MODELING HELIOSPHERIC PHENOMENA WITH THE MULTI-SCALE FLUID-KINETIC SIMULATIONS SUITE: FROM THE SOLAR SURFACE TO THE LOCAL INTERSTELLAR MEDIUM

Allocation: NSF PRAC/1.21 mnh
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EXECUTIVE SUMMARY

Blue Waters 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 towards the heliopause and perturbations it creates in the LISM; (4) mixing of the SW and LISM plasma at the heliospheric interface owing to the heliopause (HP) instability and magnetic reconnection; (5) the influence of the heliosphere on the observed anisotropy of TeV galactic cosmic rays; and (6) the application of 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 multi-TeV cosmic ray observations.

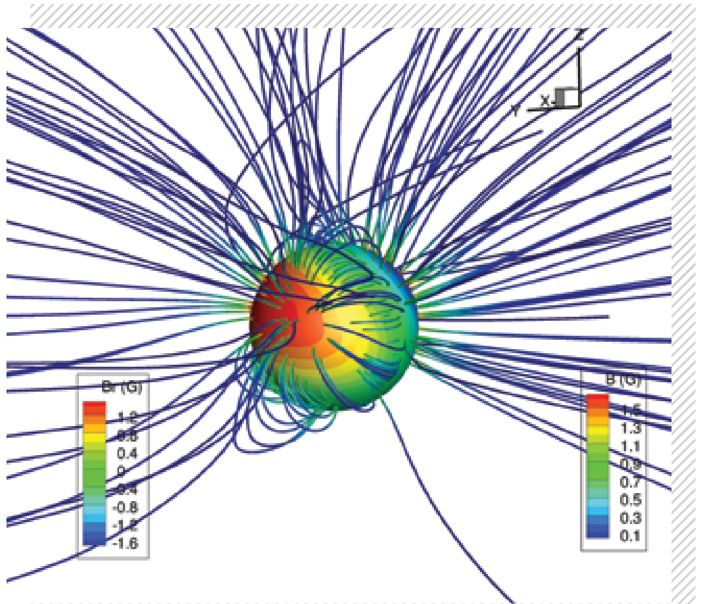

FIGURE 1: Magnetic field line distributions around the Sun are shown together with the radial magnetic field contours on the photosphere.

INTRODUCTION

Voyager 1 and 2 (V1 and V2) spacecraft crossed the heliospheric termination shock (TS) in December 2004 and in August 2007, respectively, and after 38 years of historic discoveries, V1 started sampling the LISM [1] while V2 is approaching the heliopause—a tangential discontinuity separating the solar wind from the LISM. The Voyagers acquire in situ information about the local properties of the Solar Wind plasma, energetic particles, and magnetic field at the heliospheric boundary [2]. V1 data related to the LISM properties gives the heliospheric studies community a unique opportunity to constrain models with observational data. Another constraint on the LISM properties is derived from the presence of pickup ions (PUIs) that are born when the thermal solar wind ions exchange charge with the LISM neutral atoms. On the other hand, the 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 the plasma properties of the region they are created. Data-driven simulations of the SW allow us to specify the inner boundary conditions. The combination of IBEX, New Horizons, SOHO, Ulysses, Voyager, and multi-TeV air shower data makes it possible to investigate physical phenomena at the heliospheric interface.

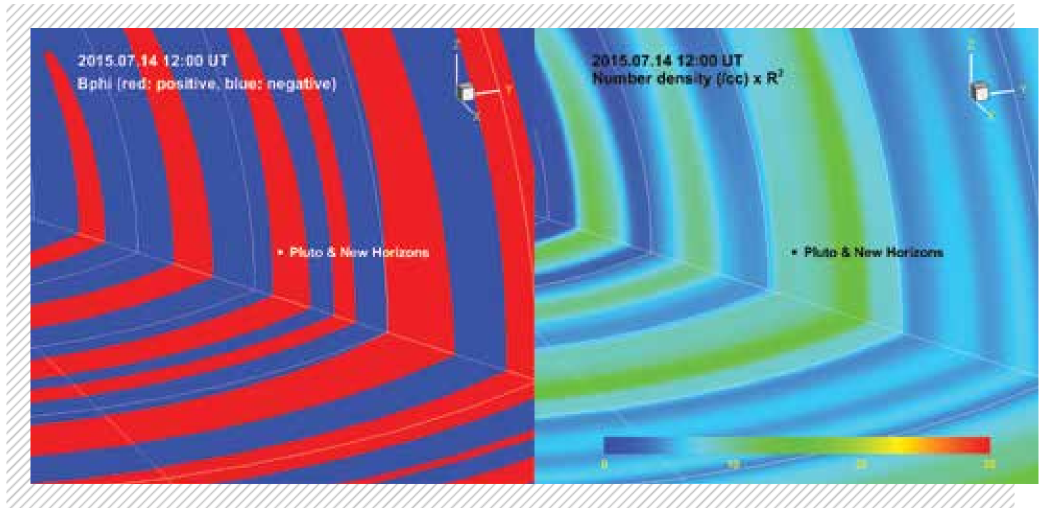

FIGURE 2: The plots magnetic field, B, polarity (left panel) and solar wind proton number density (right panel) on 14 July 2015 12:00 UT. Red and blue colors indicate positive and negative signs of the toroidal component of B, respectively. Proton density is shown scaled to 1 AU values.

METHODS & RESULTS

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 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.

