtained in the fast solar wind are compared with the results of theoretical modelling.

1 Introduction

Convected structures, series of Alfvénic fluctuations, microstreams were observed in the heliosphere (see Goldstein et al., 1995; Kallenrode, 2001 and references therein). Nonlinear phenomena in the solar wind flow involving dispersive Alfvén waves were analyzed in a number of papers (see, for example Buti et al., 1999) with taking into account finite plasma β effects and mode coupling. Spatio-temporal evolution was studied using one-dimensional hybrid simulation. A number of nonlinear equations was derived to describe one-dimensional MHD waves propagating under different angles to the ambient magnetic field (Petviashvili and Pokhotelov, 1992). If MHD mode coupling or anisotropy effects are included into consideration, the problem becomes essentially two- or three-dimensional. Two-dimensional effects manifest themselves in modification of MHD wave spectra and appearance of plasma instabilities. There are several ways to generalize nonlinear wave equations for two-dimensional case. Incompressible disturbances in a cold plasma with strong magnetic field are described by stream function and field-aligned component of the vector potential (Kadomtsev and Pogutse, 1973; Strauss, 1976). Plasma with finite β requires extra variables to include compressional effects and field-aligned disturbances associated with slow magnetosonic waves. In general, a creation of vortices is intrinsic feature of both Alfvén and drift nonlinear waves (see Horton and Hasegawa, 1994 and references therein). They are caused by vortex nonlinearity and, for the simplest cases, studied in terms of Hasegawa-Mima and Petviashvili-Pokhotelov equations which admit vortex solutions. It was shown that presence of long-lived organized coherent vortices plays an important role in two-dimensional plasma dynamics. These 2D vortex structures are quite common in space plasmas and were observed in ionosphere (so-called black aurora) (Johnson and Chang, 1995), solar wind (Polygiannakis and Moussas, 2000), the Earth distant magnetotail (Hones et al., 1978) and plasma sheet (Verkhoglyadova et al., 2001). It should be noted that vortex structures were extensively studied in the ionosphere and the magnetosphere of the Earth. Theoretical models and numerical simulations revealed monopole vortex, dipole vortex and vortex chain solutions for nonlinear equations described drift and inertial Alfvén waves in a low-beta plasma (Chmyrev et al., 1988). Qualitative agreement with satellite data and ionospheric measurements has been shown (Chmyrev et al., 1991). Another approach was developed for Alfvén vortices in a magnetized electron-positron plasma. It was shown that finite amplitude shear Alfvén waves evolve to vortex structure which process affects both particle and energy transport in the pulsar magnetosphere (Yu et al., 1986).

The solar wind plasma shows many features of fully developed magnetohydrodynamical multiscale turbulence. Experimental data provide an evidence that quasi two-dimensional structures exist in nearly incompressible regions of the solar wind. The slab turbulence and quasi two-dimensional tur-

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bulence are both present and well separated (Ghosh et al., 1998). The latter one is associated with Alfvénic type disturbances, which are predominant in the fast solar wind. Typical MHD vortex turbulence is characterized by a power law spectrum with the index being close to $-3...-1.5$ (Hasegawa and Horton, 1994). The experimental data gives the values varying from -2.2 to -1.7 (Burlaga, 1992; Goldstein et al., 1995).

It seems reasonable to consider formation of magnetic vortices at strongly nonlinear stage of Alfvén waves evolution in heliosphere. Special kind of solutions represents magnetic field depressions with a core bounded with a discontinuity, which could contribute to the theory of magnetic holes in the solar wind. This model can be considered as development of one-dimensional nonlinear model proposed in Buti et al. (2001). Similar approach was developed in the papers Shukla and Stenflo (1999), Verkhoglyadova et al. (2001) and incorporated both shear Alfvén and compressional disturbances in a warm inhomogeneous space plasma. Experimental features of the model will be discussed.

2 Model for 2D nonlinear Alfvén waves in plasma with flow

We consider homogeneous cold plasma with background magnetic field directed along Z–axis and restrict our model to incompressional limit. This approach is different from one developed in the paper Zank and Matthaeus (1993). We study low β plasma with purely MHD Alfvénic disturbances and no compressional corrections at the first step. The basic set of equations can be written in terms of two scalar functions, velocity flux Ψ and field-aligned component of magnetic potential A (Kadomtsev and Pogutse, 1973; Petviashvili and Pokhotelov, 1986):

$$\frac{d}{dt}\,\Delta_\perp\Psi+\frac{d}{dz}\,\Delta_\perp A=0\,,\qquad \frac{d}{dt}\,A+\frac{\partial}{\partial z}\Psi=0\,,$$

where $\frac{d}{dt}=\frac{\partial}{\partial t}+\{\Psi,\ ...\}$, $\frac{d}{dz}=\frac{\partial}{\partial z}-\{A,\ ...\}$, and the operator $\{...,...\}$ denotes the Poisson's brackets. The nonlinearity originates from the operator $\frac{d}{dt}=\frac{\partial}{\partial t}+(V\nabla)$ in the Navier-Stokes equation. Dimensionless variables are obtained by scaling with proton gyroperiod and Alfvén velocity. Magnetic field disturbances $\boldsymbol{B}=\nabla\boldsymbol{A}\times\boldsymbol{e}_z$ and flow velocity $\boldsymbol{V}=\boldsymbol{e}_z\times\nabla\Psi$ are expressed through the flux functions. Convective electric field is defined by $\boldsymbol{E}=-\nabla_\perp\Psi$.

