

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

AN EVOLVING MHD VORTEX STREET MODEL FOR QUASI-PERIODIC SOLAR WIND FLUCTUATIONS

Edouard Siregar, D. Aaron Roberts, and Melvyn L. Goldstein

Laboratory for Extraterrestrial Physics, NASA-Goddard Space Flight Center, Greenbelt, Maryland

Abstract. We use magnetohydrodynamic (MHD) simulation to provide a dynamical basis for the "vortex street" model of the quasi-periodic meridional flow observed by Voyager 2 in the outer heliosphere. Various observations suggest that near the current sheet at solar minimum one can expect to find a vorticity distribution of two opposite shear layers with an antisymmetric staggered vorticity pattern due to structured high-speed wind surrounding low-speed equatorial flow. We show that this flow pattern leads to the formation of a highly stable vortex street through the nonlinear interaction of the two shear layers. Spatial profiles of various simulated parameters (velocity, density, meridional flow angle and the location of magnetic sector boundaries) and their relative locations in the quasi-steady vortex street are generally in good agreement with the observations. A strong, flow-aligned magnetic field, such as would occur in the inner heliosphere, inhibits the development of the street which would then be masked by the background interplanetary turbulence. The flow produced by the street induces a (relatively small) transport of plasma and magnetic flux as a result of the meridional flow away from the ecliptic region.

I. INTRODUCTION

During an extended time interval near solar minimum a surprising quasi-periodic meridional (out-of-ecliptic) solar wind plasma flow in the outer heliosphere was revealed by the Plasma Science experiment on board Voyager 2 [Lazarus *et al.*, 1988; McNutt, 1988]. The observed period of flow variations was about 25.5 days or approximately the time for one solar rotation. During the interval spanning 1986 to early 1988 Voyager 2 moved from 20 to 25 AU and was in the ecliptic plane as well as within 2° of the heliospheric equator. Combined observations from Pioneer 11 and Voyager 2 also show that a velocity shear of 200 km/s/ 15° exists when one moves from the heliospheric equator to higher latitudes [Gazis *et al.*, 1989]. We expect this shear to be approximately symmetric about the equator.

The underlying dynamics of the periodic non-radial plasma flow remains unknown. However, two models based on shear induced vortex shedding [Burlaga, 1990; Veselovsky, 1989] are consistent with the observed periodicity. These models suggest that a heliospheric "Karman vortex street"—a regular series of vortices of alternating signs as seen in the flow past a cylinder under a wide range of conditions [Karman, 1911]—may somehow produce the meridional solar

wind flow. The Burlaga model, based on two rows of steady two-dimensional incompressible infinite line vortices, produces roughly the correct speed and transverse flow profiles, but has the limitation of infinite flow velocities at the centers of the vortices. Veselovsky also suggests the existence of vortices in the outer heliosphere, and derives his conclusion using a first order solution to the polytropic gas dynamic equations. In these models, however, no attempt is made to study the nonlinear dynamical formation and stability of the vortex street. Also, the effects of compressibility and the correlation between pressure and other variables is not assessed. Some models of the meridional flow invoke compressibility instead of shear as the central ingredient of the process; these will be considered briefly in the discussion section.

In this letter, and more thoroughly in a related paper (Siregar *et al.*, submitted manuscript, hereinafter Paper I), we study the question of the formation, time dependence, stability and evolution of such a vortex street using the complete two-dimensional compressible MHD equations. This compressible model also allows us to address questions such as the correlation of density or pressure fluctuations with other parameters, and the effect of compressibility on the growth of the relevant instabilities. We show that a vortex street (usually observed in nature only as an amplifying instability in the wakes of bluff bodies) can form provided that a perturbation belonging to a specific class is added to two shear layers or vortex sheets. We argue here that this class of perturbations is exactly the kind expected from the structure of coronal holes and fast plasma streams near the Sun around solar minimum. We further find that the vortex distribution formed during the short inertial or nonlinear time scale is stable on the long dissipative time scales. We also briefly address the question of plasma and magnetic flux transport away from the current sheet region, although a detailed analysis will be deferred to a subsequent paper.

