Three-Dimensional MHD Simulation of Solar Wind Structure

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Abstract. We examine the 3-D structure of field lines in the expanding solar wind using an MHD code that allows the imposition of streams, a current sheet, flux tubes, microstreams, waves, and quasi-2-D turbulence. We find the natural development of closed field lines and lines with more complex geometry in the current sheet region. We show that microstreams cause an increased divergence of the field lines. The various initially strange looking heliospheric field lines we find have observational support in early work by K. Schatten and others, who found very similar structures using simple projection methods, as well in more recent work examining the nature of current sheet crossings. Our simulations exhibit most of the solar wind field configurations suggested by Schatten in his Solar Wind Two review.

1. INTRODUCTION

The solar wind magnetic field, as observed at one or a few points with interplanetary spacecraft, exhibits nearly impenetrable complexity, especially near the interplanetary current sheet. Even a large collection of spacecraft would not fully reveal the field configuration. Simulations provide an alternate avenue to discerning the three-dimensional structure, and comparisons with spacecraft measurements provide tests of whether or not we have a good representation. This paper presents a brief overview of recent results of our MHD simulations of the solar wind, emphasizing the global aspects that result from a variety of more-or-less realistic time-dependent boundary conditions. Of course, MHD simulations at attainable resolutions have inherent limitations. We only simulate large- to moderate scales (hours to days in the spacecraft frame), and the lack of kinetic effects precludes a proper treatment of, e.g., reconnection. Nonetheless, we believe that such features as global field lines and larger-scale fluctuation amplitudes are well represented here.

2. METHOD

Our MHD simulations use a spherical 3-D mesh and Flux-Corrected-Transport to deal with sharp gradients. The equations are given in Goldstein, et al. [this volume]; see also [1]. The code runs on parallel machines using MPI.

Typical simulation grid resolutions are \(70^3\) to \(150^3\) and none of the qualitative results here changed as the resolution increased. The inflow boundary is supersonic and super-Alfvénic, and is where we impose waves; quasi-2-D fluctuations; stream shear layers; microstreams; a tilted, rotating current sheet; and pressure balanced structures. The outer radial boundary has outflow conditions, and the sides of the box have either outflow (direct extrapolation or continuation of the linear gradient) or periodic conditions, the latter typically being more stable when possible.

3. OBSERVATIONS

K. Schatten produced 2-D pictures of fields by assuming a stationary wind and using kinematic projections [2]. The resulting two-dimensional vector fields revealed kinks, loops, and reversals that suggested the relevance of a variety of possible models in different situations. Such structures have become more prevalent in the literature associated with complex heliospheric current sheet crossings and various solar ejecta (see [3] and references therein). Many studies have shown that heliospheric current sheet (HCS) crossings involve a rotation with a very small normal component to the magnetic field (see, e.g., [4]). Here we demonstrate that the typical current sheet field rotation and some of the complexity can result from very simple boundary conditions involving a tilted, rotating current sheet in an initially uniform flow. We also show that a “field line random walk” [5] is easily driven by microstreams as also discussed by Suess et al. [6].

The first figure shows the typical interplanetary field configuration near a current sheet, namely, the field does...
FIGURE 1. Helios 2 hourly-averaged observations of a sector crossing showing the common feature of the displacement in time of the zeros of the radial and tangential magnetic fields. This phenomenon is common in the Helios data, and it is consistent with the results reported by Smith [4].

FIGURE 2. Time series from a point (“spacecraft”) in our MHD simulation of a tilted, rotating current sheet. Note the similarity to Figure 1. The component normal the plane of the vector rotation is very small, again consistent with observations (e.g., [4]).

not simply change sign, but rather undergoes a rotation. A signature of this is the displacement in time of the zeros of the radial and tangential components, consistent with the typical case found by Smith [4].

FIGURE 3. The three-dimensional configuration corresponding to Figure 1 from 0.5 to 2.5 AU with the inflow field magnitude with a central null shown as color contours, and the field shown by yellow and red lines. The natural way to have a transition with a rotation is to form loops that are closely confined to the current sheet region.

FIGURE 4. Current Sheet Crossing: Helios 2 Data

FIGURE 4. Current Sheet Crossing: Simulation

4. SIMULATIONS

The second figure shows time series at a point for a typical current sheet crossing in a simulation of a rotating current sheet with no waves or shear imposed. Note the characteristic displacement of the zeros of the magnetic field. The normal component of the field (not shown) is very small, consistent with the near zero values often observed [4].