Standard approach is used to find a partial vortex solution, which is a localized structure moving with velocity u in a plane (ξ, y), where $\xi=x-ut+\alpha z$, and the angle α denotes inclination of a vortex axis to the background magnetic field (Horton and Hasegawa, 1994; Petviashvili and Pokhotelov, 1992; Verkhoglyadova et al., 2001). The set of equations reduces to the form:

$$\left\{\widetilde{\Psi},\ \Delta_\perp\widetilde{\Psi}\right\}-\left\{\widetilde{A},\ \Delta_\perp\widetilde{A}\right\}=0,\qquad \widetilde{\Psi}=\Psi+u\ y$$
$$\left\{\widetilde{\Psi},\ \widetilde{A}\right\}=0,\qquad \widetilde{A}=A+\alpha y$$

We will seek for the simplest functional dependence of $\widetilde{A}$ on $\widetilde{\Psi}$, i.e. solution $A=s\Psi$, where the parameter $s=\alpha/u$ is taken from the localization condition at infinity $x, y\rightarrow\infty$: $\Psi, A\rightarrow 0$, $\widetilde{\Psi}\rightarrow u\ y$, $\widetilde{A}\rightarrow\alpha\ y$. Then the first equation of the set takes the form:

$$\Delta_\perp\Psi=-k^2\ (\Psi+uy)\,,\quad r\le a\,;$$
$$\Delta_\perp\Psi=p^2\ \Psi,\quad r>a\,.$$

Polar coordinates (r,θ) are introduced in the plane. Vortex solution of an arbitrary radius a takes the form (Larichev and Reznik, 1976):

$$\Psi=\begin{array}{ll}(C_1J_1\,(kr)-ur)\sin\theta, & r\le a\,;\\ C_2K_1\,(pr)\sin\theta, & r>a\,;\end{array}\tag{1}$$

Here J_1 is the first-order Bessel function of the first kind, K_1 is a first-order modified Bessel function of the second kind. Solution (1) describes a plane structure moving with a velocity u within $r\le a$. The solution in outer region $r>a$ corresponds to the case of $u=0$ and describes a motionless, but disturbed plasma (see Fig. 1). One can consider this nonlinear wave structure as a generalization of MHD vortex rings or convective cells associated with linear Alfvén waves (Alfvén and Falthammar, 1963). For $s=\pm1$ we obtain a partial case of a plane wavefront and linear shear Alfvén wave.

There is a number of free parameters $(u, a, \alpha, k, p, C_1, C_2)$ in the solution. We set the continuity condition at the vortex boundary $(r=a)$ to determine the amplitudes (Petviashvili and Pokhotelov, 1992):

$$[\Psi]=0\,,\tag{2}$$

where $[\Psi]=\Psi\,(r=a+0)-\Psi\,(r=a-0)$ is the notation for a jump of Ψ. Introduce the generalized vorticity g_0 at the boundary, $\Psi\,(r=a)+u\,a\sin\theta=g_0\sin\theta$. Thus we define

$$C_1=\frac{g_0}{J_1\,(k\,a)}\qquad C_2=\frac{g_0-ua}{K_1\,(pa)}\tag{3}$$

According to the standard approach the continuity condition

$$\left[\frac{\partial\Psi}{\partial r}\right]=0\tag{4}$$

is assumed and the parameter p is defined. The number of free parameters reduces to five: (u, a, α, k, g_0).

One can obtain plasma velocity and magnetic field components from the flux functions:

$$V_r=-\frac{1}{r}\frac{\partial\Psi}{\partial\theta}\qquad B_r=-s\ V_r$$
$$V_\theta=\frac{\partial\Psi}{\partial r}\qquad B_\theta=-s\ V_\theta\tag{5}$$

Note, that for linear shear Alfvén waves, the relation between dimensionless magnetic field and plasma velocity disturbances is $\boldsymbol{B}=-\boldsymbol{V}$. This ratio could be modified for nonlinear disturbances with plasma rotation and field line bending. Vortices ensure a balance between centrifugal force and tension of magnetic field lines.

