Blue Waters Symposium
Sunriver, OR, 3 – 6 June, 2019

Modeling Physical Processes in the Solar Wind and Local Interstellar Medium

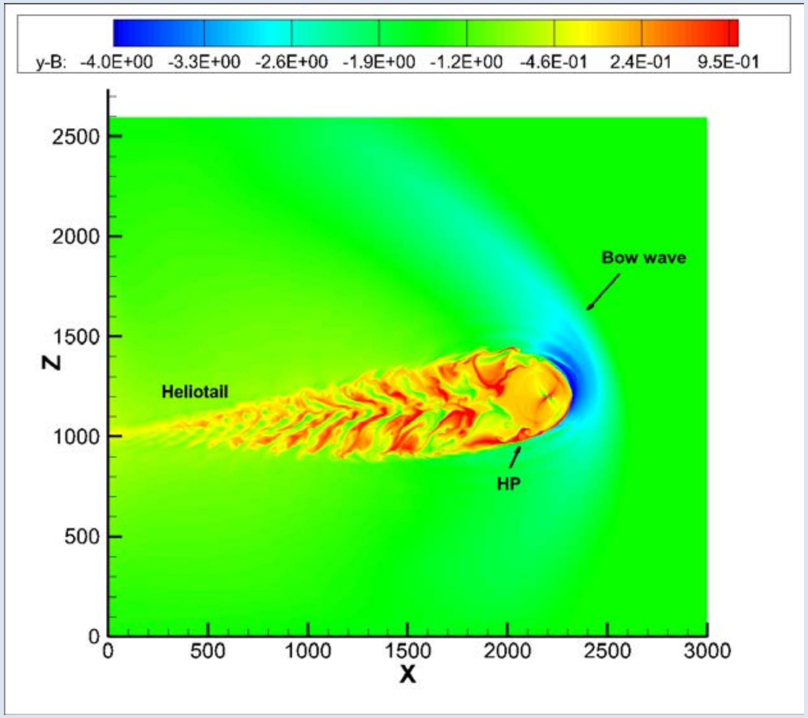
N.V. Pogorelov and J. Heerikhuisen

University of Alabama in Huntsville
Department of Space Science
Center for Space Plasma and Aeronomic Research

In collaboration with L. Carrington, T. K. Kim, I. A. Kryukov, V. Roytershteyn, T. Singh, M. S. Yalim, and M. Zhang

Key Challenges

1. Flows of partially ionized plasma are frequently characterized by the presence of both thermal and nonthermal populations of ions and neutral atoms. This occurs, e. g., in the outer heliosphere – the part of interstellar space beyond the solar system whose properties are determined by the solar wind (SW) interaction with the local interstellar medium (LISM).



The Sun is at the origin, the LISM flow is from the right to the left. Their interaction creates a heliospheric termination shock, a heliopause, and a bow wave that may include a sub-shock inside its structure.
The LISM is partially ionized and the mean free path of charge exchange between H atoms and H+ ions is such that this process should be modeled kinetically.

2. We perform MHD-kinetic and multi-fluid simulations of the SW–LISM interaction using the boundary conditions based on observational data from multiple sources. Numerical results are intended to shed light on a number of fundamental physical processes occurring throughout the heliosphere and in the vicinity of the heliopause: plasma instabilities, magnetic reconnection, kinetic effects of partial ionization in plasma, including the birth of secondary neutral atoms and nonthermal, pickup ions (PUIs), and phenomena driven by MHD turbulence.

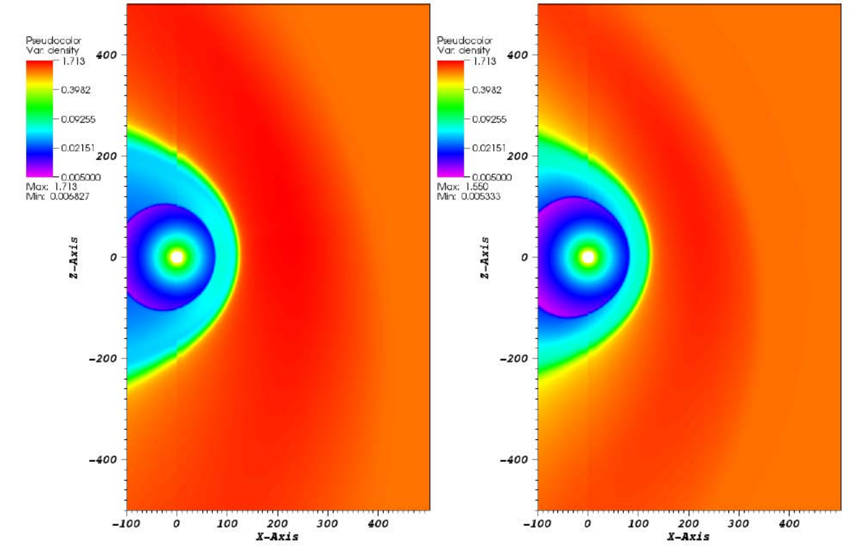


Figure 2. Plasma density distributions in the meridional plane for the single-ion-fluid model (left panel) and for the case when the PUI and thermal ion fluids behave as co-moving, but distinguishable components (right panel)