Figure 3 illustrates the 3-D configuration associated with Figure 2. We see the formation of loops when a current sheet field is imposed at the boundary. This is not due to reconnection inside the box, but rather to the inconsistency of the imposed ideal field reversal conditions with real MHD flows. In particular, the self-consistent fields cannot maintain the initial magnetic-kinetic pressure balance, leading to flows transverse to the current sheet. In this situation, the natural configuration seems to be one with a small normal component and loops that come from the decoupled phasing of the zeros of the radial and tangential magnetic fields as a function of radial distance from the Sun. We have considered many input boundary conditions, such as either imposing or extrapolating the radial and/or normal field from the box, all with the same result. Note that there are magnetic stresses in the resulting configuration such that the field tension tends to oppose the flow, but the stresses are small and simulations show the field is frozen in at least to tens of AU (as far as we have gone).

When waves or other perturbations are imposed, the current sheet fields can become more complex. Spiral fields that initially look like they violate div($\mathbf{B}$) = 0 can result from a variety of causes. In Figure 4 we show a case involving a slow time dependence in the boundary rotation rate (vaguely mimicking solar irregularities). Here the phasing between the radial and tangential mag-
FIGURE 4. The loops of the previous figure can metamorphose into more complex patterns when other features are added to the boundary conditions. Here, a slow linear increase in the effective solar rotation rate leads to spiral patterns; these are also seen with other types of boundary variability such as the imposition of quasi-two dimensional fluctuations or waves. The images show normalized (by a function of $r$) magnetic field magnitude surfaces.

Magnetic fields change with time. This produces a near-null point where there is a small field component perpendicular to the plane embedded in a spiral. We also show an analytically generated spiral with $\text{div}(\mathbf{B}) = 0$ that demonstrates that the fields can spiral as long as they vary appropriately in three dimensions. While our boundary conditions are somewhat artificial, we believe that real solar boundary conditions are very likely to generate complex fields of which those shown here are a simple subset. Moreover, since the field at the center of the spiral is a near-null, these field configurations may be one possible configuration associated with interplanetary “magnetic holes” (see [7] and references therein), although the scale of the structures here is large due to the slow changes that cause them.

A more complex case is illustrated in Figure 6 where waves and shear interact with current sheet loop fields to produce configurations that have many kinks and loops. These configurations may contribute to the complexity seen in various observations (e.g., [3] and references therein).

Field line wandering due to microstreams is illustrated in Fig. 7. The initial waves were nearly planar, but transverse wave vectors and perturbed fields are generated by small-scale shear from corotating wind speed irregularities with amplitudes consistent with the variability in typical fast wind. Further studies will demonstrate the relative importance of this and other suggested origins for the field line meandering such as the motion of the field footpoints on the Sun. This origin of meandering was discussed previously [6], but we believe this is the first simulation of this effect. Note that the scale on which the random walk occurs is determined by the transverse scale of the pattern on the surface, and that field lines originating in relatively uniform, small region of the flow (not shown) tend to stay together.

5. SUMMARY

We have shown, through MHD simulation, that the interplanetary field can become quite complex despite simple boundary conditions. The rotation of the magnetic field across sector boundaries is very likely due to the formation of loop fields near the Sun. Many complex patterns of the magnetic field can occur, especially near the current sheet; this was expected, but now we can simulate fairly realistic cases in 3-D. Field lines can “random walk” due to irregularities in the flow. This may be more important than solar surface field wanderings, but this must be checked. Finally, spiral fields are possible configurations in MHD flows, and may be associated with magnetic holes.
FIGURE 5. The nearly planar spiral pattern of the fields in the previous figure is consistent with a divergenceless field because of variations in the third dimension. Above we show field lines for an analytical solution of $\nabla \cdot (B) = 0$. The “tail” of the spiral is flattened to be near the sector boundary in the previous simulation.

FIGURE 6. Waves, streams (slow surrounded by fast, as shown in the inflow contours), and a current sheet can lead to highly complex loops that do not completely return to the Sun. Lines outside the current sheet region simply wave gently in response to the imposed plane waves (nearly uniform in angular variables) because of the large transverse correlation length (see [8]).

FIGURE 7. A stationary, corotating, radial flow pattern on the inflow boundary of the simulation leads to the wandering (“random walk”) of (red) field lines shown above. The flow pattern is shown by the color contours on the input surface, with slow flow surrounded by fast flow.

REFERENCES


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