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Modeling Solar Wind Flow with the Multi-Scale Fluid-Kinetic Simulation Suite

N. V. Pogorelov,[1,2] S. N. Borovikov,[2] M. C. Bedford,[1] J. Heerikhuisen,[1,2] T. K. Kim,[1] I. A. Kryukov,[2,3] and G. P. Zank[1,2]

[1]*Department of Physics, University of Alabama in Huntsville, Huntsville, AL 35899, U.S.A.*

[2]*Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, U.S.A.*

[3]*Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, 119526, Russia*

Abstract. Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) is a package of numerical codes capable of performing adaptive mesh refinement simulations of complex plasma flows in the presence of discontinuities and charge exchange between ions and neutral atoms. The flow of the ionized component is described with the ideal MHD equations, while the transport of atoms is governed either by the Boltzmann equation or multiple Euler gas dynamics equations. We have enhanced the code with additional physical treatments for the transport of turbulence and acceleration of pickup ions in the interplanetary space and at the termination shock. In this paper, we present the results of our numerical simulation of the solar wind (SW) interaction with the local interstellar medium (LISM) in different time-dependent and stationary formulations. Numerical results are compared with the Ulysses, Voyager, and OMNI observations. The SW boundary conditions are derived from in-situ spacecraft measurements and remote observations.

1. Sunward SW flow and the "Voyager Paradox"

The heliospheric interface formed due to the interaction of the solar wind (SW) with the local interstellar medium (LISM) is a unique natural laboratory providing a variety of observational results that require interpretation on a theoretical level. Recent *Voyager* 1 ($V1$) observations of the nearly vanishing and even negative radial velocity component may have serious consequences for the overall pattern of the SW and LISM plasma flows in the vicinity of the heliopause (HP) and coupling of the interstellar and heliospheric magnetic fields (ISMF and HMF). The absence of the termination shock particles (TSPs) – anomalous cosmic rays originated at the heliospheric termination shock (TS) – in the $V1$ observations since September 2012 (see Fig. 1 raises questions about the likelyhood of the spacecraft crossing the HP and penetrating into the LISM. If this indeed happened, the width of the inner heliosheath (IHS, a region of the SW plasma between the heliospheric termination shock, TS, and the HP) in the $V1$ trajectory direction would be considerably smaller than that in standard steady-state models. E.g., the heliosheath widths in the MHD-kinetic simulation by (Pogorelov et al. 2008,

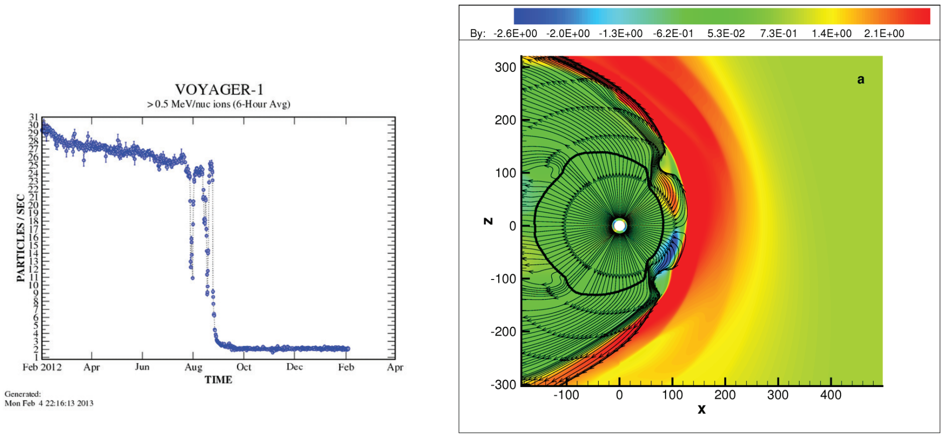

Figure 1. (*Left*) Termination shock particle flux from the CRS instrument onboard $V1$ starting Feb. 2012. Observational data from `http://voyager.gsfc.nasa.gov/heliopause/heliopause/data.html`. (*Right*) The distribution of the out-of-plane component, B_y, of the magnetic field vector in the meridional plane defined by the LISM velocity vector $\mathbf{V}_\infty$ and the Sun's rotation axis shows the formation of a distinct magnetic barrier. The streamlines start on the heliocentric circle of 15 AU radius in the meridional plane are shown neglecting the out-of-plane velocity component, v_y. The regions with no streamlines seen at the HP exist because of a substantial v_y. The TS is shown with a thick black line. Distances are given in AU. The y-axis is directed into the figure plane. [Pogorelov et al. (2012).]