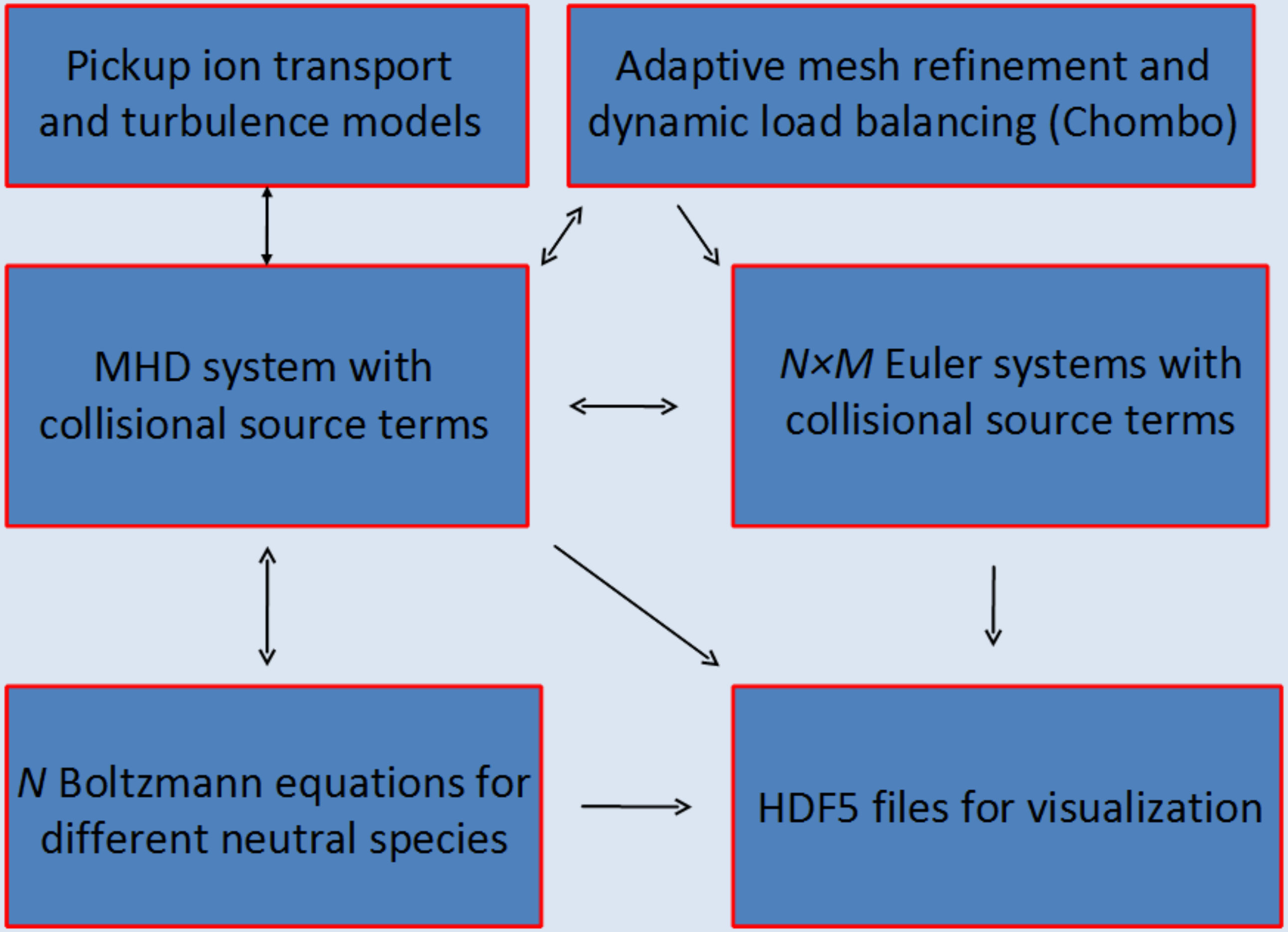
From Pogorelov et al. (2016): density distributions along the Voyager 1 trajectory in simulations for a single ion mixture and PUIs modeled as a separate ion fluid. The width of the heliosheath diminishes in accordance with Voyager 1 measurements.

3. Numerical simulations are, on the one hand, data-driven, and on the other hand validated by observations. Moreover, quantities missing from the observational data sets are recovered by modeling through fitting the Voyager in situ measurements, the time-dependent IBEX ribbon and distributed ENA flux, the (interstellar) hydrogen defection plane (HDP) orientation, Lyα absorption profiles in directions toward nearby stars, and 1–10 TeV cosmic ray anisotropy measurements. The solar wind perturbs the LISM substantially: about 1000 AU upwind and 10,000 AU in the tail.

4. Solar wind simulations from the solar surface to Earth's orbit are important for space weather predictions, ensuring safety of personnel and electronics on board spacecraft.

5. We build on the success of our previous PRAC projects, which allowed us to explain and often times even predict observed phenomena. To address these problems, we developed a tool for self-consistent numerical solution of the MHD, gas dynamics Euler, and kinetic Boltzmann equations. Our Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) solves these equations using an adaptive-mesh refinement (AMR) technology. The grid generation and dynamic load balancing are ensured by the Chombo package.

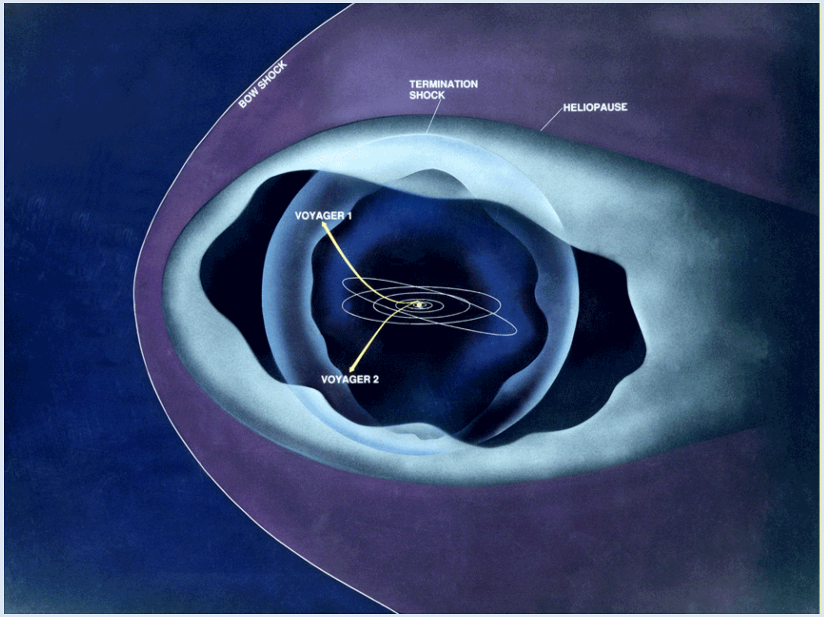
The Structure of the Multi-Scale Fluid-Kinetic Simulations Suite



Non-thermal (pickup) ions are created when SW ions experience charge exchange with interstellar neutral atoms.

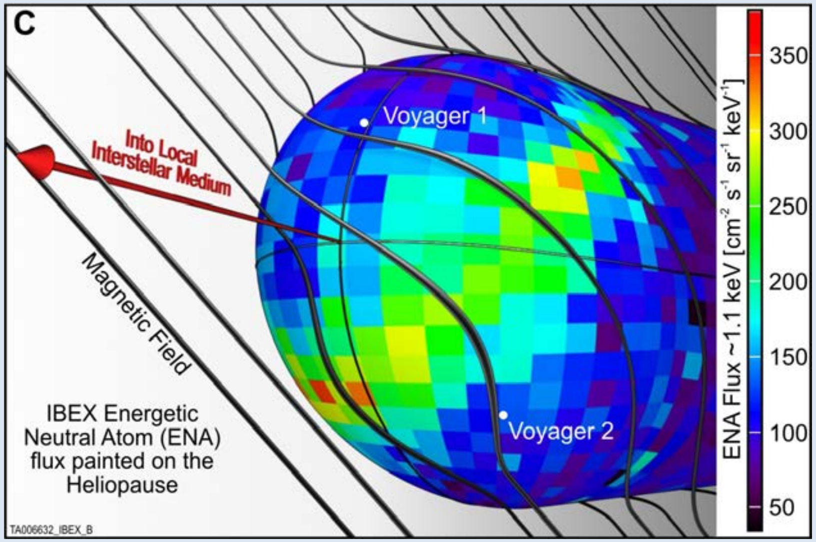
Further charge exchange of PUIs with neutral atoms creates energetic neutral atoms (ENAs) measured by IBEX.

