MODELING HELIOPHYSICS PHENOMENA WITH A MULTI-SCALE FLUID-KINETIC SIMULATION SUITE

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EXECUTIVE SUMMARY:

We investigated physical phenomena occurring when the solar wind (SW) interacts with the local interstellar medium (LISM). These problems include (1) issues related to the mixing of the SW and LISM plasma at the heliospheric interface defined by the heliopause (the boundary of the heliosphere, the spherical region around the Sun that is filled with solar magnetic fields and the outward-moving solar wind consisting of protons and electrons) in particular due to the heliopause instability and magnetic reconnection at its surface; (2) the influence of the heliosphere on the observed anisotropy of teraelectronvolt (TeV) galactic cosmic rays; (3) the dynamic effect of non-thermal ions, and (4) the influence of time-dependent phenomena on the energetic neutral atom flux observed by the Interstellar Boundary Explorer (IBEX) space mission. Our simulations are critical for the explanation of Voyager and IBEX measurements pertinent to the SW–LISM interaction, and Tibet, Milagro, Super-Kamiokande, IceCube, and ARGO-YGB observatories' measurements of the cosmic ray anisotropy.

INTRODUCTION

Voyager 1 (V1) and Voyager 2 (V2) spacecraft crossed the heliospheric termination shock in December 2004 and August 2007, respectively [6,7]. After 37 years of historic discoveries, Voyager 1 started sampling the local interstellar medium (LISM) while Voyager 2 is approaching the heliopause (HP), a tangential discontinuity separating the solar wind (SW) from the LISM. V1 and V2 acquire *in situ* information about the local properties of the SW plasma, energetic particles, and magnetic field at the heliospheric boundary [8]. In addition to the thermal component, the SW plasma has a non-thermal component represented by pickup ions (PUIs). These are born when thermal SW ions exchange charge with the LISM neutral atoms. On the other hand, IBEX is measuring line-of-sight integrated fluxes of energetic neutral atoms (ENAs) in different energy bands [4]. Since most ENAs are created during charge exchange between hot PUIs and LISM neutral atoms, they bear the plasma properties of the region in which they are created.

The combination of IBEX and Voyager observations gives us a unique opportunity to investigate physical phenomena at the heliospheric interface and the transport of galactic cosmic rays into the heliosphere. Additionally, by fitting a narrow "ribbon" of an enhanced ENA flux discovered by IBEX and a TeV cosmic ray anisotropy measured at Tibet, Milagro, Super-Kamiokande, ICECube, and ARGO-YGB observatories (see [10] for an extensive list of references) we can constrain the properties of the LISM at large distances from the heliopause.

METHODS & RESULTS

To address the problems described above, we solved the equations of ideal magnetohydrodynamics (MHD) equations coupled with the kinetic Boltzmann equation describing the transport of neutral atoms. In a less strict, but very efficient approach, the flow of atoms is modeled with a few systems of the Euler gas dynamic equations describing different atom populations dependent on the domains of their origin. We developed both fluid dynamics and kinetic models for PUIs and turbulence generated by kinetic instabilities of their distribution function. All these are components of a Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS)—an adaptive mesh refinement code we built on the Chombo reference framework.

During the second year of our Blue Waters allocation, we (1) performed high-resolution simulations of the heliopause instability [1,5] and identified areas of possible magnetic reconnection near the heliopause crossed by Voyager trajectories (fig. 1), (2) analyzed the heliotail flow for different LISM conditions and proved [10] that the observed TeV cosmic ray anisotropy may be explained by the LISM magnetic field distortion by the heliosphere, and (3) investigated the effect of non-thermal ions on time-dependent plasma distributions [3]. The results are published in six papers and reported at 14 (11 invited) scientific meetings. By addressing the basic physical phenomena occurring at the interface of the heliosphere and LISM, our results are of substantial importance for heliospheric physics, physics of the interstellar medium, and plasma physics in general. Our collaboration with the Blue Waters team further promotes the application of adaptive technologies to contemporary plasma physics problems through the development of publicly available packages suitable for multiple applications.

WHY BLUE WATERS?

Our simulations are computationally intensive. This is especially true in the following typical situations: (1) Neutral atoms are modeled kinetically and we need of the order of 10^{12} particles in our Monte Carlo simulations. These simulations require particle splitting, multiple grids, and careful coupling with the MHD module, and cannot be performed on other smaller resources. They also produce multiple data sets exceeding 0.5 TB each. Hybrid parallelization becomes obligatory. (2) Computational region sizes are very large, as in the case of long-tail simulations. (3) Very deep adaptive mesh refinement (AMR) is necessary near magnetic reconnection sites. This will be our grand challenge in the final year of our allocation and help explain Voyager data. Additionally, we will perform parametric simulations of the heliospheric tail to fit IBEX and TeV cosmic ray anisotropy observations.

PUBLICATIONS

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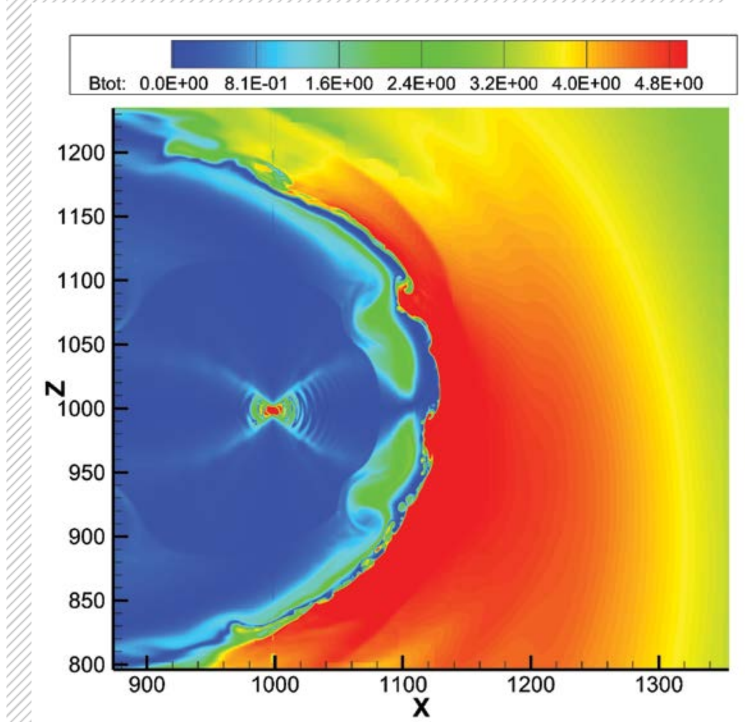

FIGURE 1: The magnetic field distribution at the interface between the SW and LISM exhibits both Rayleigh Taylor instability of the heliopause due to charge exchange between ions and neutral atoms and signatures of tearing mode instability typical of magnetic reconnection. The simulation was performed with the local AMR ratio of 32.