The major results of the work are (1) we have performed data-driven solar wind flow simulations starting from the solar surface (Fig. 1); (2) we have calculated solar wind propagation from Earth orbit to Pluto along the New Horizons spacecraft trajectory (Fig. 2) and further to the heliopause and demonstrated good agreement with observational data; (3) we have explained the existence of extended regions of the solar wind sunward flow near the heliopause and spontaneous transition to turbulence; (4) we have performed high-resolution simulations of the heliopause instability and identified the areas of possible magnetic reconnection near the heliopause crossed by Voyager trajectories (Fig. 3), which allowed us to put forward a possible explanation of V1 observations that showed a few consecutive increases and decreases in the galactic and anomalous cosmic ray flux intensities; (5) we have analyzed the heliotail flow and quantity distribution in the heliospheric bow wave for different LISM conditions and revealed [4] that the observed multi-TeV cosmic ray anisotropy may be explained by the LISM magnetic field distortion by the heliosphere; and (6) we have investigated the effect of non-thermal ions on time-dependent plasma distributions in the solar wind and LISM.

By addressing the basic physical phenomena occurring at the interface of the heliosphere and LISM, our research is of importance for the 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.

WHY BLUE WATERS

(1) Our simulations are computationally intensive. Neutral atoms are modeled kinetically and we need of the order of 1012 particles in our Monte Carlo simulations. These simulations require particle splitting, multiple grids, and careful coupling with the MHD module. They also produce multiple data sets sometimes exceeding 1 TB, which requires hybrid parallelization. (2) Computational region sizes are very large, as in the case of long-tail simulations to about 10,000 AU. (3) Very deep adaptive mesh refinement is necessary near magnetic reconnection sites. With the support of the Blue Waters PAID program we are able to upgrade MS-FLUKSS to use GPUs. We will use our new allocation (PRAC project ACI-1615206) to perform simulations of the turbulent SW-LISM interaction.

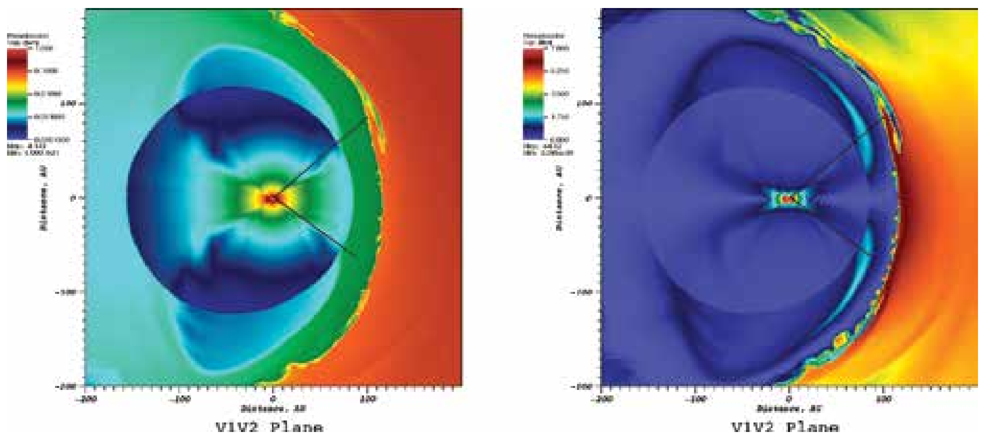

FIGURE 3: Distributions of the magnetic field strength (right panel) and plasma density (left panel) in the plane defined by the current directions of the Voyager 1 and Voyager 2 trajectories demonstrate the heliopause instability at V1 and signatures of magnetic reconnection at V2.

NEXT GENERATION WORK

On a next-generation Track-1 system in the 2019-2020 timeframe, we plan to extend MS-FLUKSS by adding the capability to perform local hybrid plasma simulations (particle ions and electron fluid) in the framework of the global MHD model. This will allow us to investigate micro-scale phenomena, e.g. particle acceleration and kinetic instabilities, in the realistic environment.

PUBLICATIONS

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DEPLOYMENT OF THE DARK ENERGY SURVEY WORKFLOWS

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EXECUTIVE SUMMARY

The Dark Energy Survey (DES) is performing a 5,000 square-degree wide field survey in five optical bands of the southern sky and a 30 square-degree deep supernova survey with the aim of understanding the nature of dark energy and the accelerating universe. DES uses the new three square-degree charged couple device (CCD) camera, DECam, installed at the prime focus on the Blanco four meter telescope to record the positions and shapes of 300 million galaxies up to redshift 1.4. During a normal night of observations, DES produces about 1 TB of raw data, including science and calibration images, which are transported automatically from Chile to NCSA to be archived and reduced. The DES data management system (DESDM) is used for the processing, calibration and archiving of this data, which has been developed by collaborating DES institutions led by NCSA. The DESDM team at NCSA has successfully deployed the DES Production Pipeline on Blue Waters. Over the course of a year of investigations, several software and network improvements were made by the Blue Waters team to accommodate our workflows, and we were able to commission our production framework successfully in the fall of 2015. Moreover, we were able to make use of the remainder of our initial allocation to process 10,814 DECam exposures on the XE Compute Nodes. This corresponds to 15% of the total data volume (over 70k exposures) that DESDM processed for the Y3A1 release.

INTRODUCTION

The goal of the DES is to understand the origin of cosmic acceleration and the nature of dark energy using four complementary methods: weak gravitational lensing, galaxy cluster counts, large-

FIGURE 1: An example of one of the 10,814 DECam exposures processed by Blue Waters in early 2016 using the FINALCUT pipeline during our initial DD time allocation.