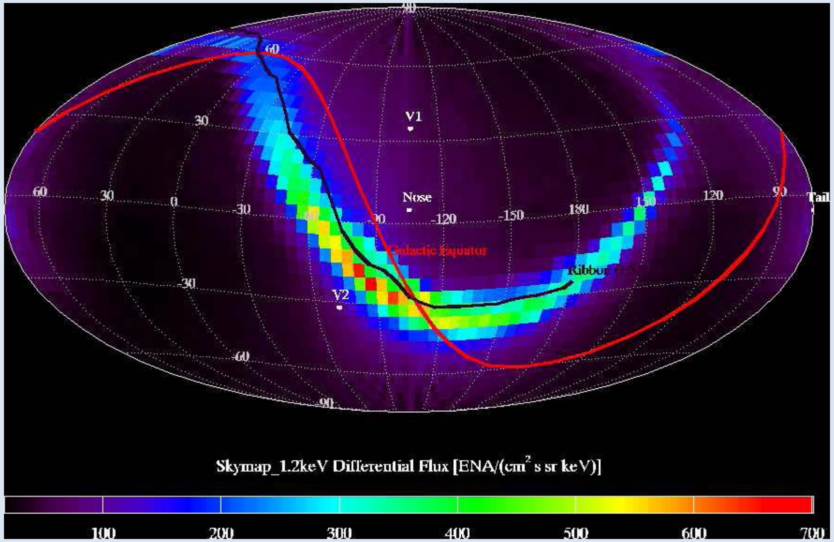
Why it matters?



Voyager 1 and *2 (V1* and *V2),* PI Edward C. Stone, crossed the heliospheric termination shock in December 2004 and in August 2007, respectively (Stone et al., 2005, 2008). After more than 45 years of historic discoveries, both V1 and V2 crossed the heliopause measures and mesure the LISM properties directly. They acquire often puzzling information about the local properties of the SW and LISM plasma, waves, energetic particles, and magnetic field, which requires theoretical explanation. In the next few years, the heliospheric community has a unique chance to analyze and interpret Voyager measurements deriving breakthrough information about physical processes occurring more than 1.3×10^{10} miles from the Sun. Illustrations courtesy of NASA at voyager.jpl.nasa.gov.

Our team has proposed a quantitative explanation to the sky-spanning “ribbon” of unexpectedly intense flux of ENAs detected by the Interstellar Boundary Explorer (IBEX, PI David J. McComas). Our physical model makes it possible to constraint the direction and strength of the interstellar magnetic field (ISMF) in the near vicinity of the global heliosphere (Heerikhuisen & Pogorelov, 2011; Heerikhuisen et al, 2014, 2015, 2017, 2019; Zirnstein et al., 2014, 2015, 2016, 2017, 2019; Pogorelov et al., 2011, 2016, 2017) . Heliophysics research is faced with an extraordinary opportunity to use *in situ* measurements from Voyagers and extract information about the global behavior of the heliosphere through ENA observations by IBEX.

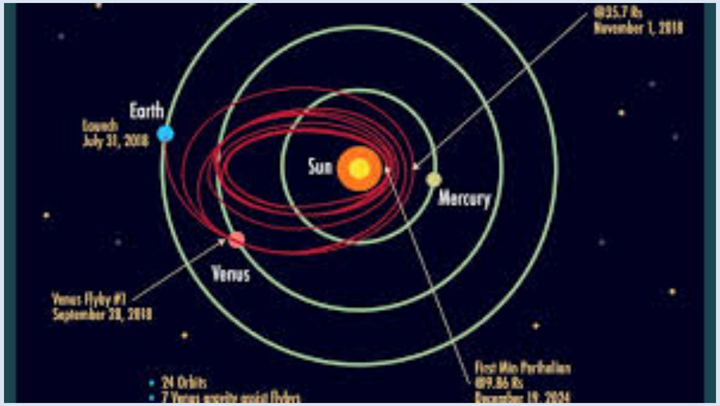




From McComas et al. (2009)

Simulated ENA flux

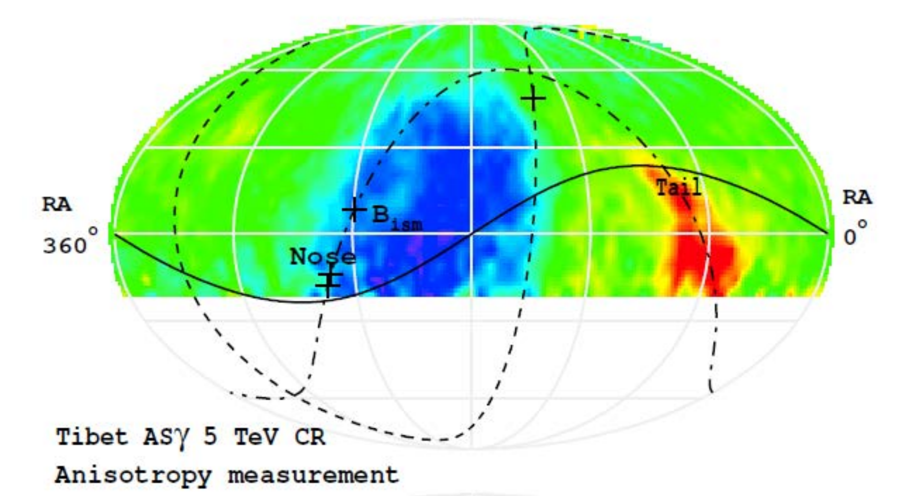
From the Parker Solar Probe web site at JHU Applied Physics Laboratory http://parkersolarprobe.jhuapl.edu/: "Parker Solar Probe will swoop to within 4 million miles of the sun's surface, facing heat and radiation like no spacecraft before it. Launching in 2018, Parker Solar Probe will provide new data on solar activity and make critical contributions to our ability to forecast major space-weather events that impact life on Earth. In order to unlock the mysteries of the corona, but also to protect a society that is increasingly dependent on technology from the threats of space weather, we will send Parker Solar Probe to touch the Sun. In 2017, the mission was renamed for Eugene Parker, the S. Chandrasekhar Distinguished Service Professor Emeritus, Department of Astronomy and Astrophysics at the University of Chicago…. This is the first NASA mission that has been named for a living individual."



Each consecutive trajectory of PSP will take it closer to the Sun.

Solar Wind Electrons, Alphas, and Protons (SWEAP) instrument (PI Justin Kasper) onboard SPP, launched in the summer of 2018, is directly measuring the properties of the plasma in the solar atmosphere. In particular, the time-dependent distribution functions will be measured, which requires the development of sophisticated numerical methods to interpret them.

Recently, a great wealth of information about the directional variation (which is commonly referred to as anisotropy) in the flux of cosmic rays arriving at Earth in the TeV to PeV energy range has been obtained by a number of ***air shower experiments***. Among those that have achieved excellent data quality with large event statistics are Tibet (Amenomori, et al. 2006, 2010); Milagro (Abdo et al. 2008, 2009); Super-Kamiokande (Guilian et al. 2007); IceCube/*EAS-Top (Abbasi* et al. 2010, 2011, 2012), and ARGO-YGB (Di Sciascio et al. 2012). The observational results are quite surprising and confusing. Zhang et al. (2019) removed the heliospheric effects hidden in the measurements made in the Tibet ASγ experiment on Earth and determined the original anisotropy of TeV cosmic rays in the LISM. The original anisotropy is almost a pure dipole resulting from particle diffusion along the Local Chimney magnetic field into the northern Galactic halo. We found that the density gradient of these cosmic rays points approximately towards Vela in the Local Bubble, suggesting that Vela could be the source of anisotropy. The heliosphere generates small-scale anisotropies off the dipole, contributing a significant fraction of high-order multipoles that make up complex patterns in the observations.



