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Mixing of the Interstellar and Solar Plasmas at the Heliospheric Interface

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Abstract. From the ideal MHD perspective, the heliopause is a tangential discontinuity that separates the solar wind plasma from the local interstellar medium plasma. There are physical processes, however, that make the heliopause permeable. They can be subdivided into kinetic and MHD categories. Kinetic processes occur on small length and time scales, and cannot be resolved with MHD equations. On the other hand, MHD instabilities of the heliopause have much larger scales and can be easily observed by spacecraft. The heliopause may also be a subject of magnetic reconnection. In this paper, we discuss mechanisms of plasma mixing at the heliopause in the context of *Voyager 1* observations. Numerical results are obtained with a Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS), which 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. The code can also treat nonthermal ions and turbulence produced by them.

1. Introduction

Although the heliosphere is the region occupied by the solar wind (SW) plasma, it is common to introduce also a notion of the outer heliosphere as a part of the solar plasma region beyond the solar system whose properties are determined by the SW interaction with the local interstellar medium (LISM). Both the Sun and LISM move with respect of the Local Standard of Rest (LSR). From the viewpoint of an observer attached to the Sun, the SW flow collides with the LISM flow. Both the SW and LISM are magnetized, so MHD equations should be reasonably well suited to model the global structure of the SW–LISM interaction. In reality, the SW plasma is collisionless in terms of the Coulomb collisions. The applicability of MHD models to model the SW–LISM interaction, like the one in Parker (1961), are based on a considerable decrease of the proton mean free path due to their scattering on magnetic field fluctuations. With *V1* and *V2* crossing the heliospheric termination shock (TS) in December 2004 and August 2007 (Burlaga et al. 2005, 2008; Decker et al. 2005, 2008; Gurnett & Kurth 2005, 2008; Richardson et al. 2008; Stone et al. 2005, 2008) and *V1* entering the LISM in August 2012 (Burlaga et al. 2013; Gurnett et al. 2013; Krimigis et al. 2013; Stone et al. 2013;

Webber et al. 2013), understanding the interaction of the SW with the LISM has become one of the most exciting areas of space physics. In addition, *V1* is now providing direct *in situ* measurement of the LISM (Burlaga et al. 2015). Of course, we are talking here about the LISM perturbed by the presence of the heliosphere. On the other hand, LISM neutral atoms (mostly H atoms) can propagate inside the heliosphere, participate in charge exchange events with protons, and produce (1) a non-thermal ion population called pickup ions (PUIs) and (2) secondary H atoms which possess the properties of parent ions.

Kinetic modeling of the neutral atom transport into the heliosphere is preferable because of the large mean free path of the resonance p–H charge exchange ($\sim$ 100 AU). Multi-Scale Fluid-Kinetic Suite (MS-FLUKSS) is an adaptive mesh refinement package that has been developed by our team since 2003. It involves an AMR treatment of ideal MHD flows in the presence of charge exchange between ions and neutrals (Borovikov et al. 2013; Pogorelov et al. 2010, 2013a). It is able to do kinetic simulations of neutral atoms by solving the Boltzmann equation with a Monte Carlo method (Heerikhuisen et al. 2006, 2008). Monte Carlo methods are rather noisy, which makes it difficult to use them for modeling the heliopause instability and/or magnetic reconnections in its vicinity. However, as shown by 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, is a reasonable alternative to MHD-kinetic simulations of the above-mentioned processes. This does not mean that it is superior over the kinetic approach (Baranov & Malama 1993; Izmodenov et al. 2005; Heerikhuisen et al. 2006; Pogorelov et al. 2009b; Heerikhuisen & Pogorelov 2011; Heerikhuisen et al. 2014). It simply serves the purposes of this paper more robustly. Situations that require better resolution of the neutral H distribution function, such as those relevant to *IBEX* measurements (McComas et al. 2009, 2012a,b), still benefit from the kinetic approach.