II. MODEL FOR THE FORMATION AND EVOLUTION OF VORTEX STREETS

Theoretical instability analysis suggested some time ago that certain growing modes can induce two neighboring layers of opposite vorticity to strongly interact and eventually form a Karman street of vortices [e.g., Abernathy and Kronauer, 1961]. More specifically (as shown in Paper I), a combination of four modes for two neighboring opposite vortex sheets creates an "antisymmetric" displacement of the sheets. It is this configuration that leads to the staggered vorticity distribution and creates the vortex street. In the case of the Sun, the rotating time-varying "boundary condition" that lies at some point near a solar coronal hole can give rise to a broad spectrum of perturbations. We argue next, following Burlaga [1990], that the dominant perturbation in the solar wind leads

Copyright 1992 by the American Geophysical Union.

Paper number 92GL01616
0094-8534/92/92GL-01616\$03.00

to antisymmetric growing modes that result in the vortex street.

At the time Voyager 2 was observing the meridional flows, IMP 8 was observing the solar wind flow at 1 AU. When it was located above the heliospheric current sheet it found one high-speed stream per solar rotation. Below the current sheet it also observed one stream, but nearly 180° out of phase with the stream on the other side. Thus a given point in the heliosphere would see an alternation of fast flows above and below the equatorial region; this situation is ideally suited to producing vortices of alternate sign. In what follows we presume that the wind is generally faster outside of the equatorial region, as indicated by the Pioneer observations [Gazis *et al.*, 1989], with enhancements due to the streams observed by IMP 8. In addition we note that the Sun's magnetic axis is not exactly aligned with its rotation axis and that this produces a warped current sheet separating the magnetic hemispheres. This will lead to compressed fast-slow stream interaction regions that will not be included in our model.

The vortex street model is also attractive in terms of fluid dynamical stability considerations. Shear flows such as jets, free convection shear, and boundary layers become fully turbulent far downstream at high Reynolds numbers ($Re = UL/\nu$ where U and L are characteristic velocities and scales of the flow and ν is the kinematic viscosity). The only exception to this is the Karman vortex street which shows remarkable stability. Observations of vortex streets in the wake of cylinders can be found at distances downstream greater than 600 diameters of the cylinder [e.g., Zdravkovich, 1969]. In addition, the vortex street configuration is robust to variations in the dissipation rate: experiments done at various Reynolds numbers [e.g., Tritton, 1977] show that periodic vortex shedding occurs at all Reynolds numbers tried experimentally (up to 10^7).

In our two dimensional MHD model we are interested in local processes that exist in the co-moving solar wind frame. Processes related to the spherical symmetry of the solar wind flow are small if we look at length scales much shorter than the distance to the Sun. Azimuthal effects cannot be addressed

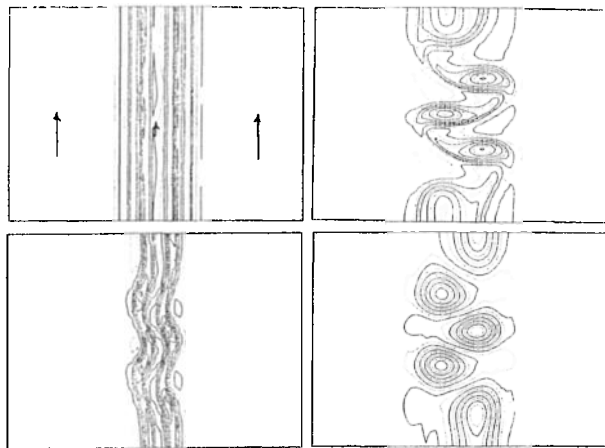


Fig. 1. The evolution of vorticity contours. The initial condition is in the upper left ($T = 0$) and subsequent times are $T = 1.08$ (lower left) $T = 3.24$ (upper right) and $T = 6.84$ (lower right). The initial mean flow velocities are depicted by the three arrows which show the two fast outer regions and the slow central region.