Tibet ASγ 5 TeV CR
Anisotropy measurement

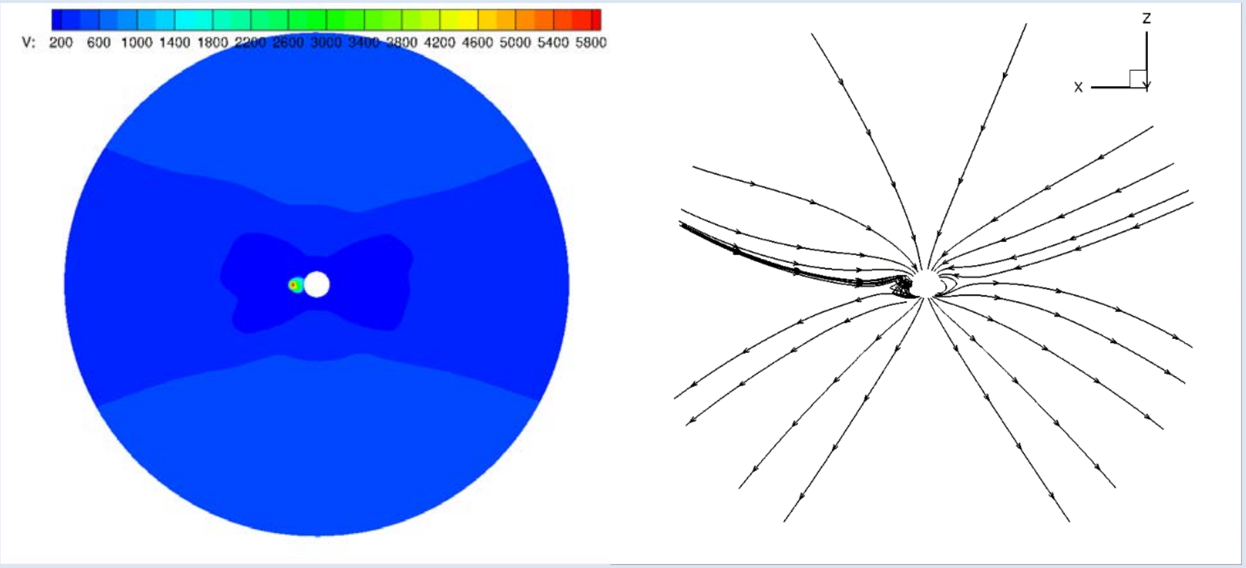
Science funding

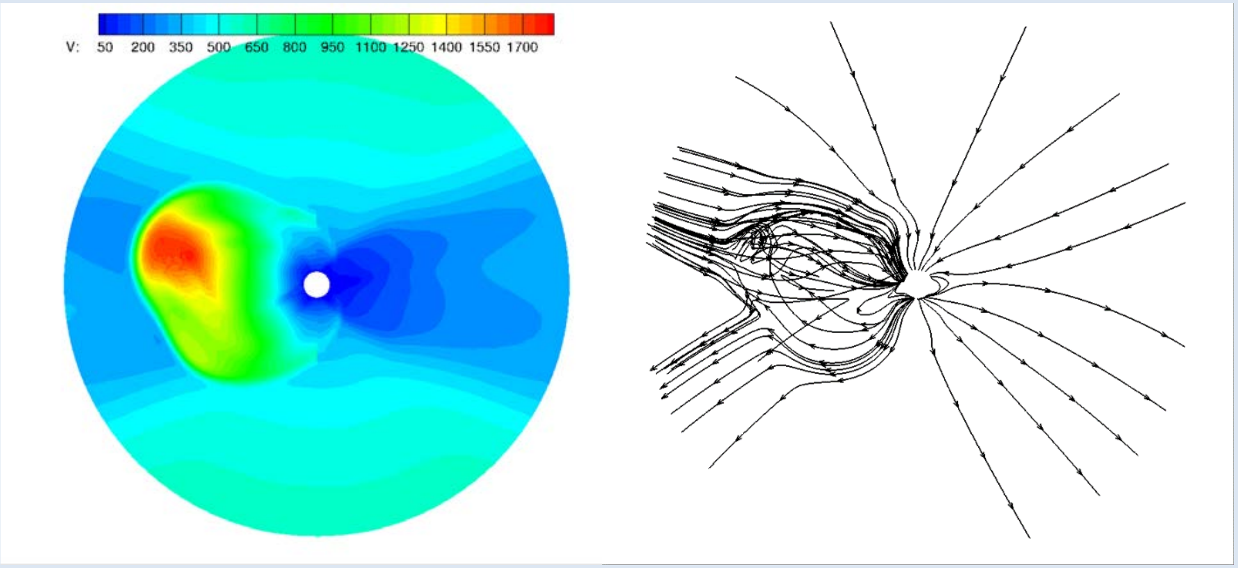
1. Pogorelov, N. (Principal), "Modeling Physical Processes in the Solar Wind and Local Interstellar Medium with Multi-scale Fluid-Kinetic Simulation Suite ," Sponsored by NSF PRAC, Federal, $10,501. (04/01/2018 – 03/31/2020).
2. Pogorelov, N. (Principal), "Pickup Ions in the Outer Heliosphere and Beyond," Sponsored by NASA, Federal, $746,285. (6/26/2018 – 6/25/2021).
3. Pogorelov, N. (Principal), "Turbulence as Indicator of Physical Processes at the Heliospheric Interface ," Sponsored by NASA, Federal, $524,773. (3/1/2019 – 2/28/2022).
4. Heerikhuisen, J. (Principal), "REU Site: Solar and Heliospheric Physics at UAH and MSFC,'' Sponsored by NSF, Federal, $621,922.00. (June 1, 2015 – May 31, 2020).
5. Heerikhuisen, J. (Principal), "Pick-up Ions and Energetic Neutral Atoms: Implications for the Termination Shock," Sponsored by NASA, Federal, $461,264.00 (May 1, 2016 – April, 30, 2020).
6. Kim, T.K. (Principal), "A Higher-accuracy Model of the Heliosphere with the Improved Background Solar Wind and Coronal Mass Ejections," Sponsored by NASA, Federal, $249,745 (10/1/2018 – 9/30/2019).
7. Pogorelov, N.V. (Principal), "Modeling Coronal Mass Ejections in the Solar Wind Driven by Photospheric Data," Sponsored by NASA, Federal, $90,000, (9/1/2018 – 8/31/2020).

