MODELING PHYSICAL PROCESSES IN THE SOLAR WIND AND LOCAL INTERSTELLAR MEDIUM WITH A MULTISCALE FLUID–KINETIC SIMULATION SUITE: CONNECTING SOLAR, HELIOSPHERIC, AND ASTROPHYSICAL SCALES

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PI: Nikolai Pogorelov[1]
Co-PI: Jacob Heerikhuisen[1]
Collaborators: Sergey Borovikov[1], Tae Kim[1], Mehmet Sarp Yalim[1]

[1]University of Alabama in Huntsville

EXECUTIVE SUMMARY

We have investigated physical phenomena occurring when the solar wind (SW) interacts with the local interstellar medium (LISM), including: (1) propagation of coronal mass ejections (CMEs) through the solar wind flow governed by photospheric magnetograms; (2) data-driven simulations of transient phenomena affecting space weather near Earth and other planets; (3) SW propagation throughout the heliosphere and perturbations it creates in the LISM; (4) the effect of nonthermal pickup ions (PUIs) on spacecraft measurements; (5) magnetohydrodynamic (MHD) instabilities and magnetic reconnection near the heliopause; (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 help interpret and predict IBEX, New Horizons, Ulysses, and Voyager spacecraft 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 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 Interstellar Boundary Explorer (IBEX), New Horizons, Ulysses, Voyager, and a fleet of near-Earth spacecraft. We use vector magnetogram data and STEREO and SOHO observations to study the propagation of coronal mass ejections toward Earth, where they affect space weather. The Voyager 1 and 2 (V1 and V2) spacecraft crossed the heliospheric termination shock (TS) in December 2004 and August 2007, respectively, and after 45 years of historic discoveries, V1 is sampling the 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 give 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 (ENAs) in different energy bands [3]. Since most ENAs are created during charge exchange between hot PUIs and LISM neutral atoms, they bear an imprint of plasma properties of the region where they were 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.

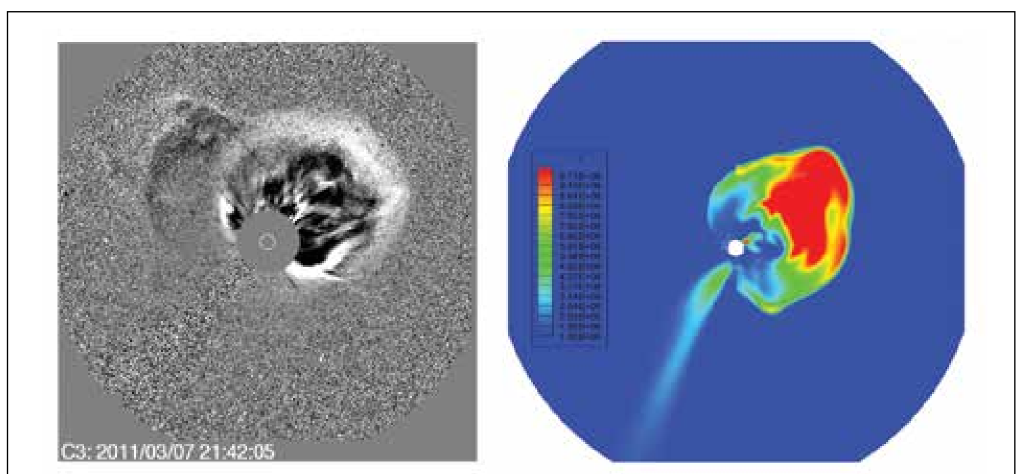

Figure 1: Comparison of CME shapes: (left panel) SOHO LASCO/C3 coronagraph difference image; (right panel) temperature contours obtained from the simulation.

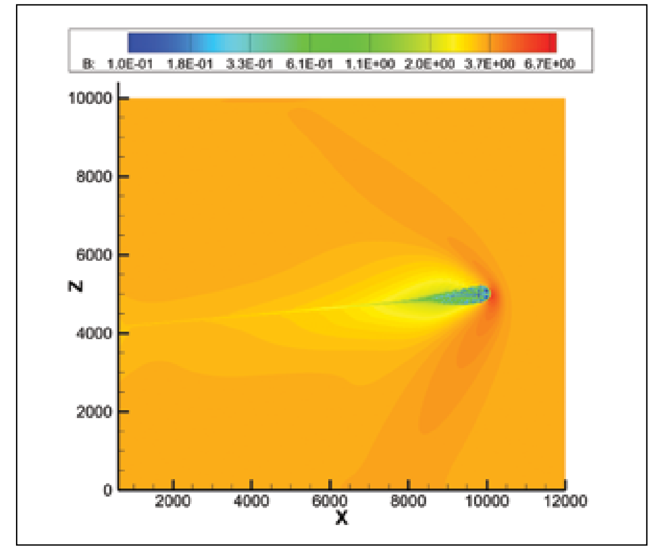

Figure 2: The distribution of magnetic field strength in the plane determined by the Sun's rotation axis and the LISM velocity vector. Because of their large gyroradius, simulations of multi-TeV cosmic ray transport toward observation sites on Earth require large computational domains.

METHODS & CODES

We solve the ideal MHD equations coupled with the kinetic Boltzmann equation describing the transport of neutral atoms. In a less strict approach, we model the flow of atoms with a few systems of the Euler gas dynamic equations describing the different atom populations dependent on the domains of their origin.

We have 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 have built on the Chombo framework. MS–FLUKSS is now capable of performing simulations with fourth-order adaptive mesh refinement (AMR), both in space and time on composite meshes, e.g., cubed spheres.

RESULTS & IMPACT

As a result of our Blue Waters allocation we have: (1) used coronograph images from the SOHO and STEREO spacecraft to simulate CMEs, starting from the lower corona of the Sun (Fig. 1); (2) used the Wang–Sheeley–Arge coronal model driven by the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model to simulate SW properties at Earth and have demonstated advantages of our model over existing space weather prediction models; (3) refined our model for shocks propagating through the LISM, demonstrating good agreement with observational data, and predicting a few events to be observed by V1 in the future; (4) performed a time-dependent simulation of the heliosphere that produces a comet-like heliotail and showed that the 11-year solar cycle leads to the formation of ENA lobes with properties remarkably similar to those observed by IBEX; (5) analyzed the heliotail flow and quantity distribution in the heliospheric bow wave for different LISM conditions in a computational box of 12,000 by 10,000 by 8,000 astronomical units, and showed that the observed multi-TeV cosmic ray anisotropy may be explained by LISM magnetic field distortion by the heliosphere; (6) used simulations on adaptive meshes to further understand MHD instabilities and magnetic reconnection at the heliopause, and (7) reproduced observations of pickup ions by New Horizons. Our results have been published in six papers (one more paper is in press and three are in preparation) and reported at more than 10 scientific meetings. In addition, our research was highlighted by the American Astronomical Society and other web news outlets.

WHY BLUE WATERS

The Blue Waters system and project staff responded in a timely manner to our concerns and were very helpful in the development of job-scheduling strategies. The overall performance and reliability of Blue Waters has been outstanding.

PUBLICATIONS & DATA SETS

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