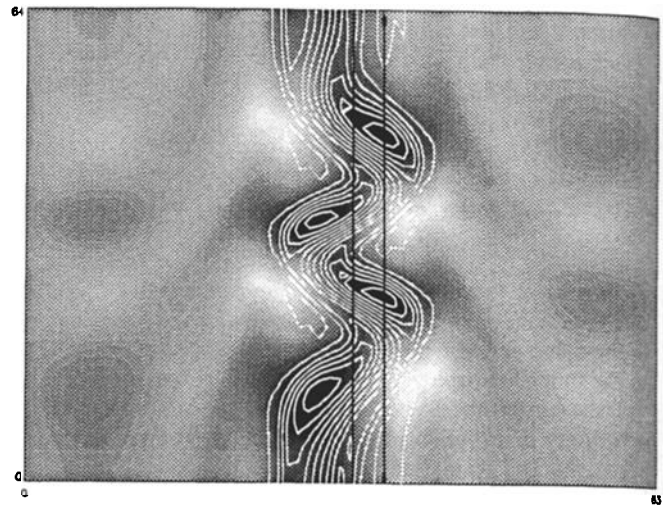


Fig. 2 The vorticity (white contours) of Figure 1 at $T = 2.16$ with low pressure/density plasma cavities (in black) located inside the spinning vortices. The two black lines show the paths through which the profiles of Fig. 3 were taken.

within the context of the 2-D model used here, but no significant periodic azimuthal flow was observed by Voyager 2. We study time and space scales large enough so that MHD theory is applicable and use a scalar pressure p defined by $p = (1/\gamma)\rho^\gamma$ where ρ is the density. A constant isotropic kinematic viscosity is used and there is no numerical modeling of dissipation other than the standard compressible Navier-Stokes terms. The equations we solve, in dimensionless form, are those for conservation of mass and momentum, and Faraday's law. In terms of the vector potential $A = a\hat{z}$, and velocity \mathbf{u} these are:

$$\begin{aligned} \partial_t \rho + \nabla \cdot (\rho \mathbf{u}) &= 0 \\ \partial_t \mathbf{u} &= -\mathbf{u} \cdot \nabla \mathbf{u} - \frac{1}{\gamma \rho M_a^2} \nabla \rho^\gamma + \frac{R_e}{\rho} \left[\nabla^2 \mathbf{u} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{u}) \right] \\ &\quad - \frac{1}{\rho M_m^2} \nabla a (\nabla^2 a) \\ \partial_t a &= -\mathbf{u} \cdot \nabla a + \frac{1}{R_m} \nabla^2 a \end{aligned} \quad (1)$$

where the sonic Mach number is $Ma = u_0/c_0$, with the characteristic polytropic sound speed $c_0 = \rho_0^{(\gamma-1)/2}$ and the Alfvén Mach number is $M_m = u_0/c_a$, with the characteristic Alfvén speed c_a . The magnetic Reynolds number $R_m = u_0 L_0 \rho_0 / \eta$ where η is the resistivity. For details on the Chebyshev-Fourier spectral collocation method used to solve these equations see Paper I. We use a 64×64 point mesh and periodic boundary conditions in both directions, and the spectral method accurately models fine scale structures down to the grid scale.

The model depends on the parameters S , M_a and R_e discussed in Paper I. The ratio S of the initial distance between the vortex sheets to the perturbation wavelength determines the interaction strength and the detailed nature of the interaction between the sheets. Also, a longer time is required to reach the final stages of evolution for larger values of S . The results are qualitatively unchanged on these time scales while S re-

mains below some critical value above which the two vortex sheets evolve independently. The Mach number M_a influences the axisymmetry of the vortices formed and the degree of filamentation of vorticity. The Reynolds number R_e is simply taken as high as possible given the number of modes in the computations and the requirement that energy not accumulate at the dissipation scales.