2009b) are 65 AU (in the $V1$ direction) and 48 AU (in the $V2$ direction), and 60 AU ($V1$) and 42 AU ($V2$), respectively for the ISMF strengths $B_\infty = 3\ \mu$G and $4\ \mu$G.

Voyager observations imply that simplistic steady-state considerations might be insufficient to explain what is observed. As shown in Pogorelov et al. (2009a, 2012), the presence of a region with a very small and even negative radial velocity component observed by $V1$ in the IHS may fairly easily be explained by the time-dependent evolution of magnetic barriers due to the stream interaction of what was originally slow and fast SW (see Fig. 1, the right panel). This interaction is especially important shortly after a solar minimum, when the latitudinal extent of slow wind starts increasing. It is important to realize that negative v_R is not a result of the HP motion back and forth with respect to some average position. In reality, the HP response to the solar cycle is very small (about 2 AU). The main reason of the sunward SW velocity is in the peculiarities of the flow near the HP. Since SW is almost always slow near the equatorial plane, the streamlines starting there will spread over the inner side of the HP. When a magnetic barrier is formed, those streamline are initially confined between the magnetic barrier and the HP. Sunward flow is the result of a sudden disappearance of one of the confining walls, i.e., the magnetic barrier. This effect is time dependent and a spacecraft can fly through the negative v_R region only accidentally, by appearing at the right place at the right time.

The presence of the region with negative radial velocity component in the SW along the $V1$ trajectory may be beneficial for the explanation of the "Voyager paradox" (an abrupt disappearance of the TSP flux) proposed by McComas & Schwadron (2012). According to McComas & Schwadron (2006), TSPs and the enrolling of their energy spectrum are strongly related to the "direct connection" of the measurement point to

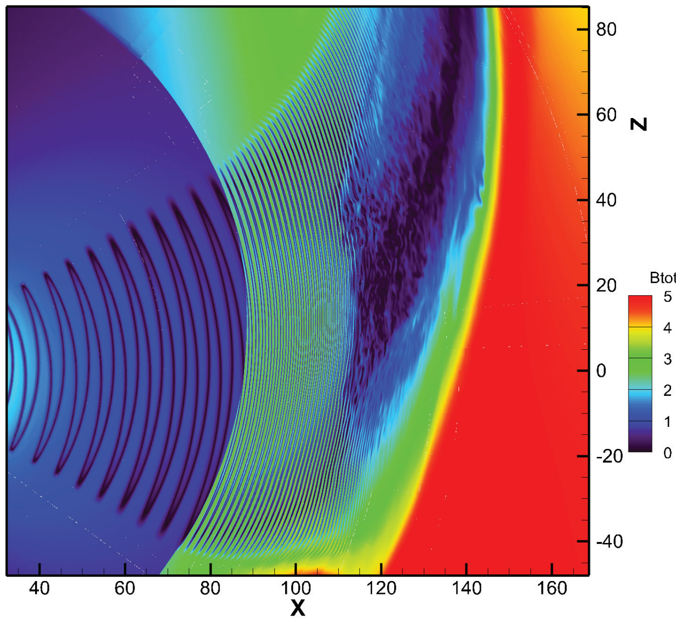

Figure 2. The distribution of the magnetic field magnitude $B = |\mathbf{B}|$ in the meridional plane shows transition to chaotic behavior in the IHS plasma.

the TS by a magnetic field line. Of course, any point in the IHS is connected to the TS, but indirect connections (more than one full rotation of the spiral heliospheric magnetic field) are not efficient for the ion acceleration because of the scattering processes Pogorelov et al. (2007). This means that the source of TSPs disappears with the direct connection of the spacecraft to the TS. One would argue that cutting of the source may not necessarily result in a sudden decrease of the TSP flux because of their convection. This could be a valid argument if it had not been for the absence of the radial plasma outflow at $V1$. This means that the spacecraft is sampling magnetic field lines that originated at low latitudes. It will take very many HMF line rotations for those to reach $V1$, and they are unlikely to carry any TSPs injected into the acceleration process at the TS. This works in favor of the McComas & Schwadron (2012) mechanism, which however should be considered in the presence of a more sophisticated flow topology in the IHS.