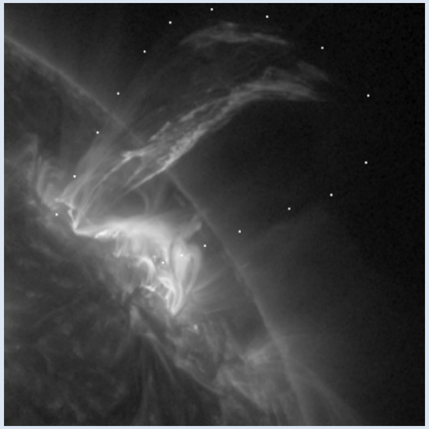
Our accomplishments supported by NSF PRAC award OAC - 1811176

1. **We quantified the impact of suprathermal protons on the global structure of the heliosphere by comparing our new model to a traditional Maxwellian fluid model, and a kappa-distribution model. We found that the differences in momentum and energy transfer rates from the protons onto neutral hydrogen between the models leads to different plasma properties in the heliotail, and also changes the size of the heliosphere. Including the energy-dependent charge exchange cross section into the collision integrals reduces these differences.**
2. **Time-dependent ENA fluxes were investigated in relation to the IBEX mission.**
3. **We used coronograh images from SOHO and STEREO spacecraft to simulations of CMEs starting from the lower corona of the Sun;**
4. **We used the Wang-Sheeley-Arge coronal model driven by the Air Force Data Assimilative Photospheric Flux Transpot (ADAPT) model to simulate SW properties at Parker Solar Probe;**
5. **We have investigated the effect of the heliopause instability on Voyager measurements of GCR fluxes;**
6. **We have derived the genuine anisotropy of TeV GCRs in the LISM and proposed a source of such anisotropy.**
7. **Our last year’s results are published in 7 papers (3 more papers are in press) and reported at over 20 scientific meetings**

Data-constrained Model for Coronal Mass Ejections Using Graduated Cylindrical Shell Method (Singh et al., 2018, 2019)

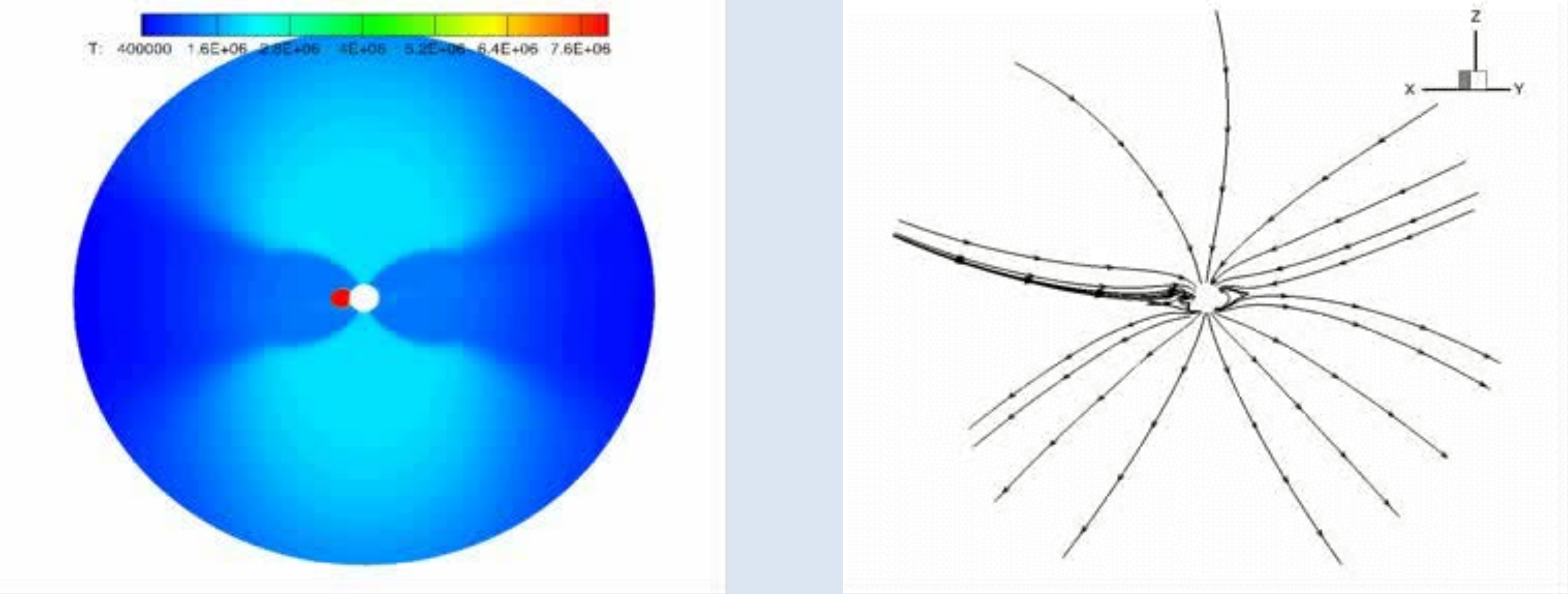






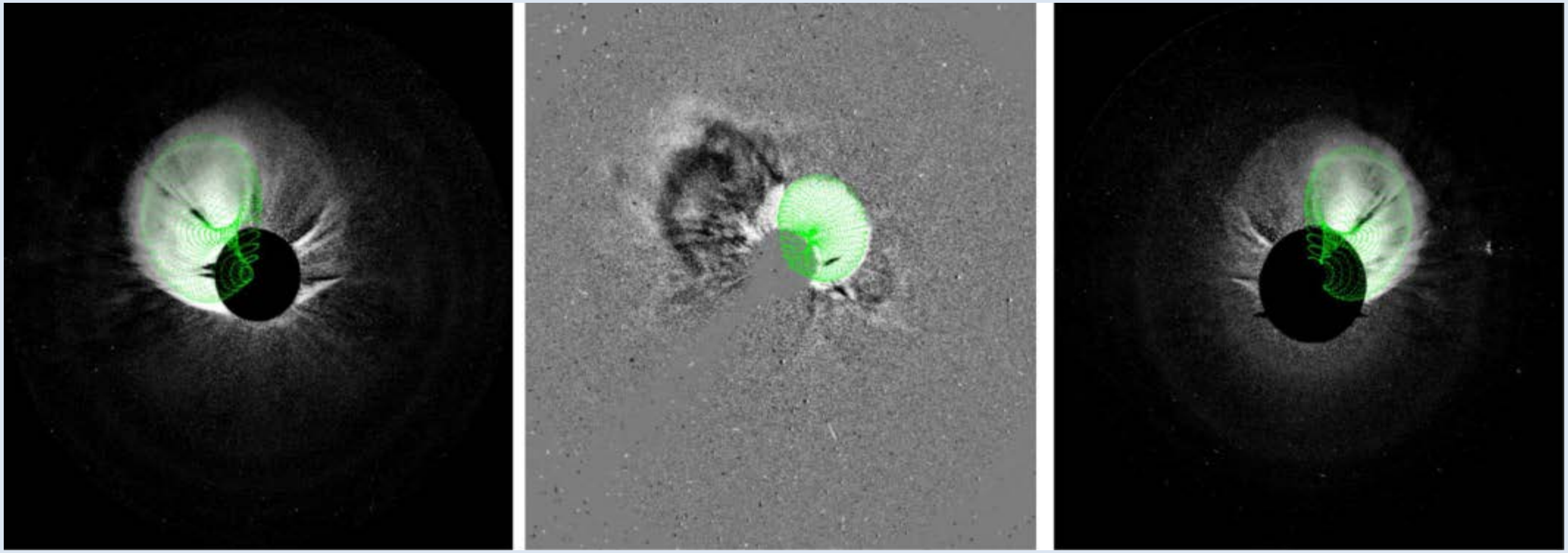
(Above) Solar eruption observed on 7 March 2011 by the Atmospheric Imaging Assembly (AIA) in 13.1 nm wavelength.