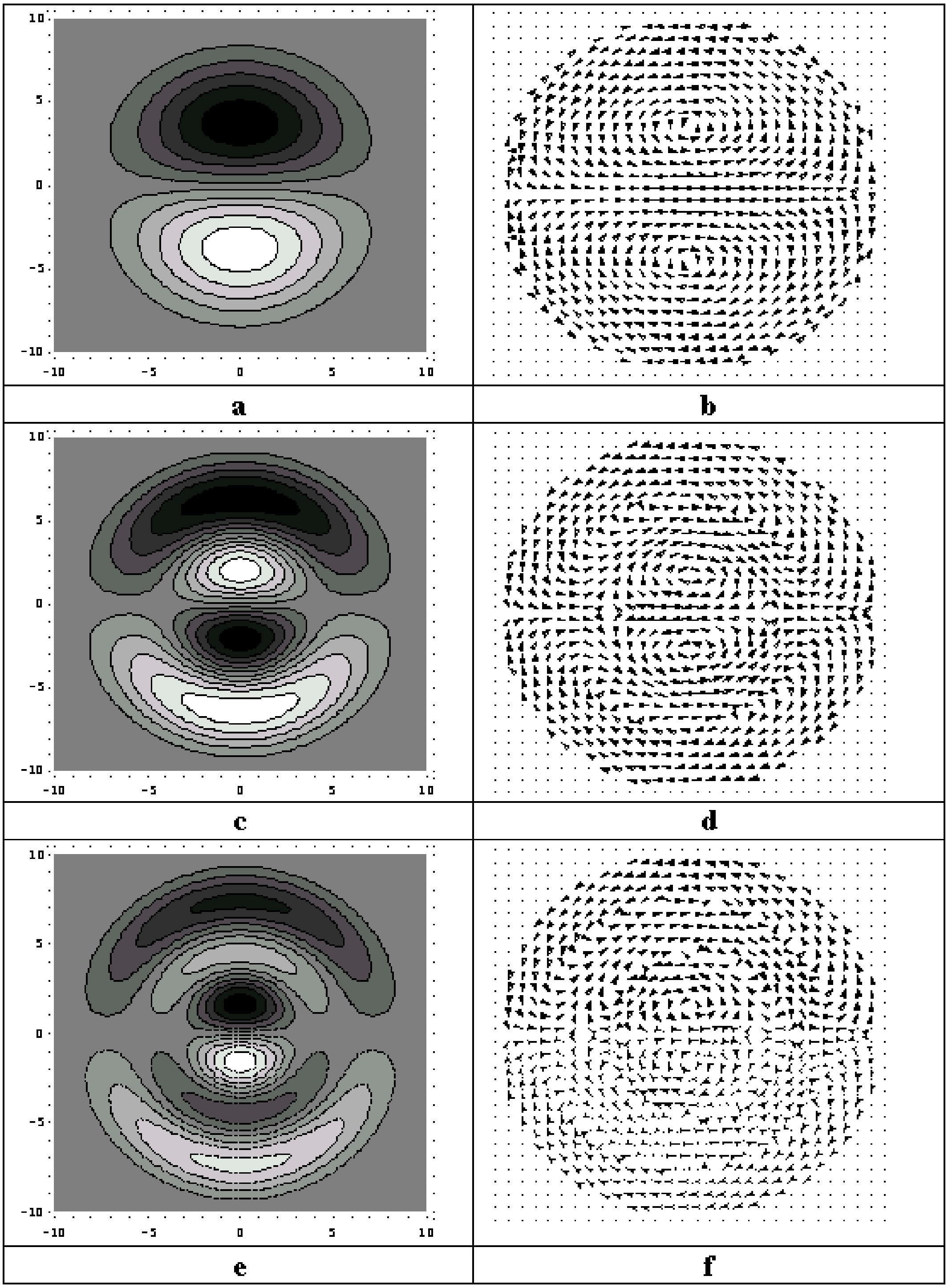


Fig. 1. Contour plot of the flux function Ψ and respective velocity field in for a vortex with dimensionless radius $a = 10$ and velocity $u = 0.06$. Plots are shown for different values of the parameter k: 0.533 **(a, b)**, 0.854 **(c,d)** and 1.17 **(e,f)**.

For the solutions (1) and (3), the continuity conditions (2)and (4) imply

$$[V_r] = 0 \quad \text{and} \quad [B_r] = 0\,, \tag{6a}$$

$$[V_\theta] = 0 \quad \text{and} \quad [B_\theta] = 0\,, \tag{6b}$$

for normal and tangential components to the vortex boundary, respectively.