The vortex street is formed out of the interactions of two thin hyperbolic tangent shear layers in equilibrium on which are superposed small sinusoidal perturbations that lead to the necessary staggered vorticity distribution (see Figure 1, top left). Because the magnetic field is perpendicular to the solar wind flow in the outer heliosphere, it has little dynamical effect in the plane of the simulation. We include a small magnetic field as a tracer to locate the position of the current sheet (initially placed in the symmetry axis of the flow). Consequently the medium evolves much as would a Navier-Stokes fluid. After the initial linear Kelvin-Helmholtz phase, the nearby shear layers of opposite vorticity come into contact in the nonlinear phase. As vorticity curls-up into large vortices, there is a repulsion of opposite vorticity, broadening the street until a stable distance is reached. After the nonlinear inertial evolution phase, there is a slow decay of the vortices and their associated pressure/density cavities (Figure 2), which otherwise retain their stable positions along the street. We have also studied situations in which the magnetic field is stronger and directed parallel to the wind direction. In these cases the development of the vortex street configuration is inhibited [see Paper I]. This situation is analogous to that in the

inner heliosphere where magnetic and free energy in the plasma shear are comparable and where no quasi-periodic meridional flows have been observed.

Pressure/density cavities are connected to the spinning vortices which eject plasma through inertial forces until a pressure equilibrium is reached. Figure 2 illustrates the density cavities associated with the large vortices. This connection is further analyzed in Paper I.

III. COMPARISON WITH INTERPLANETARY OBSERVATIONS

We now wish to compare the results of the simulation to the observations of *Lazarus et al.* [1988] of the quasi-periodic velocity variations in the outer heliosphere. This comparison will be similar to that of *Burlaga* [1990] in that the vortex street formed is in some respects similar to the ideal Karman street he considered. Note, however, that the street formed here arose from dynamical interactions based on the observed characteristics of the flow, and that no singularities occur in the simulation as they do at the cores of ideal vortices.

We start by scaling the velocity and distance. The vortex street model has a spacing λ related to the period of the meridional x-directed flow of about 25.5 days; giving λ a value around 6 AU (see *Burlaga* [1990]). Since we have $S = 0.075$, that makes the initial distance d between the vortex sheets equal to 0.45 AU. The vorticity contour plots in Figures 1 illustrate a typical evolution of the vortex street. At the later times, when the Karman street has evolved into a quasi-steady state d is about 2.5 AU. If one dimensionless unit of velocity is taken to be 250 km/s, then the initial central plasma around the current sheet region has a speed of 425 km/s and the regions outside have a speed of 575 km/s in these computations. The dimensionless time used on the figures is given by $T \equiv 2ut/\lambda$ where $2u$ is the velocity difference across each sheet. We can translate t into days by using $2u = 575 - 425 = 150$ km/s and $\lambda = 6$ AU $= 9 \times 10^8$ km.

In order to compare our model to other models and the observations of Voyager 2, we study a number of plasma variables taken along radial trajectories in the neighborhood of the current sheet. The profiles are taken after the short inertial time scales during which the vortex street develops and gets