(Right) Simulated velocity and magnetic field lines 1 min (top panel) and 1 hr (bottom panel) after the eruption.



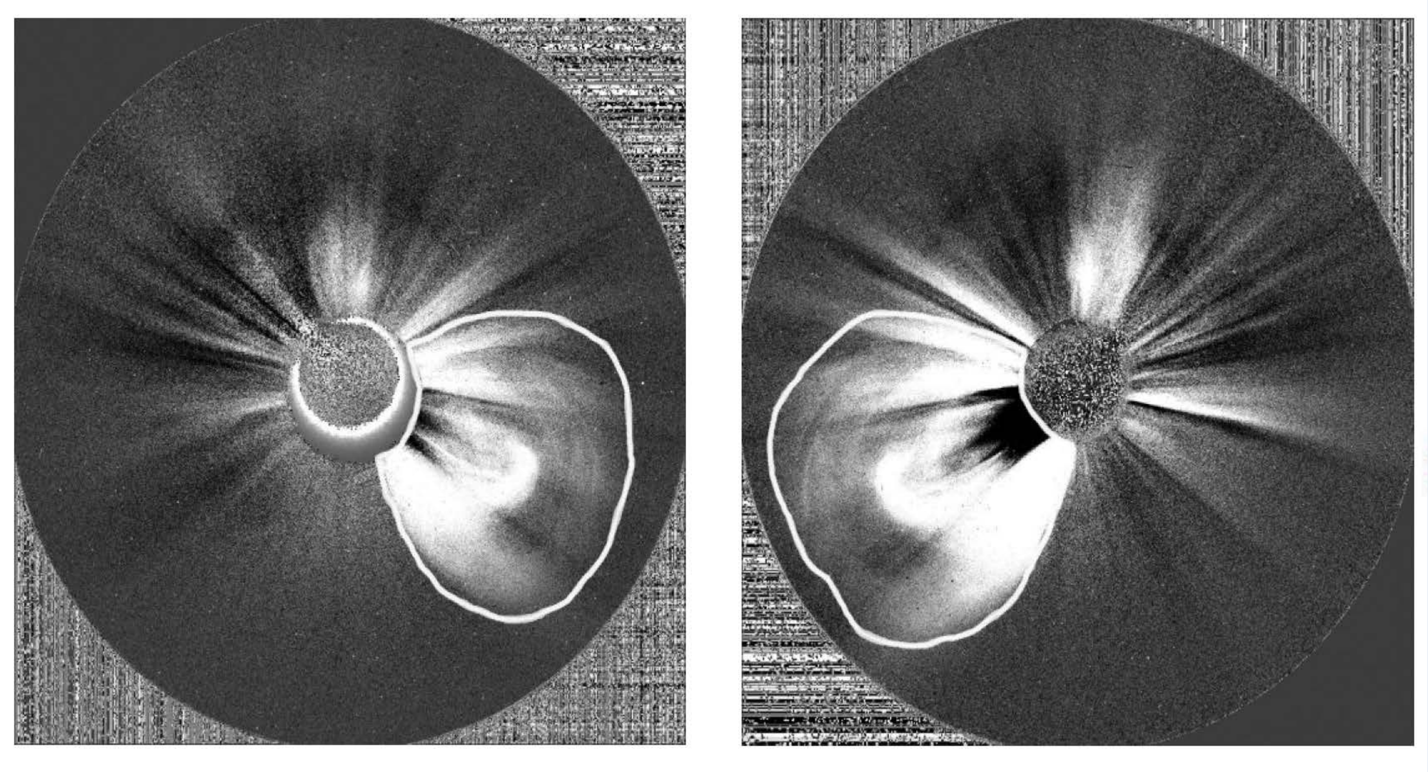
Animations of the SW temperature and magnetic field lines as the CME propagates towards Earth.

Observations used



Graduate Cylindrical Shell (GCS) model is used to find speed, tilt and direction of CME (Thernisian et. al. 2006)

Observations used



True mass is calculated from 2 viewpoints of STEREO A and B white light coronagraphs to remove projection effects (Colaninno & Vourlidas 2009)