The subject of this paper is to analyze the mixing of the solar and interstellar plasmas at the heliopause. From the ideal MHD perspective, the heliopause is a tangential discontinuity that separates the SW plasma from the LISM plasma. Some physical processes, however, that make the heliopause smeared and permeable. They can be subdivided into kinetic and MHD categories. Kinetic processes occur on small length and time scales, and cannot be resolved with MHD equations. On the other hand, MHD instabilities of the heliopause have much larger scales and can be easily observed by spacecraft. The heliopause may also be a subject of magnetic reconnection. In this paper, we discuss mechanisms of plasma mixing at the heliopause in the context of *Voyager 1* observations.

2. Instability of the heliopause

Even from an MHD perspective, the heliopause is an infinitely thin tangential discontinuity with a surface electric current shielding the SW from the LISM only in the ideal limit of vanishing resistivity and viscosity. In the presence on non-ideal effects, one would expect to see a mixing layer with the width determined by dissipative effects, both of molecular and electric origin. According to (Fahr et al. 1986) the width of the mixing layer is narrow. Since there is a shear flow at the heliopause, one would expect Kelvin–Helmholtz (KH) type instabilities reasonably far away from the flow stagnation points (Ruderman & Fahr 1995; Ruderman & Belov 2010; Chalov 1996).

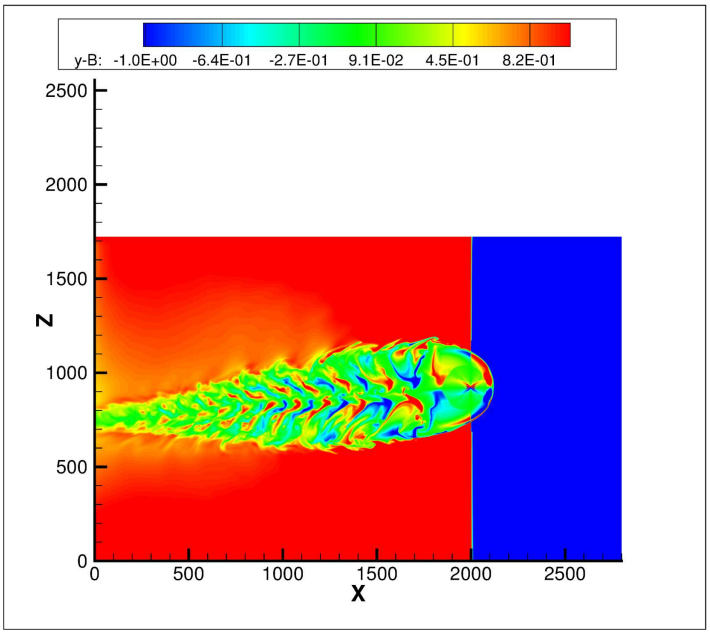

Figure 1. The Kelvin–Helmholtz instability of the heliopause flanks. The figure shows the toroidal (ϕ) component of the magnetic field in the meridional cross-section of the heliosphere. The field variation outside the heliopause is not seen because of the chosen colormap. The calculation takes into account solar cycle effects in a statement similar to Pogorelov et al. (2009a). The patches of opposite polarity seen in the heliotail are due to periodic changes of the solar dipole polarity.

The heliopause is unconditionally unstable without magnetic field tension taken into account. This why, early, hydrodynamic simulations of the SW–LISM interaction often exhibited unsteady behavior of the heliopause (Wang & Belcher 1998). The presence of magnetic field tension usually only delays this convective-type instability. At our current state of knowledge, we can earnestly state that solutions with a stable, numerically smeared heliopause in the far tail of the heliosphere (see, e.g., Pogorelov & Matsuda 1998; Ratkiewicz et al. 1998; Pogorelov et al. 2004; Opher et al. 2006) are artifacts of the decrease in spatial resolution typical of expanding spherical grids. A solution that illustrates the KH instability of the HP flanks is shown in Fig. 1. Notice how drastically this solution differs from that in Opher et al. (2015), where the heliospheric magnetic field is assumed monopolar and solar cycle effects are ignored.

Attributed to charge exchange by Liewer et al. (1996) and Zank et al. (1996), the Rayleigh–Taylor instability of the HP was analyzed both analytically and numerically by Florinski et al. (2005) and Borovikov et al. (2008) assuming an axially symmetric configuration of the SW–LISM interaction, which requires the absence of the HMF and the assumption of the LISM velocity and ISMF vectors being parallel to each other. The latter assumption results in the ISMF vanishing at the LISM stagnation point on the HP and ensures a relatively weak ISMF when *V1* crosses the HP. As a result, magnetic field tension is unable to suppress instability.

