MODELING PHYSICAL PROCESSES IN THE SOLAR WIND AND LOCAL INTERSTELLAR MEDIUM WITH A MULTISCALE FLUID–KINETIC SIMULATION SUITE

Allocation: NSF PRAC/2,140 Knh
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EXECUTIVE SUMMARY

Blue Waters time allocation through the NSF PRAC award was used to investigate physical phenomena occurring when the solar wind (SW) interacts with the local interstellar medium (LISM): (1) the origin of the SW on the solar surface and its further acceleration to supersonic velocities; (2) the effect of transient phenomena on space weather on Earth; (3) the SW propagation throughout the heliosphere and perturbations it creates in the LISM; (4) the effect of the heliospheric boundary layer on the plasma oscillation events observed by Voyager 1 in the LISM; (5) MHD (magnetohydrodynamics) instabilities and magnetic reconnection; (6) the influence of the heliosphere on the observed anisotropy of TeV galactic cosmic rays; and (7) using observations from multiple spacecraft to reconstruct otherwise missing properties of the SW and LISM. Our simulations are important for the explanation of IBEX (Interstellar Boundary Explorer), New Horizons, Ulysses, and Voyager measurements, as well as air shower observations.

RESEARCH CHALLENGE

The grand challenge of this research is to investigate physical phenomena that start on the solar surface and result in the SW acceleration and propagation through interplanetary space toward the boundary of the heliosphere, where the SW interacts with the LISM. Our simulations are data-driven and help interpret observations from such space missions as IBEX, New Horizons, Ulysses, Voyager, and a fleet of near-Earth spacecraft. We use vector magnetogram data and STEREO observations to study the propagation of coronal mass ejections toward Earth, where they affect space weather. Voyager 1 and 2 (V1 and V2) spacecraft crossed the heliospheric termination shock (TS) in December 2004 and in August 2007, respectively, and after 40 years of historic discoveries, V1 is sampling the local interstellar medium (LISM) [1], while V2 is approaching the heliopause (HP)—a tangential discontinuity separating the 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 [2], while their observations at the same distance from the Sun are markedly different. V1 data related to the LISM properties gives the heliospheric community a unique opportunity to study physical processes beyond the HP. IBEX is measuring line-of-sight integrated fluxes of energetic neutral atoms (ENA) in different energy bands [3]. Since most ENA are created during charge exchange between hot PUI (pickup ions) and LISM neutral atoms, they bear the plasma properties of the region in which they are created. The LISM-related objectives of the proposal are to use observational data for the analysis of the SW–LISM interaction, including the heliospheric boundary layer on the LISM side of the HP and the effect of charge exchange on the bow shock, instabilities, and magnetic reconnection near the HP, modifications to the LISM properties due to the presence of the heliosphere, and magnetic field dissipation in the heliosheath between the TS and HP.

METHODS & CODES

We solve the ideal magnetohydrodynamics (MHD) equations coupled with the kinetic Boltzmann equation describing the transport of neutral atoms. In a less strict 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 have developed both fluid dynamics and kinetic models for PUI 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 have built on the Chombo framework from LBNL.

RESULTS & IMPACT

As a result of the work supported by our Blue Waters allocation through the NSF PRAC award OCI-1615206 we have: (1) performed data-driven simulations of coronal mass ejections starting from the solar surface; (2) simulated the SW propagation along the Ulysses, Voyager, and New Horizons trajectories, and also at Uranus (Fig. 1); (3) modeled shocks propagating through the LISM and demonstrated good agreement with observational data; (4) explained the increase in the frequency of plasma waves observed by V1 in the LISM by the presence of a heliospheric boundary layer of depressed plasma density at the surface of the heliopause (Fig. 2); (5) performed high-resolution simulations of the heliopause instability, identified the areas of possible magnetic reconnection near the heliopause, and predicted that V2 is likely to observe more reconnection than V1; (6) shown that the heliospheric magnetic field may be dissipating in the heliosheath producing turbulence in the SW flow; (7) analyzed the heliotail flow and quantity distribution in the heliospheric bow wave for different LISM conditions, and showed that the observed multi-TeV cosmic ray anisotropy may be explained by the LISM magnetic field distortion by the heliosphere; and (8) investigated the heliotail structure from IBEX observations and the implications for the 11-year solar cycle in the heliosheath. The results are published in 10 papers and reported at over 20 (nine invited) scientific meetings. By addressing the basic physical phenomena occurring at the interface of the heliosphere and LISM, our research is of importance for solar and 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.

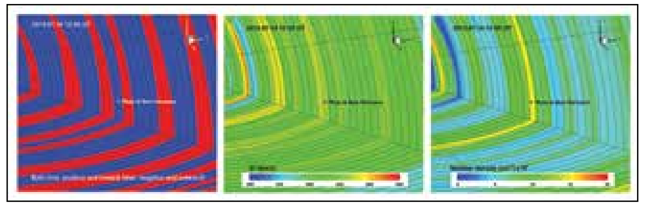

Figure 1: Simulated interplanetary magnetic field direction, which exhibits the Sun's rotation effects, solar wind radial velocity, and proton number density (scaled to 1 AU values) at the time of the New Horizons spacecraft's closest approach to Pluto. Two cross-sections are shown: by the solar equatorial plane and the plane containing the solar rotation axis and Pluto.

WHY BLUE WATERS

First, neutral atoms are modeled kinetically, and we need on the order of 10^{12} particles in our Monte Carlo simulations. These simulations require particle splitting, multiple grids, and coupling with the MHD module. They also produce multiple data sets sometimes exceeding 1 terabyte, which require hybrid parallelization. Computational region sizes are very large, as in the case of long-tail simulations to about 10,000 AU (astronomical units). (3) Very deep adaptive mesh refinement is necessary near magnetic reconnection sites.

PUBLICATIONS AND DATA SETS

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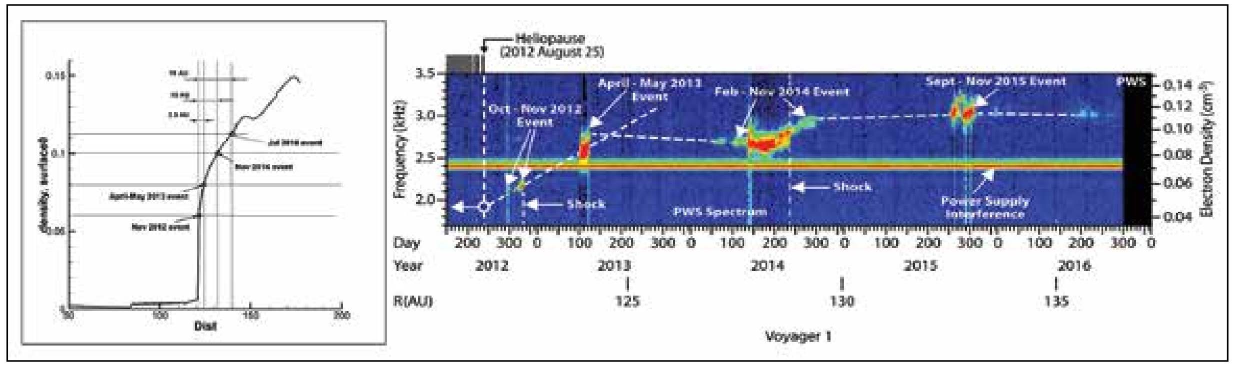

Figure 2: The distribution of plasma density (left panel) along the V1 trajectory and its comparison with the plasma wave events detected by the spacecraft beyond the heliopause (right panel).