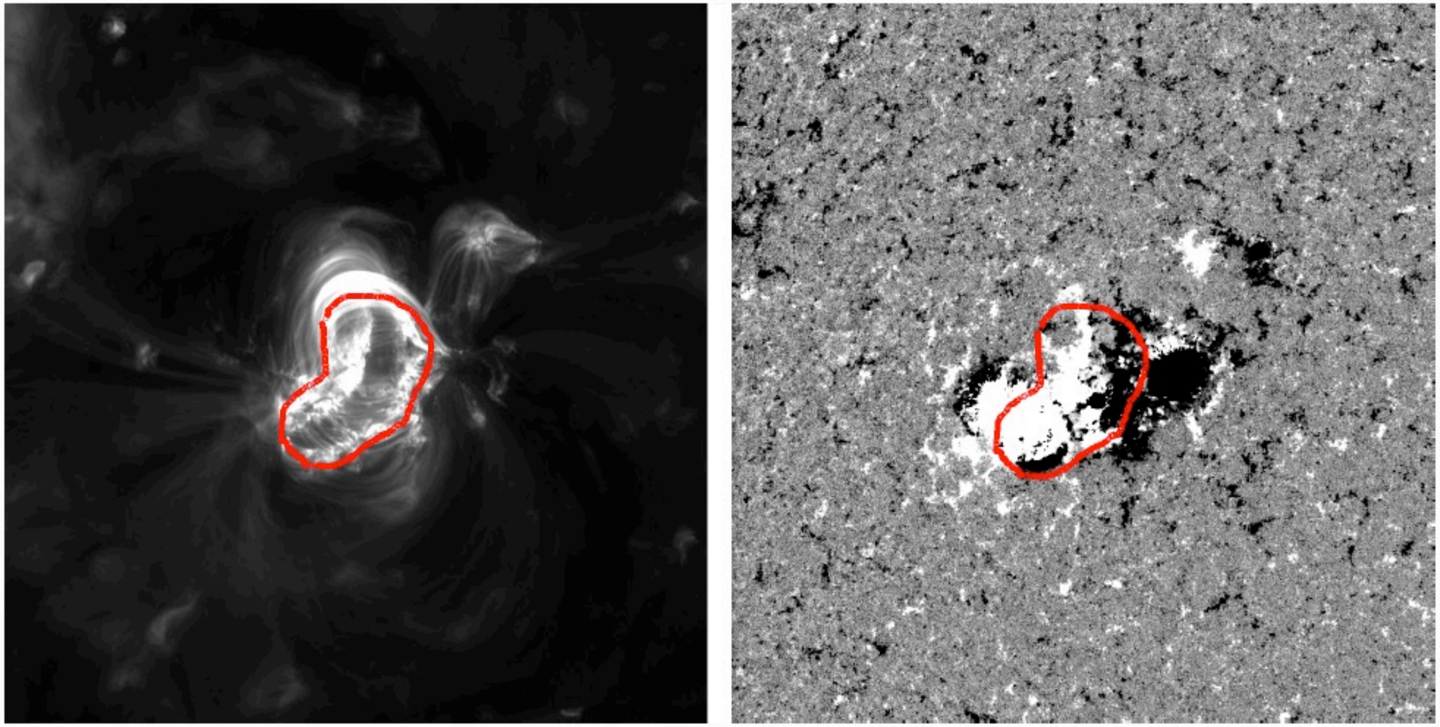
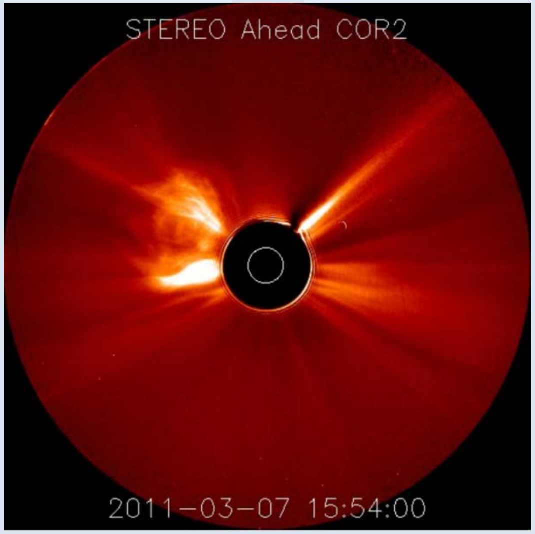
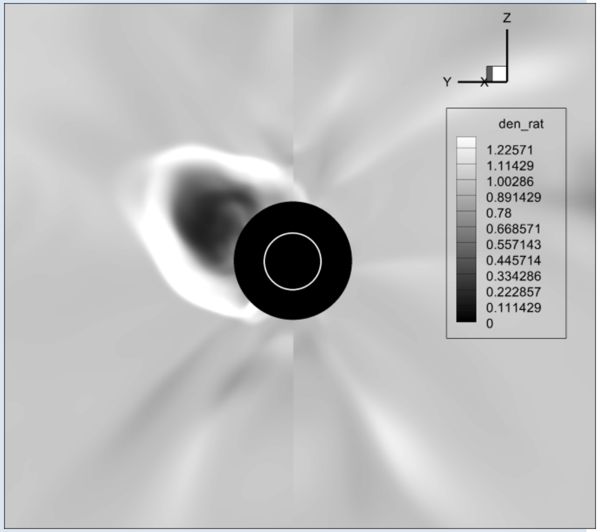


Figure 2. (*left*) Post eruption arcade as seen in SDO AIA 193 imager at 16:21 UT. The area between the footpoints is enclosed by red points. (*right*) The same area is used in pre-eruption SDO HMI LOS magnetogram at 13:00 UT to find reconnected flux. The box size in both frames is 400 Mm.

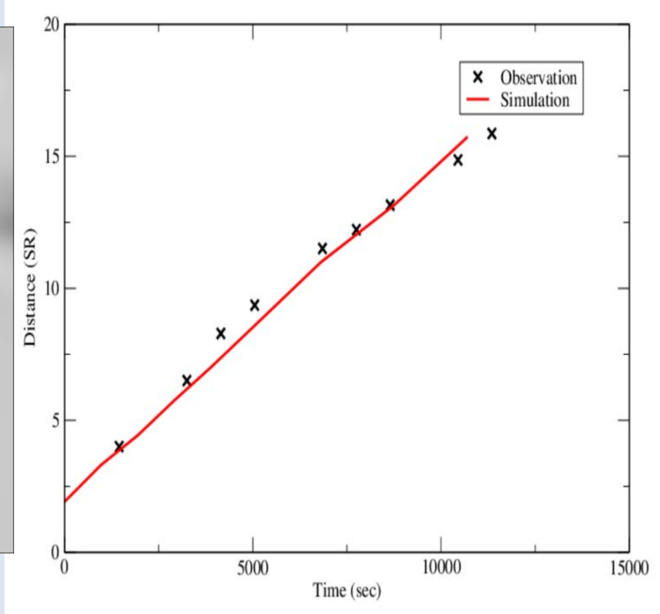
Poloidal flux of CME is measured from the unsigned reconnected flux in the area covered by post eruption arcade (Gopalswamy et. al. 2017)