The Kadomtsev-Pogutse set of equations also permits a linear wave solution. Consider combined solution of a shear Alfvén wave and a vortex in the model. This limiting case takes place both near the vortex core ($r \to 0$) and far from the nonlinear structure ($r \to \infty$), where velocity and magnetic field disturbances in a vortex are small and close to the linear ones. We seek for a solution with $\Psi = \Psi_L + \Psi_V$ and $A = A_L + A_V = \Psi_L + s\Psi_V$, where the shear Alfvén wave is described by Ψ_L and A_L. Flux function for a vortex, Ψ_V, is defined by Eq. (1). Thus, $A_L = \Psi_L$ and $\Psi_L \exp(i\ (\omega t - \boldsymbol{\kappa r}))$. The set reduces to

$$\frac{\partial}{\partial t}\Psi_L + \frac{\partial}{\partial z}\Psi_L + (s-1)\{\Psi_L, \Psi_V\} = 0\,,$$

$$\frac{\partial}{\partial t}\Delta_\perp\Psi_L + \frac{\partial}{\partial z}\Delta_\perp\Psi_L + (s-1)\left(k^2\{\Psi_L, \Psi_V + u\,y\} - \kappa^2\{\Psi_L, \Psi_V\}\right) = 0\,,\ r \le a\,;$$

$$\frac{\partial}{\partial t}\Delta_\perp\Psi_L + \frac{\partial}{\partial z}\Delta_\perp\Psi_L + (s-1)\left(-p^2\{\Psi_L, \Psi_V\} - \kappa^2\{\Psi_L, \Psi_V\}\right) = 0\,,\ r > a$$

Assuming almost linear perturbations $|\Psi_V\,(r \to 0)| \ll 1$ in the region $r \le a$, we obtain a dispersion relation

$$\omega = \kappa_z - (s-1)\ \kappa_x u$$

and a condition on flux functions:

$$\{\Psi_L, \Psi_V + u\,y\} = 0$$

The first expression is similar to the dispersion relation of shear Alfvén waves in a plasma flowing with the velocity $-u\boldsymbol{e_x}$:

$$\omega = \kappa_z - \kappa_x u$$

This assumption is consistent with a vortex velocity field derived from Eq. (1) at $r \approx 0$ and describes plasma motion through the structure at $y \to 0$. Thus, a continuous transition between nonlinear structures and linear waves takes place under the condition of $s = 2$.

Outside the vortex core ($r > a$) the similar expressions can be obtained for a vanishing flow at infinity $\Psi_V\,(r \to \infty) \to 0$:

$$\omega = \kappa_z \qquad \text{and} \qquad \{\Psi_L,\ \Psi_V\} = 0\,.$$

They correspond to linear waves in motionless plasma. In a general case of finite disturbances we can not neglect interaction between Alfvén waves and nonlinear structures.

We studied the model of vortices or convective cells, which represent 2D large-amplitude shear Alfvén waves in a plasma flow. They are plane structures inclined to the background magnetic field. Magnetic field and velocity disturbances are related in anti-phase with the factor of 2. Observational features of the structures will be discussed in next sections.

3 Vortex with embedded discontinuity

The solar wind is characterized by large-amplitude Alfvénic turbulence and numerous tangential and rotational discontinuities. We use the above approach to obtain a self-consistent solution of a nonlinear structure with a discontinuity at the vortex boundary. This discontinuity can not exist without a nonlinear Alfvén wave.

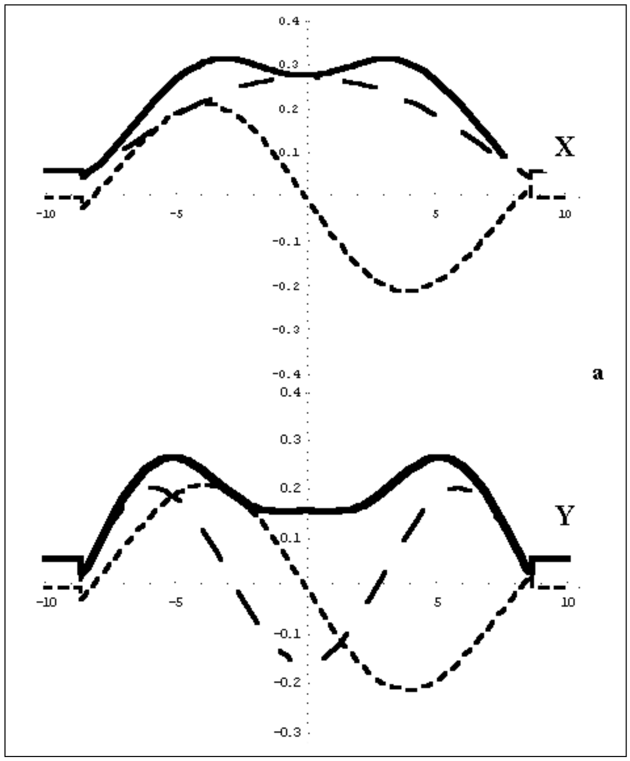


Fig. 2. Profile of magnetic field magnitude B (solid) and components B_x (long dash), B_y (short dash) for $y = 5$ **(a)** and $x = 5$ **(b)**.