Multi-Scale Fluid-Kinetic Suite (MS-FLUKSS) is a suitable tool to solve rather sophisticated problems related to the SW propagation and its interaction with the LISM (Pogorelov et al. 2010). It involves an AMR treatment of ideal MHD flows in the presence of charge exchange between ions and neutrals. Because such collisions are extremely infrequent, we treat the transport of neutral atoms kinetically, by solving the Boltzmann equation with a Monte Carlo method (Heerikhuisen et al. 2006, 2008). As shown in Pogorelov et al. (2009c), a multi-fluid approach (Zank et al. 1996), based on the hydrodynamic treatment of the neutral atom populations born in thermodynamically distinct regions of the heliospheric interface, may be in good agreement the MHD-kinetic simulations. This approach has also been implemented in MS-FLUKSS on both Cartesian and spherical grids. Additionally, we have implemented different models of the SW turbulence and a fluid dynamics approach to treat pickup ions (PUIs) as a

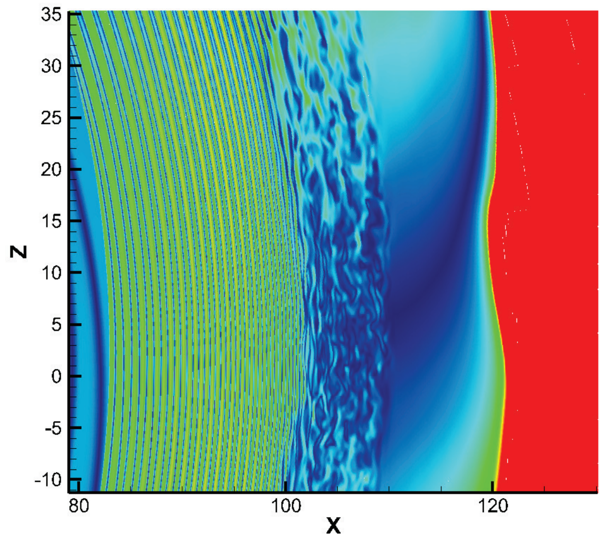

Figure 3. The distribution of *B* in the meridional plane. Transition to chaotic behavior of the HMF in the IHS: the initial stage. As the grid resolution is increased successively by adding additional level of the grid refinement, a smooth region of small magnetic field between the chaotic region and the HP shows what was obtained with a smaller space resolution.

separate plasma population that generates small-scale turbulence that heats up SW ions as they propagate towards the HP.

In this paper, we will present one more illustration of the MS-FLUKSS application to modeling the SW–LISM interaction. This one demonstrates transition to chaotic plasma behavior in the IHS, which is the result of the heliospheric current sheet (HCS) being compressed, due to the flow deceleration, below the spatial resolution distance.

2. Transition to Chaotic Behavior in the IHS

Here we consider the SW–LISM interaction pattern for the parameters from Opher et al. (2012). This will allow us not only to compare our results, but also analyze the magnetic field behavior in the IHS for a "turbulent" regime, presumably due to the magnetic field reconnection across the HCS. Grid resolution of about 0.1 AU is sufficient for resolving the HCS quite deep inside the IHS. However, when the resolution becomes insufficient to follow exceedingly compressed regions of opposite HMF polarity, magnetic field does not simply dissipate as in Pogorelov et al. (2009b) or Opher et al. (2012), but also becomes chaotic (see Fig. 2). The initial stage of this transition is shown in more detail in Fig. 3. The origin of this behavior will require further investigation. Here we will analyze its consequences for the IHS flow. In particular, it is interesting to understand the energy redistribution.

Figure 4 shows the distributions of the plasma temperature *T* (*left panel*) and the out-of-plane component of the magnetic field vector (*right panel*. We see that

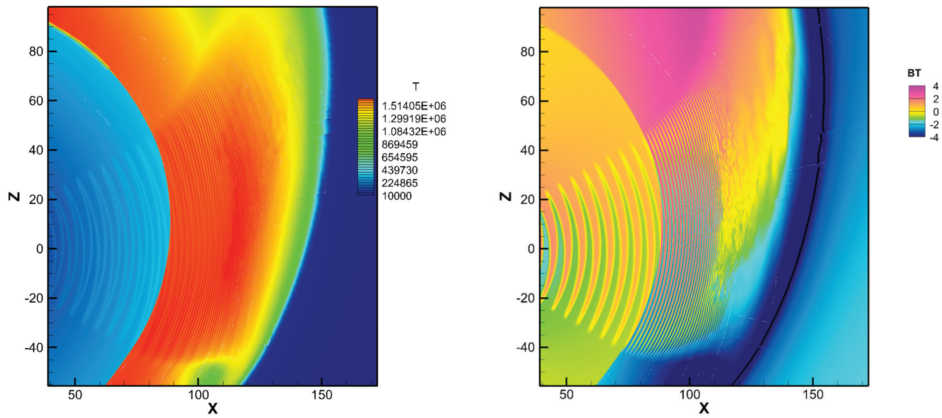

Figure 4. The distributions of plasma temperature (*left panel*) and out-of-plane component of the magnetic field vector (*right panel*) in the meridional plane.