Being a tangential discontinuity, the HP is unconditionally unstable in the absence surface tension (e.g., due to magnetic fields). Magnetic field tension can stabilize the

HP in the absence of charge exchange. Charge exchange and magnetic field tension compete with each other. Three-dimensional, steady-state simulations, even performed with an extremely high resolution near the HP (~ 0.02 AU), showed no signs of instability at the HP nose (Borovikov et al. 2011).

Instead, it should be subject to different type of instability, which makes mixing of the SW and LISM plasmas "spotty.'. Borovikov & Pogorelov (2014) showed that even in the presence of HMF and ISMF the nose of the HP is indeed not a smooth tangential discontinuity, but is Rayleigh–Taylor unstable, which results in the LISM material penetration deep inside the SW. They also showed that the HP flanks are always subject to a Kelvin–Helmholtz instability. The instabilities are considerably suppressed near the HP nose by the heliospheric magnetic field in steady-state models, but reveal themselves in the presence of solar cycle effects. Arguably, *V1* may be in one of such instability regions and therefore observing plasma densities much higher than those in the pristine SW. These results may be an explanation of the *V1* early penetration into the LISM.

Attributed to charge exchange by Liewer et al. (1996) and Zank et al. (1996, 1999), the Rayleigh–Taylor instability of the HP was considered numerically by Florinski et al. (2005) and Borovikov et al. (2008) assuming an axially symmetric configuration of the SW–LISM interaction, which requires the absence of the HMF and the assumption of the LISM velocity and ISMF vectors being parallel to each other. The latter assumption results in the ISMF vanishing at the LISM stagnation point on the HP and ensures a relatively weak ISMF when *V1* crosses the HP. Being a tangential discontinuity, the HP is unconditionally unstable in the absence surface tension (e.g., due to magnetic fields). Magnetic field tension can stabilize the HP in the absence of charge exchange. Charge exchange and magnetic field tension compete with each other. Three-dimensional, steady-state simulations, even performed with an extremely high resolution near the HP (~ 0.02 AU), showed no signs of instability at the HP nose (Borovikov et al. 2011).

Borovikov & Pogorelov (2014) showed that the solar cycle creates conditions favorable for the HP instability and deep penetration of the LISM plasma into the IHS. The primary reason of the instability is charge exchange, but temporary decreases of the HMF strength at the *V1* latitude prevent the magnetic field tension from stabilizing the HP. As discussed by Fahr et al. (1986) and Ruderman & Fahr (1995), ram pressure variations related to solar cycle may also contribute to the HP destabilization. However, our simulations show violent instabilities in the absence of HMF even for a steady, spherically symmetric SW. Deep penetration of the LISM plasma into the heliosphere is a plausible explanation of *V1* observations.

Avinash et al. (2014) performed a linear analysis of the HP stability in an incompressible fluid approximation and found that there are always wavenumbers for which the HP is RT-unstable regardless of the directions of the magnetic field on both sides of the HP. This result is in contradiction with Borovikov & Pogorelov (2014), where it was shown that the heliospheric magnetic field plays a crucial role in the stabilization of the HP. E.g., the solution in the HMF presence remains stable even in the ISMF absence. On the contrary, the ISMF presence cannot stabilize the HP in the HMF absence. Avinash et al. (2014) state that the HP might be unstable in the simulation of Borovikov & Pogorelov (2014) because of non-linear perturbations caused by solar cycle effects. This statement is incorrect because of the above arguments. As explained by Borovikov & Pogorelov (2014), they invoke solar cycle effects (Pogorelov et al. 2009a, 2013b) simply because the HMF becomes small on the inner side of the HP