Consider a highly localized vortex moving in a plasma according to the solution (1):

$$\Psi = \begin{cases} (C_1 J_1\,(k\,r) - u\,r)\sin\theta, & r \le a\,; \\ 0, & r > a\,; \end{cases}$$

Velocity of the relative motion of a plasma is $\boldsymbol{V_a} = -u\boldsymbol{e}_\xi$. From a continuity condition (2) we get

$$\Psi\,(r = a - 0) = \Psi\,(r = a + 0) = (g_0 - u\,a)\sin\theta = 0$$

and

$$\begin{aligned} C_1 &= \tfrac{u\,a}{J_1(k\,a)} \\ g_0 &= u\,a \end{aligned} \tag{7}$$

Introduce a finite jump in $\partial\Psi/\partial r$ at the vortex boundary $r = a$:

$$\left[\frac{\partial\Psi}{\partial r}\right] = \Delta\sin\theta \tag{8}$$

Physically we imply a finite jump in tangential components:

$$[V_\theta] = \Delta\sin\theta, \qquad [B_\theta] = -s\ [V_\theta]\ . \tag{9}$$

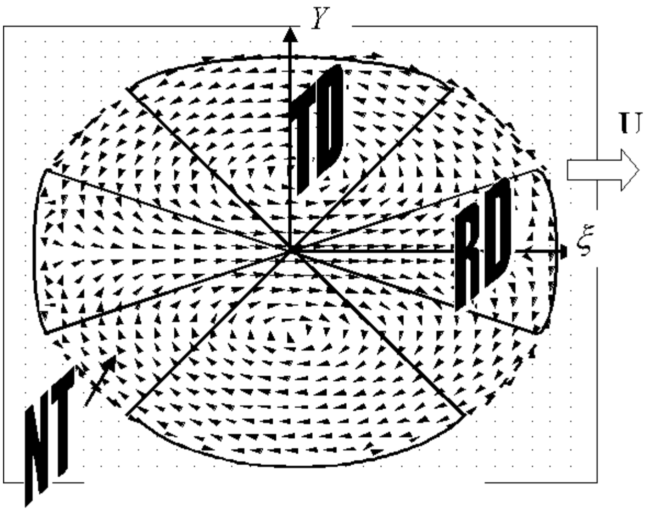


Fig. 3. Scheme for discontinuity types associated with the vortex solution (11). U indicates velocity of the structure.

Typical profile of magnetic field in a vortex is shown in Fig. 2.

Normal velocity component to the boundary (V_n) consists of a normal component of the vortex velocity field V_r and a normal component of the ambient plasma flow around the structure in the vortex' reference frame $V_a^n = V_a \cos\theta$, where $V_a = -u$ is the velocity of a relative motion:

$$V_n\,(a) = V_r\,(a) + V_a^n = V_r\,(a) - u\cos\theta$$

According to the ideal MHD boundary conditions and the Eqs. (5) we obtain:

$$\begin{aligned} B_n\,(a) = -V_n\,(a) &= B_r\,(a) + B_a \cos\theta \\ &= -s\,V_r\,(a) + u\cos\theta\ , \end{aligned}$$

where $B_a = -V_a$ for a linear Alfvénic flow. Continuity of $V_n\,(a)$ and $B_n\,(a)$ implies that $V_r\,(a) = 0$, which is consistent with the solution (7).

Because of the relative motion with $V_a^\tau = -V_a \sin\theta$ (see Fig. 3), a tangential velocity component to the boundary (V_τ) has a discontinuity according to Eq. (7):

$$[V_\tau] = [V_\theta] - V_a \sin\theta = (\Delta + u)\sin\theta = 2u\sin\theta$$

and

$$\Delta = u \tag{10}$$

which is consistent with the ideal MHD boundary conditions and

$$[B_\tau] = -[V_\tau] = [B_\theta] = -s\,[V_\theta] = -s\Delta\sin\theta$$

The self-consistent solution of a vortex with embedded discontinuity depends on two free parameters u and a:

$$\Psi = \begin{cases} \left(\frac{u\,a}{J_1(k\,a)} J_1\,(k\,r) - u\,r\right)\sin\theta, & r \le a\ ; \\ 0, & r > a \end{cases} \tag{11}$$

Using the solution (11) and the conditions (5) and (7)–(10) we can define the parameter k from the equation:

$$J_1'\,(ka) = 0 \tag{12}$$

There is an infinite set of solutions of Eq. (12) with every k corresponding to a definite type of vortex (Fig. 1).

This discontinuity at a vortex boundary looks similar to the MHD one, but its nature changes with vortex phase angle θ. For the rotational-like discontinuity we get Eqs. (9), (11):

$$[V_\theta] = 0 \qquad \text{for} \qquad \theta = 0, \pi\ ;$$
$$[V_\theta] = \pm\Delta \qquad \text{for} \qquad \theta = \pm\pi/2\ ;$$

The discontinuity changes from pure tangential at the vortex "flank", becomes rotational at other positions and vanishes at the "nose".