the plasma temperature starts increasing in the areas where magnetic energy becomes small. This means that part of the magnetic energy is transformed into thermal energy. Figure 5 shows the distributions of the magnetic field (*left panel*) and velocity components along a straight line parallel to the current $V1$ trajectory. We see here that the gradient of the radial velocity component U_R decreases immediately after the SW plasma penetrates into the region of chaotic magnetic field, i.e., the flow deceleration toward the HP becomes smaller. This means that a part of the magnetic energy is transferred to the kinetic plasma energy.

Another interesting feature seen in the right panel is that there exists a region of single magnetic field polarity at the inner surface of the HP. This magnetic field is fairly strong ($> 4\ \mu$G) and its polarity is that of the HMF in the southern hemisphere. In the $V1$ trajectory direction, this region follows the region of small, chaotic magnetic field. This distribution of magnetic field should also result is the decrease of the TSP flux. In this case, however, the reason for that is even more spectacular than the case shown in the previous section. Indeed, in order to have southern polarity of **B** in the northern hemisphere, at the $V1$ location, a substantial portion of the SW flow that originated at negative latitudes should turn northward. This means that $V1$, once it crossed the boundary between the mixed polarity and unipolar field, becomes abruptly shielded from the TSP source. The described SW behavior is, of course, due to the large ISMF used in this simulation. Moreover, the choice of the ISMF direction we used here following Opher et al. (2012) is not in agreement with the recommendations of Heerikhuisen & Pogorelov (2011) based on the fitting of the *Interplanetary Boundary Explorer* ribbon of enhanced energetic neutral atom flux. However, if the ISMF is strong enough and the density on H atoms in the LISM is on the small side of the probable interval (Vallerga 1996), the possibility of a strong asymmetry of the IHS flow becomes more likely.

In addition, we demonstrated that our solution differs from that in Opher et al. (2012) for the same set of boundary conditions. Firstly, we do not see what should be identified as a tangential discontinuity stretching across the HCS-covered region in the IHS (see Figs. 2 and 3 in Opher et al. 2012). Secondly, the IHS area covered by the wavy HCS and further by the stochastic, low magnitude magnetic field does not

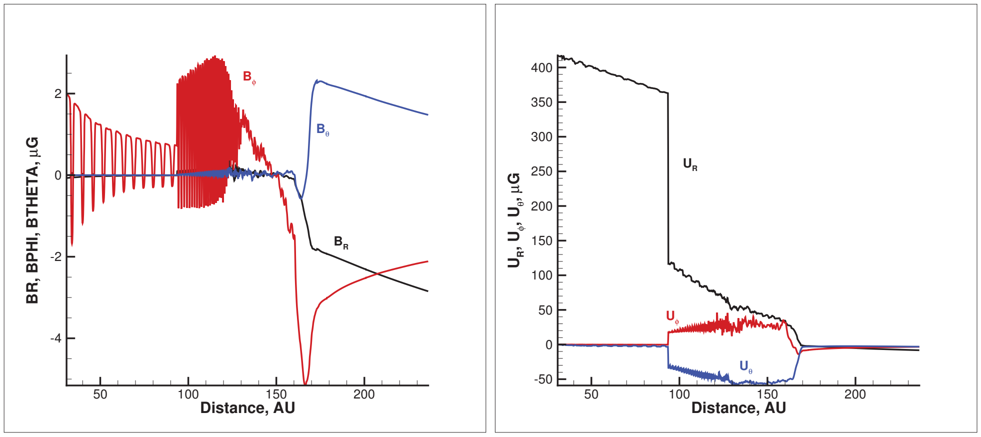

Figure 5. The distributions of the magnetic field magnitude (*left panel*) and radial component of the velocity vector (*right panel*) along a straight line parallel to the current *V*1 trajectory.

disappear abruptly at a certain positive latitude (like in Fig. 2 of Opher et al. 2012) but is rather convected, frozen into the plasma flow, along the inner side of the HP all the way to the heliotail.

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