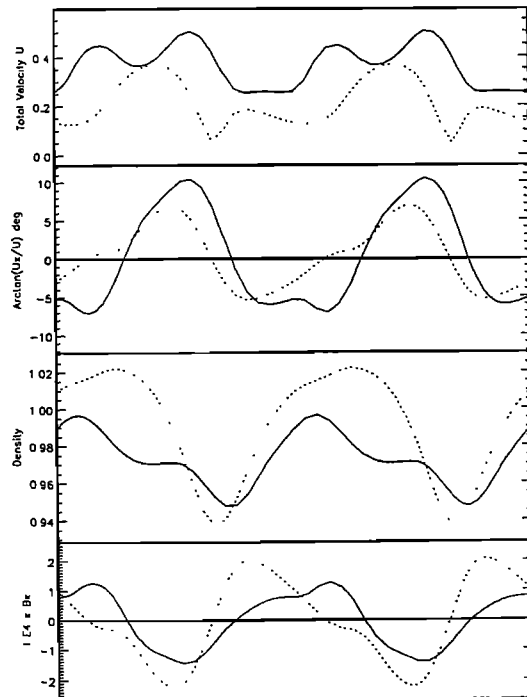


Fig. 3. Plasma parameter profiles for $T = 2.16$ along the flow direction taken on the central flow axis (solid) and through the centers of the vortices (dashed). The profiles show (top to bottom) the total plasma velocity with its characteristic double peaked maxima, the meridional angle $\text{Arctan}(u_x/U)$ in degrees, the pressure/density, and the transverse component of the magnetic field which undergoes two sign changes per period of meridional flow.

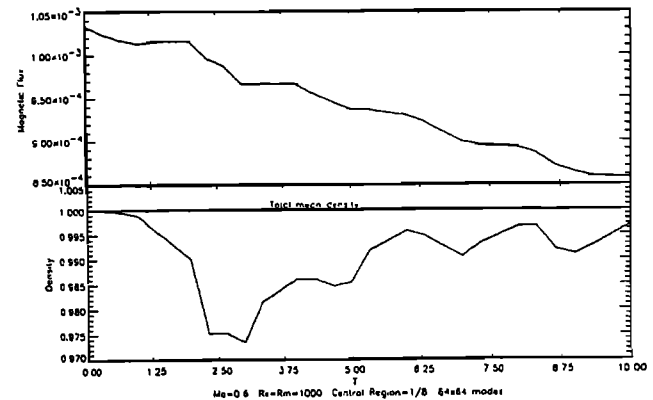


Fig. 4. (Top) Time evolution of the averaged $|B|$ in the central current sheet region (over $1/8$ of the width of the box). (Bottom) Time evolution of the averaged density in the same region.

organized through nonlinear interactions within the shear layers and their perturbations ($T = 2.16$; see Figure 2). In the above units, this corresponds to 150 days, which at 425 km/s corresponds to about 37 AU. This is slightly farther out than the observations, but the qualitative features remain unchanged over this range of distances. The first signs of the double maxima profiles for the solar wind speed characteristic of the quasi-periodic flows occur around $T = 1.08$ and thus, according to our model, the observed quasi-periodic meridional flow corresponds to early stages of a vortex street.

We study profiles of the density, the total velocity $U(y) = [u_x^2 + u_y^2]^{1/2}$ and the meridional angle $\vartheta(y) = \arctan[u_x/U]$ along lines in the streamwise y -direction (vertical direction in Figures 1 and 2). The plotted values of U are given in terms of fractions of sound speed units, *i.e.* the Mach number. Here x is transverse to the flow (horizontal direction in Figures 1 and 2). The periodic variations of the total velocity U and the meridional flow angle are illustrated in Figure 3 which show profiles in the center of the street as solid lines and profiles passing nearly through the centers of the vortices as dotted lines. As in Burlaga's simple line vortex model, the total velocity exhibits two maxima per period, but the maxima are not of equal intensity. Note that there are two maxima per rotation for both the cuts, although they are qualitatively quite different. The observations show a similar wide variability, and this perhaps indicates that the spacecraft is sampling different portions of the structures on each pass. The meridional angle shows a substantial deflection of the flow from the radial direction with one period per solar rotation in agreement with observations. Figure 3 shows the strong correlation of pressure/density maxima with the increase in total velocity, although the density fluctuations in our model are smaller than the observed. We believe this difference may be due to the neglect of the warp of the current sheet which leads in the real case to interaction regions and associated large density enhancements, but further simulations will be required to determine this. The presence of pressure variations in this model is consistent with suggestions that pressure is at least intimately related to the meridional flows [McNutt, 1988]. The formulation in Eqs. (7) and (8) of the latter paper may be consistent with a vortex street origin of these flows.