It should be noted that the condition (8) is consistent with the "classic" MHD boundary condition. Taking into consideration velocity field near a vortex boundary (Fig. 3) and relative streaming of a plasma in opposite direction around the structure, one can notice that a velocity jump occurs at a boundary, which becomes maximum at the "flanks". This effect physically creates and maintains the boundary condition.

4 Comparison with experimental data

The model (7)–(12) represents a set of nonlinear MHD structures with disturbances localized in the region of $r < a$. The geometry of a vortex velocity field is defined by parameter k (see Fig. 1). The structure is situated in a plane (ξ, y) with normal inclined by an angle α to the background magnetic field. Inasmuch as $\alpha \ll 1$, we conclude that $u = 2\alpha \ll 1$. It means that vortex is moving across magnetic field lines with a velocity which is much smaller than the Alfvén velocity. Such structures can create vortex tubes elongated under the angle α to the background magnetic field (Petviashvili and Pokhotelov, 1986; Verkhoglyadova et al., 2001).

Consider the ratio of normal components to the discontinuity. We obtain $B_r/V_r = -1$ strictly at the boundary, but this ratio is equal to -2 inside a vortex, which value can be revealed as a typical feature of developed Alfvénic turbulence (Goldstein et al., 1995). This ratio can be also observed in the close vicinity of a discontinuity (Neugebauer et al., 1984).

Another important consequence of the model is alignment of velocity and magnetic field changes across a tangential discontinuity (Neugebauer, 1985; Neugebauer et al., 1986). This type of discontinuity occurs as a partial case under the general boundary conditions (9). We get $B_n\,(a) = -V_n\,(a) = 0$ at $\theta = \pm\pi/2$, with $[B_\tau] = -[V_\tau] = -2\Delta$. While crossing a discontinuity at "flank" regions one obtains that tangential velocity and magnetic field are related. In the vicinity of discontinuity $[B_\theta] = -2\,[V_\theta]$. We believe that this effect could explain a number of measurements (Neugebauer, 1985).

Table 1. Summary of physical properties of discontinuities (ratio of the normal component to the field magnitude and ratio of magnitude jump to the field magnitude) according to (Neugebauer et al., 1984)

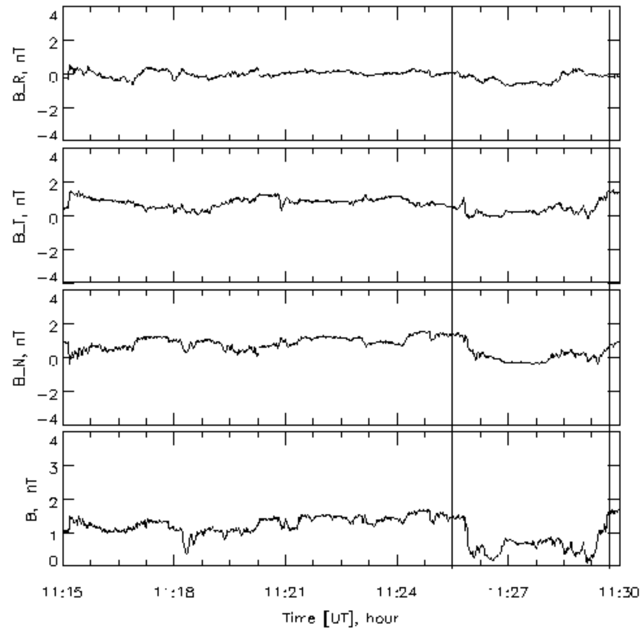
Type	$Bn/\lvert B\rvert$	$[\lvert B\rvert]/\lvert B\rvert$
Rotational (RD)	High	Low
Tangential (TD)	Low	High
Either (ED)	Low	Low
Neither (NT)	High	High

Table 2. Occurrence rate for the solar wind measurements (Neugebauer et al., 1984) and the model predictions for discontinuity types. We consider RD and NT categories together, because of ambiguity of B evaluation and presence of strong normal component for these discontinuity types. Model prediction is $RD : TD : ED : NT = 23 : 46 : 0 : 31$

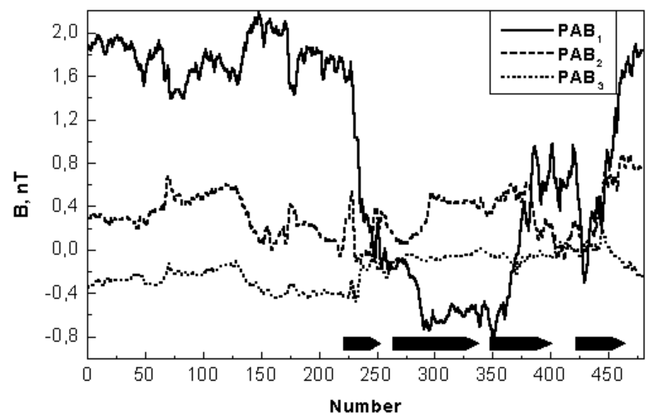
	slow solar wind	fast solar wind	model prediction
$RD + NT$	38...44	57... 63	54
$TD + ET$	56...62	37... 44	46

