COUPLING THE SOLAR WIND AND LOCAL INTERSTELLAR MEDIUM IN THE ERA OF THE NEW HORIZONS, INTERSTELLAR BOUNDARY EXPLORER, PARKER SOLAR PROBE, ULYSSES, AND VOYAGER SPACECRAFT

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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, Huntsville

EXECUTIVE SUMMARY

The research team has investigated physical phenomena occurring when the solar wind (SW) interacts with the local interstellar medium (LISM). These include: (1) the effect of non-Maxwellian plasma distribution on the SW–LISM interaction; (2) the propagation of coronal mass ejections, constrained by multi-viewpoint images, through the solar wind flow governed by photospheric magnetograms; (3) transient phenomena affecting space weather at Earth and other planets; (4) magnetohydrodynamic (MHD) instabilities and magnetic reconnection in the presence of turbulence; (5) the effect of nonthermal pickup ions (PUIs) on spacecraft measurements; (6) energetic neutral atom observations from the Interstellar Boundary Explorer (IBEX) through direct 3D, MHD–kinetic simulations; (6) the heliospheric effect on the observed anisotropy of galactic cosmic rays with energies on the order of TeV and the origin of this anisotropy; and (7) the global structure of the solar wind flow along the Parker Solar Probe (PSP) trajectory. Our simulations help interpret IBEX, New Horizons, PSP, Ulysses, and Voyager measurements, as well as air shower observations.

RESEARCH CHALLENGE

The Grand Challenge of this research is to investigate fundamental physical phenomena that start on the solar surface and result in solar wind acceleration and propagation through interplanetary space toward the boundary of the heliosphere, where the solar wind interacts with the local interstellar medium. The research team studied plasma instabilities, magnetic reconnection, cosmic ray transport, and kinetic effects of partial ionization in plasma. These included the birth/death of secondary neutral atoms and nonthermal PUIs, and phenomena driven by MHD turbulence. Most of the research team's simulations were data-driven and also validated by observations from such space missions as IBEX [1], New Horizons (NH) [2], PSP [3], Ulysses [4], Voyager [5], and the fleet of near-Earth spacecraft.

To drive the coronal model, the researchers used the wealth of magnetogram data accompanied by the satellite missions STEREO and SOHO observations. This allowed the team to develop a new approach, preserving the shape and speed of a coronal mass ejection as well as the plasma mass and poloidal magnetic field fluxes carried by it. Simulations were especially focused on the interstellar mission of Voyager 1 and 2 (V1 and V2) spacecraft, which crossed the entire heliosphere and are now traversing the LISM. For the first time in the history of mankind, we are acquiring *in situ* information on the properties of LISM plasma, energetic particles, and magnetic fields at the heliospheric boundary. Voyager data are complemented by the IBEX observations of energetic neutral atoms (ENAs) in different energy bands. Since ENAs are born owing to charge exchange of nonthermal PUIs with other neutrals, the team was able to investigate the effect of non-Maxwellian proton distribution function on the heliospheric structure and support the interstellar origin of the IBEX ribbon.

METHODS & CODES

The researchers solved the equations of ideal MHD coupled with the kinetic Boltzmann equation describing the transport of neutral atoms. In a less strict approach, the flow of atoms was

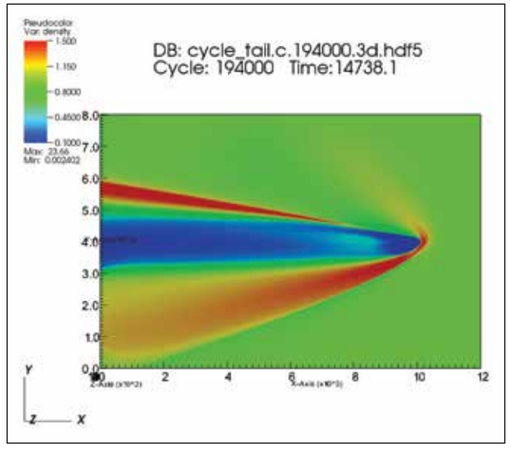

Figure 1: Solar wind interaction with the local interstellar medium. Plasma density distribution in the cross-section of maximum flaring of the heliopause exhibits a very long heliotail and additional, unexpected discontinuities.