The current sheet, which initially is embedded in the slow plasma region between the two vortex sheets separates regions of opposite magnetic fields. Figure 3 (bottom) shows that for each period of the flow the cross-stream (x) component of the magnetic field undergoes two sign reversals as observed by Voyager. These reversals are generally very near the locations of the zeros of the transverse velocity; we do not know if a warp in the current sheet would lead to the displacements seen in the spacecraft data or whether some other explanation is required.

Figure 4 shows that the net effect of the presence of the vortex street in the equatorial region is a transport of plasma and $|B|$ away from that region. As will be shown in Paper II, the local relationship between plasma density and magnetic energy is not a simple one, even in the frozen-in approximation. The decrease of the mean $|B|$ in the central current sheet region with time is shown in Figure 4 (top). The field decreases even after vortices start to decay under the influence of dissipation, when the density begins to rise; density decreased monotonically during the "inertial" formation stage of the evolution. At this stage in the study, we do not have a full understanding of

the flux transport. The flux decay is not only due to the magnetic resistivity which is very small here. Qualitatively, however, this shows that flux can be transported to higher and lower latitudes by the presence of a central vortex street. This is particularly interesting in light of the recent observation that the "flux deficit" in the outer heliosphere seems to be systematically present in the Voyager data only at the time of the quasi-periodic flows [L. Burlaga, private communication, 1992].

IV. CONCLUSIONS

We have shown that the model of an evolving MHD vortex street is consistent with the observations of Voyager 2 and other spacecraft. In this model the solar rotation and the coronal hole structure create a vorticity distribution which belongs to the special class of growing antisymmetric perturbations. This class leads to the formation of a vortex street. The essential signatures of an underlying vortex street are double peaked maxima of the total velocity, the single peaked value of the meridional angle and the correlation between the pressure fluctuation maxima with the rise in the total plasma velocity. In addition, we find that there is some transport of plasma and magnetic flux away from the heliocentric equator. These basic features are robust under reasonable changes of the parameters M_a and S . A large enough flow-aligned interplanetary field stabilizes the shear instability and inhibits the development of the Karman street and this can explain the lack of observation of vortex street signatures in the inner heliosphere.

Acknowledgments. This research was supported, in part, by the Space Physics Theory Program at the Goddard Space Flight Center. During this period, Dr. Siregar was a National Research Council Associate. We thank L. F. Burlaga for many useful discussions.

REFERENCES

- Abernathy F. H. and Kronauer R. E., The formation of vortex streets, *J. Fluid Mech.* 13, 1, 1961.
- Burlaga, L.F., A heliospheric vortex street?, *J. Geophys. Res.* 95, 4333-4336, 1990.
- Gazis, P. R., J. D. Mihalov, A. Barnes, A. J. Lazarus, and E. J. Smith, Pioneer and Voyager observations of the solar wind at large heliocentric distances and latitudes, *Geophys. Res. Lett.*, 16, 223, 1989.
- Karman, T. V., Über den mechanismus des widerstandes, den ein bewegter kopper in einer flussigkeit erfährt, *Gottinger Nachrichten, Math.-Phys. Kl.*, 509-17, 1911.
- Lazarus, A. J., Yedidia, B., Villanueva, L., McNutt, R. L. and Belcher, Jr. J. W., Meridional plasma flow in the outer heliosphere, *Geophys. Res. Lett.*, 15, 1519-1522, 1988.
- McNutt, R., Meridional plasma flow in the outer heliosphere, *Geophys. Res. Lett.*, 15, 1523-1526, 1988.
- Tritton D.J., *Physical fluid dynamics*, Van Nostrand Reinhold, New York, 1977.
- Veselovsky, I. S., Solar wind vortex flow in the outer heliosphere, *Nuclear Physics Institute*, preprint, 1989.
- Zdravkovich, M.M., Smoke observations of the formation of a Kármán vortex street, *J. Fluid Mech.*, vol. 37, part 3, 491-496, 1969.

(Received: May 13, 1992;
accepted: June 24, 1992.)