An occurrence rate of detecting certain type of a discontinuity while crossing a vortex boundary is studied. According to the paper (Neugebauer et al., 1984) we calculate the values of $B_n\ (a)\,/|B(a)|$ and $[|B|]\,/|B(a)|$ and evaluate ranges of phase angle θ that correspond to high B_n and small changes in $|B|$ (rotational discontinuity). The classification criteria for discontinuity types is quantitatively presented in the Table 1. Regions of rotational discontinuity, tangential discontinuity, and ambiguous cases (ET stands for "either discontinuity", and NT for "neither discontinuity") are selected (Fig. 3). The resulting ratio of discontinuities is $RD : TD : ET : NT = 23 : 46 : 0 : 31$. By definition, the category NT includes "suspicious cases" which could not be accurately put in any of the two categories because of uncertainty of data processing for respective measurements. However, this category includes discontinuities with high normal magnetic field component across it, and we define these cases as being rotational discontinuities in our theoretical modelling. Thus, one can obtain the ratio $(RD + NT) : TD = 54 : 46$, which is close to the results obtained in a high-speed solar wind flow (63 : 37 and 57 : 44) (Neugebauer et al., 1984), (see Table 2). As far as the model describes strong Alfvénic turbulence, our result shows less coincidence with measurements made for slow-speed solar wind regions, which are characterized by complicated nonlinear processes possibly involving compressional waves.

Study of nonlinear Alfvén waves in the heliosphere reveals their arc-polarization properties (Tsurutani et al., 1994, 1996). Vortices are nonlinear two-dimensional Alfvénic structures. Model magnetic field hodograms retain elliptic-like polarization and contain parts of arcs associated with discontinuity. A comparison is made between measurements of large-amplitude Alfvén waves with discontinuities and results of theoretical modelling. Consider an example of experimental data obtained with the Ulysses in the high-speed solar wind over the north solar pole. High-resolution magnetic



(a)



(b)

Fig. 4. The Ulysses magnetometer data (1-s resolution) for the time interval 11:15–11:30 UT, 208 day, 1995, show a pair of discontinuities (about 11:26 UT and 11:29 UT) **(a)**. The satellite was moving in a high-speed solar wind above the north solar pole at heliocentric distance about 2 AU. Lower panel represents magnetic field components found using the Minimum Variance Analysis **(b)**.