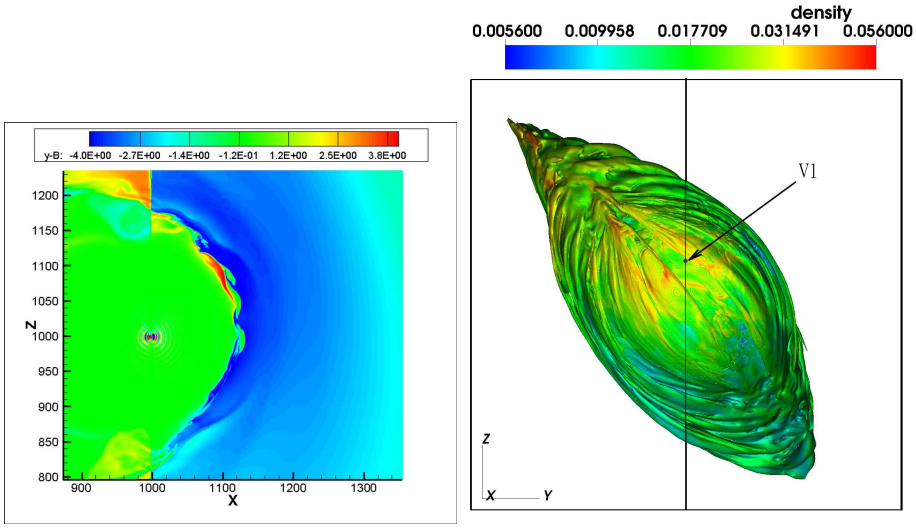

Figure 2. (*Left panel.*) The Rayleigh–Taylor type instability of the heliopause results in a "spotty" mixing of the heliospheric and interstellar plasma. The figure shows the toroidal (ϕ) component of the magnetic field in the meridional cross-section of the heliosphere. The calculation takes into account solar cycle effects in a statement similar to Pogorelov et al. (2009a). It can be seen that *Voyager* 1 trajectory may pass through a sequence of plasma layers belonging alternatively to the SW and LISM until the spacecraft leaves the heliosphere. (*Right panel.*) The LISM view of the unstable heliopause and the point where *Voyager* 1 crossed it. The topology of the LISM penetration into the heliosphere is ordered by the *BV*-plane defined by the velocity and magnetic field vectors in the unperturbed LISM. The surface of the heliopause is colored by the plasma density (from Borovikov & Pogorelov 2014).

in the course of the solar cycle. This results in the destabilization of the HP during such periods of time. Afterwards, the instability evolves even when the HMF acquires greater values (see Fig. 2, *left panel*).

Besides, Avinash et al. (2014) propose that the penetration of the LISM plasma into the inner heliosheath may drag ISMF lines in such a way that they become nearly perpendicular to the equatorial plane. This idea, however, will likely work only in axially-symmetric formulations (see, e.g., Florinski et al. 2005; Borovikov et al. 2008), where the penetration must be circular, indeed causing magnetic field lines dragged into the IHS in the meridional plane rotation towards the equatorial plane. In reality, the penetration is not circular and is structured by the *BV*-plane (see Fig. 2, *right panel*).

3. Summary

Summarizing, the heliopause is subject of Kelvin–Helmholtz and Rayleigh–Taylor MHD instabilities. Without magnetic fields and fully ionized plasma where charge exchange does not exist, the heliopause is unconditionally unstable. The magnetic field (HMF and ISMF) presence of strength currently accepted for the SW and LISM can only delay convective instability of the heliopause flanks. According to our simulations, although charge exchange between neutral atoms provides the source of HP instability at the HP nose, the HMF has ability to suppress it, at least for 3D grid resolutions of the

order or slightly exceeding those that show the nose instability in 2D. The effect of the ISMF is of less importance. As demonstrated by Borovikov et al. (2008), secondary neutral atoms born in the heliosphere play destabilizing role on the HP flanks. In the course of solar cycle, the HMF temporarily becomes small in the vicinity of the HP along the *Voyager* 1 trajectory. Then, the HP nose instability is developed and further evolves when the HMF increases. MS-FLUKSS, with its adaptive mesh refinement capabilities, is a powerful tool to address these problems in more detail in the future. In particular, magnetic reconnection scenarios can be explored.

It is possible that other, kinetic instabilities are also present in the HP vicinity. These should be addressed with proper kinetic methods.

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