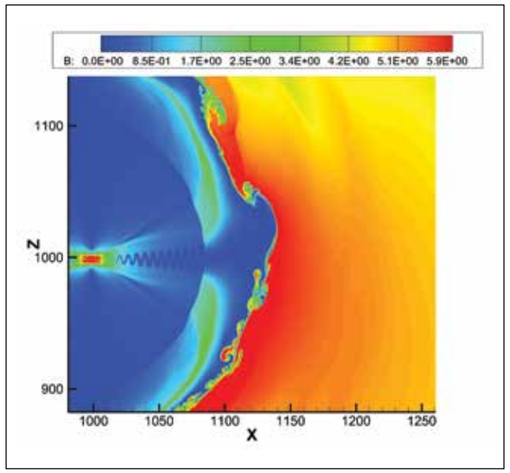

Figure 2: Solar wind interaction with the local interstellar medium. A snapshot of the time-dependent distribution of magnetic field magnitude at the heliospheric boundary. The heliopause instability is stronger in the northern hemisphere, but there are signatures of magnetic reconnection in the southern hemisphere.

modeled with a few systems of the Euler gas dynamic equations describing the atom populations that differ by the domain of their origin. The team has 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—an adaptive mesh refinement code built on the Chombo framework.

RESULTS & IMPACT

- The team has developed a powerful data-driven solar model that allowed for the simulation of the solar wind flow and interplanetary magnetic field as a function of time along the Earth; New Horizons spacecraft; and Pluto, Neptune, and Uranus trajectories.
- This work represents a substantial breakthrough in modeling flows of partially ionized plasma in the presence of PUIs by designing special boundary conditions for the latter at the heliospheric termination shock. This is of utmost importance because such boundary conditions are intrinsically kinetic.
- The team has developed a unique solar wind model that is based on synchronous vector magnetograms from the Solar Dynamics Observatory. This made it possible, for the first time in the history of solar wind simulations, to create a mathematically consistent model of solar corona.
- This study has analyzed quantitatively the distribution of quantities in the heliospheric boundary layer—a region of interstellar plasma in front of the heliopause that is characterized by depressed plasma density and enhanced interstellar magnetic field. The MHD instabilities and magnetic reconnection have been analyzed with high resolution in space and time, owing to the high computing power of Blue Waters.
- The research group's numerical simulations have shown features of magnetic reconnection near the heliopause in the southern hemisphere and, in particular, near the point where Voyager 2 crossed the heliopause.
- The researchers have reproduced the 5 TeV cosmic ray anisotropy observed in the Tibet air shower experiment. It has been demonstrated that the heliosphere provides most of the higher-than-dipole contributions to this anisotropy. The cosmic ray anisotropy in the pristine LISM has been derived and the likely source of this anisotropy has been identified.
- The team's new, data-driven coronal mass ejection simulations have been extended to involve the poloidal magnetic flux observations in the photosphere, which improves the quality of simulations tremendously.
- This project's numerical simulation results have found their way to the broader space science community and received publicity. A few internal and national press releases were focused on this research, powered by Blue Waters.

WHY BLUE WATERS

Blue Waters is not just a supercomputer with higher-than-usual allocation opportunities. It comes with an efficient and highly professional support staff, who responded to all our concerns and were very helpful in the development of job scheduling and visualization strategies. The PAID and Student Fellowship opportunities were also extremely valuable.

PUBLICATIONS & DATA SETS

F. Fraternale, N. V. Pogorelov, J. D. Richardson, and D. Tordella, "Magnetic turbulence spectra and intermittency in the heliosheath and in the local interstellar medium," *Astrophys. J.*, vol. 874, p. 40, 2019.

J. Heerikhuisen, E. J. Zirnstein, N. V. Pogorelov, G. P. Zank, and M. Desai, "The effect of suprathermal protons in the heliosheath on the global structure of the heliosphere and heliotail," *Astrophys. J.*, vol. 874, p. 76, 2019.

T. Singh, M. S. Yalim, and N. V. Pogorelov, "A data-constrained model for coronal mass ejections using the graduated cylindrical shell method," *Astrophys. J.*, vol. 864, p. 18, 2018.

T. Singh, M. S. Yalim, N. V. Pogorelov, and N. Gopalswamy, "Simulating solar coronal mass ejections constrained by observations of their speed and poloidal flux," *Astrophys. J. Letters*, vol. 875, p. L17, 2019.

E. J. Zirnstein, J. Heerikhuisen, D. J. McComas, N. V. Pogorelov, D. B. Reisenfeld, and J. R. Szalay, "Simulation of the solar wind dynamic pressure increase in 2014 and its effect on energetic neutral atom fluxes from the heliosphere," *Astrophys. J.*, vol. 859, p. 104, 2018.