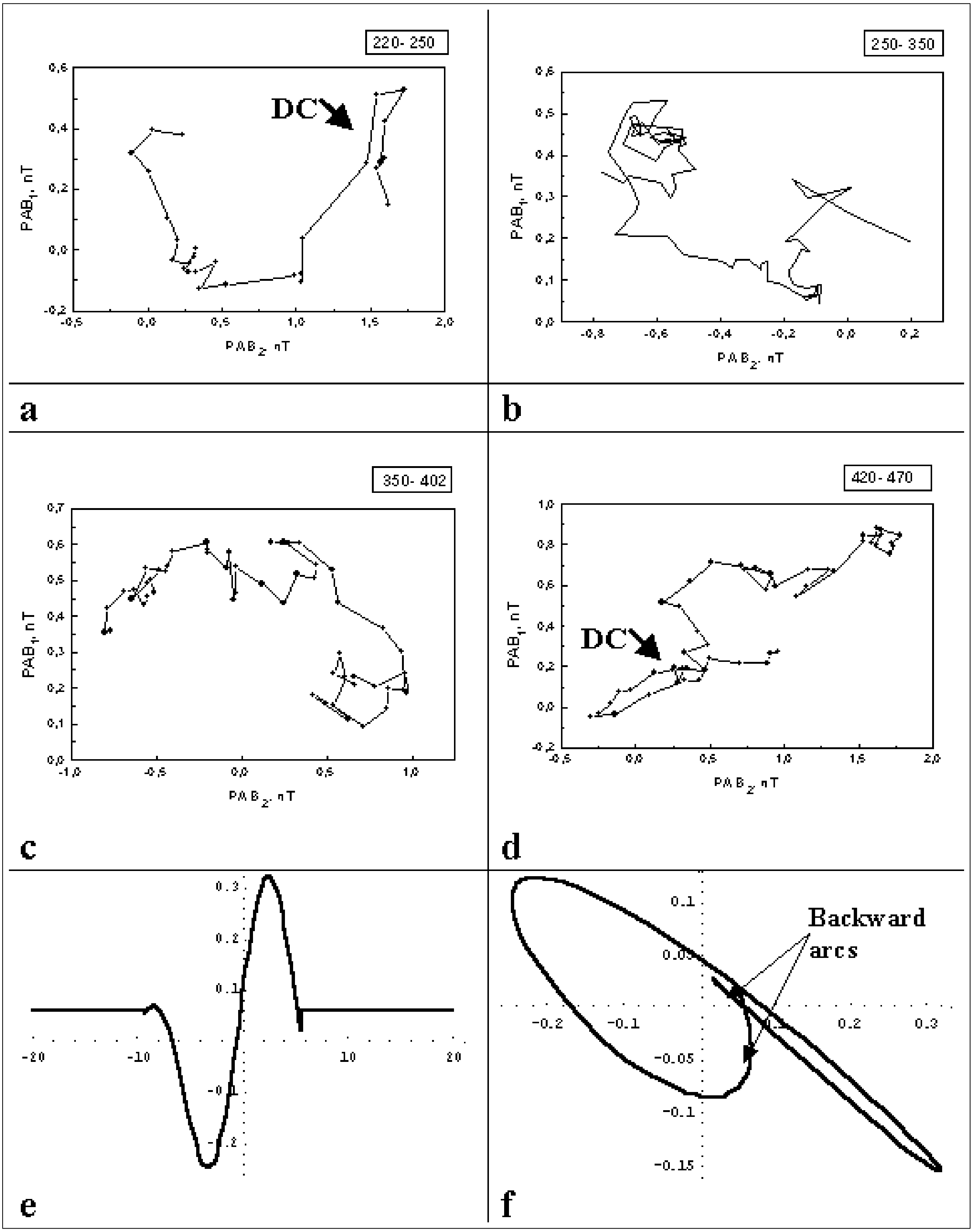


Fig. 5. Hodogram for the 1st discontinuity **(a)**, magnetic minimum **(b)**, magnetic maximum **(c)**, and for the 2nd discontinuity **(d)** of the pair. Results of theoretical modelling show a magnetic field profile for "shallow" potential well **(e)** and hodogram **(f)**.

field data for the time interval 11:15–11:30 UT, 27 July 1995 are presented in Fig. 4a. A pair of discontinuities is selected for detailed study. Using the Minimum Variance Analysis we calculate magnetic field components, which correspond to directions of maximum (B_1), medium (B_2), and minimum (B_3) variations (see Fig. 4b). A bipolar structure inside the magnetic well is noted. Hodograms for time intervals with the first discontinuity, magnetic minimum, magnetic maximum and the second discontinuity are presented in Fig. 5a–d. Discontinuity time intervals are characterized by backward motions. Other time intervals show arc-polarization. Model magnetic field profile and corresponding hodogram calculated for a vortex crossing are shown in Fig. 5e and f. We consider a "shallow" potential well with a discontinuity, that results in small backward motions in the plane (B_1, B_2). Shape of a polarization arc is caused by magnetic field asymmetry and depends on a direction of the vortex crossing. The results of theoretical modelling are similar to the experimental results showing relationship between interplanetary discontinuities and nonlinear Alfvén waves (Tsurutani et al., 2002).

5 Conclusion

We consider a model for solar wind plasma as a turbulent medium which consists of a mixture of nonlinear Alfvén waves and quasi-two dimensional MHD vortices. The latter structures represent a stage in dynamical evolution of the shear plasma motions and magnetic field fluctuations. The proposed model describes the localized nonlinear structure formation in the regions where a significant number of MHD discontinuities is present in the solar wind. Thus the power spectrum of the interplanetary magnetic field fluctuations is affected by the discontinuities and related nonlinear structures. Our new model includes Alfvén vortices with embedded discontinuity. A set of vortex solutions is obtained and the magnetic and velocity vector fields are analyzed.

Several features of this model are important toward explaining interplanetary observations. The first is the ratio of normal components to the discontinuity B_r/V_r which is not necessary equal to -1, but can be close to -2. The alignment between velocity and magnetic field vectors takes place for vortex crossings.

The second point is that spacecraft crossing such vortices will typically observe a pair of discontinuities, but with dissimilar properties. Occurrence rate for different discontinuity types obtained with theoretical modelling is consistent with observations in high-speed solar wind stream.

The third point is that the structure crossing will provide an arc-polarization properties of magnetic field disturbances. Discontinuity crossing provides a backward rotation of magnetic field vector and can be observed as part of a backward arc. The Ulysses magnetometer data are used to illustrate the point.

This is a simplified approach to 2D Alfvénic turbulence developed in terms of ideal MHD and cold plasma environment, which shows an opportunity to include both Alfvénic vortices and related discontinuities in the self-consistent model. Further study will include:

- development of a theory of pressure-balanced structures with inclusion of finite plasma β effects and field-aligned disturbances;
- estimate of pitch-angle scattering by resonant particle interactions with vortices and energy transfer perpendicular to the large-scale magnetic field;
- construction of vortex turbulence spectrum in heliosphere;
- detailed comparison of the vortex model predictions with the database of the Ulysses measurements.

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