Observation



Simulation

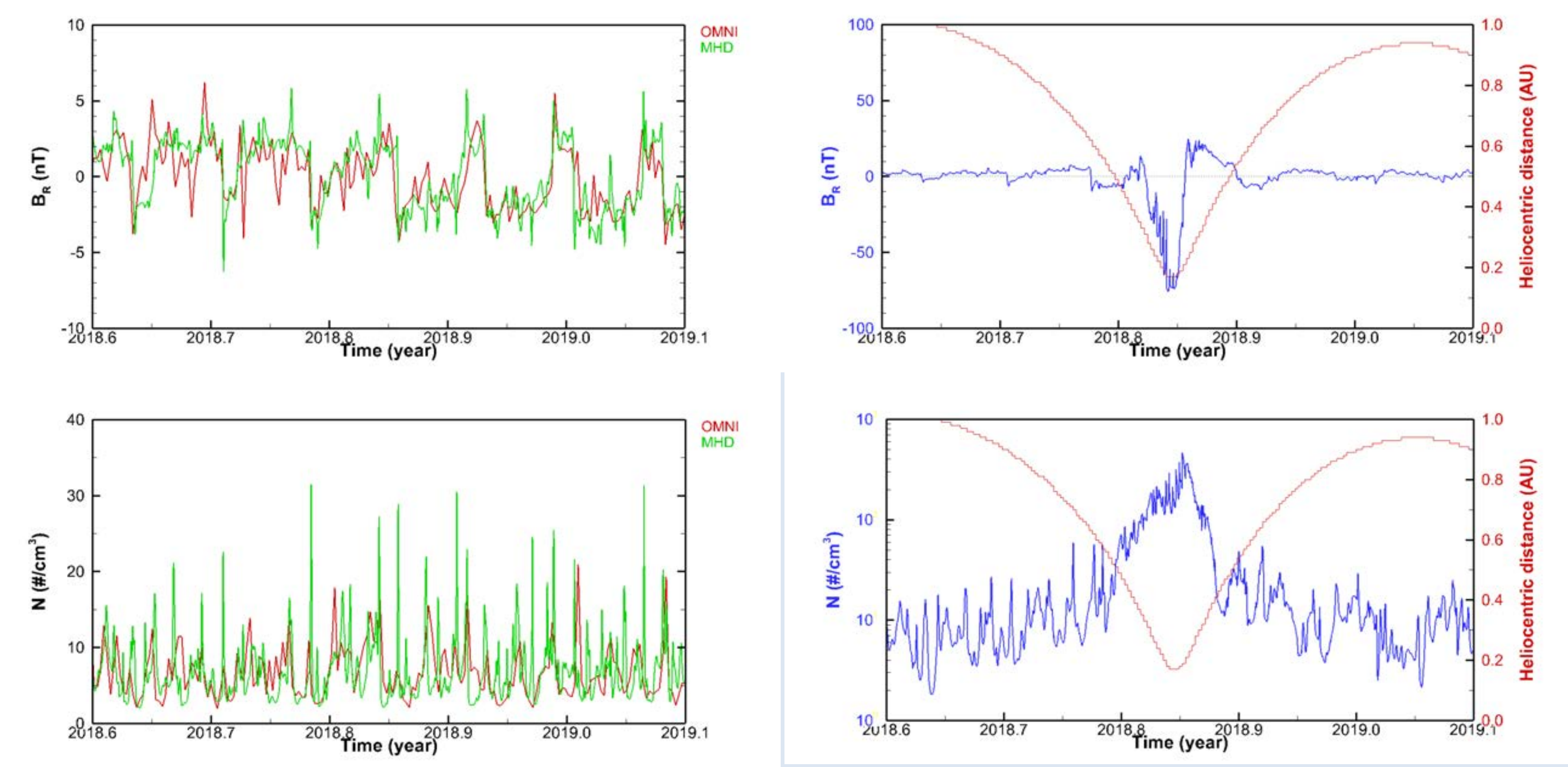


Comparison

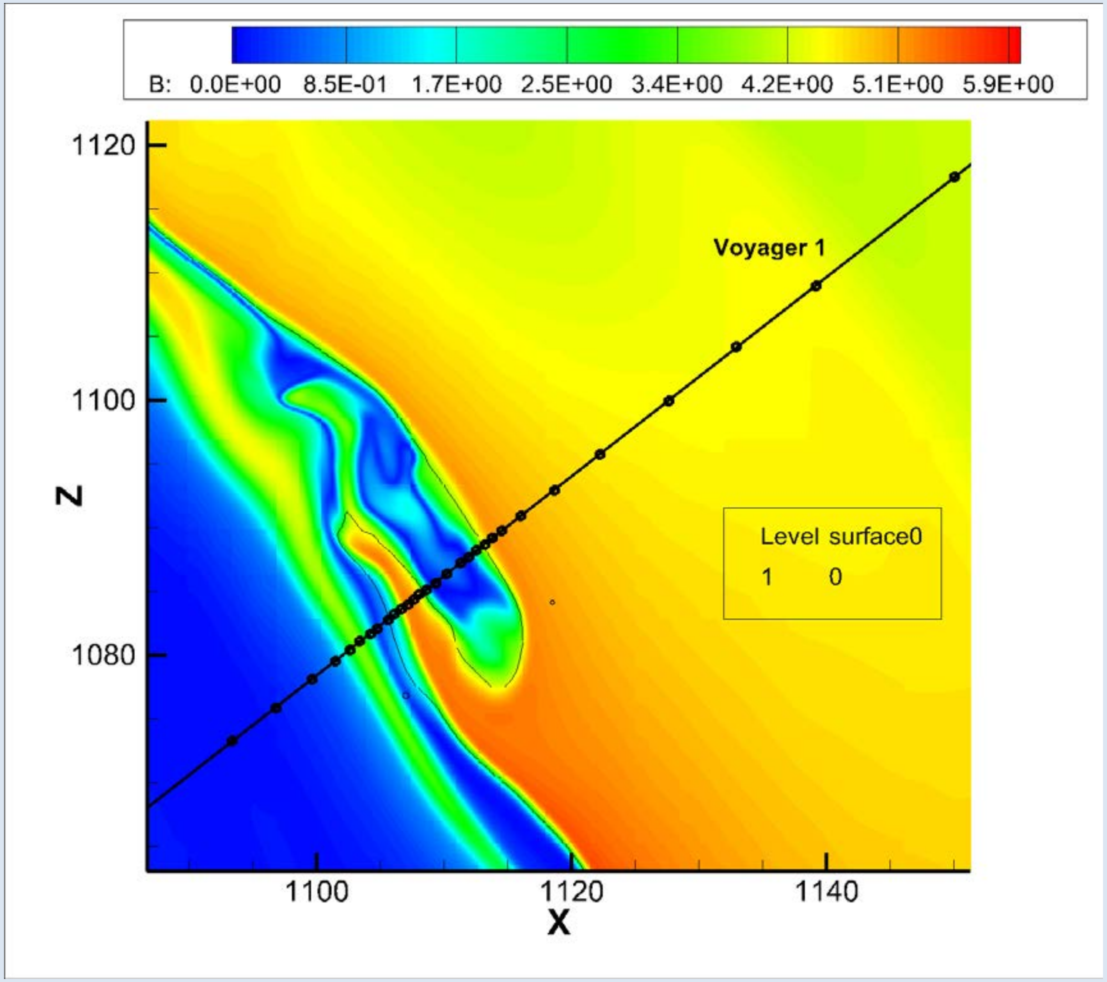
We calculated the 2011-03-07 the CME velocity of 812 km/s. We measured the poloidal flux from post eruption arcade area as 4.85×10^{21} Mx and mass was calculated as 3.86×10^{15} g.

For above values, we found that using a1, r0, r1 and a as 2.51, 0.52, 1.34, and 0.14, respectively, we actually simulate a CME with speed 897 Km/s, poloidal flux 4.90×10^{21} Mx, and mass of 3.84×10^{15} g.

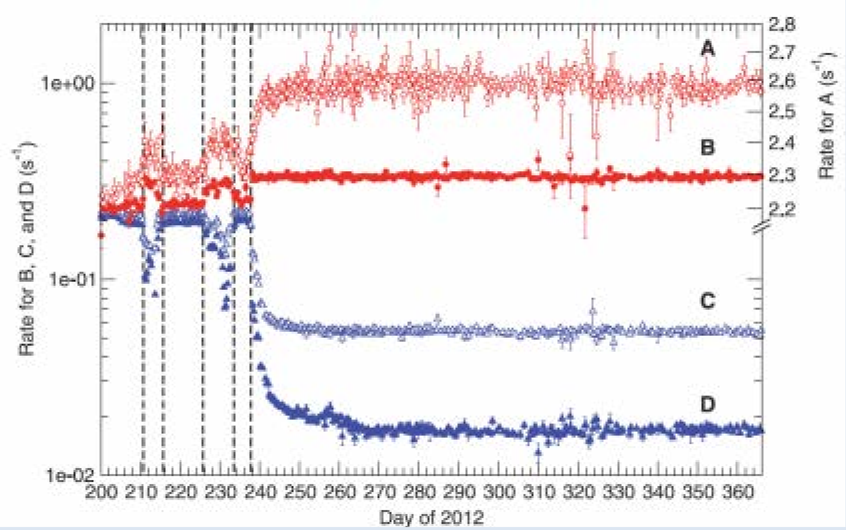
Solar wind simulations along the PSP trajectory governed by the WSA/ADAPT boundary conditions at 25 solar radii



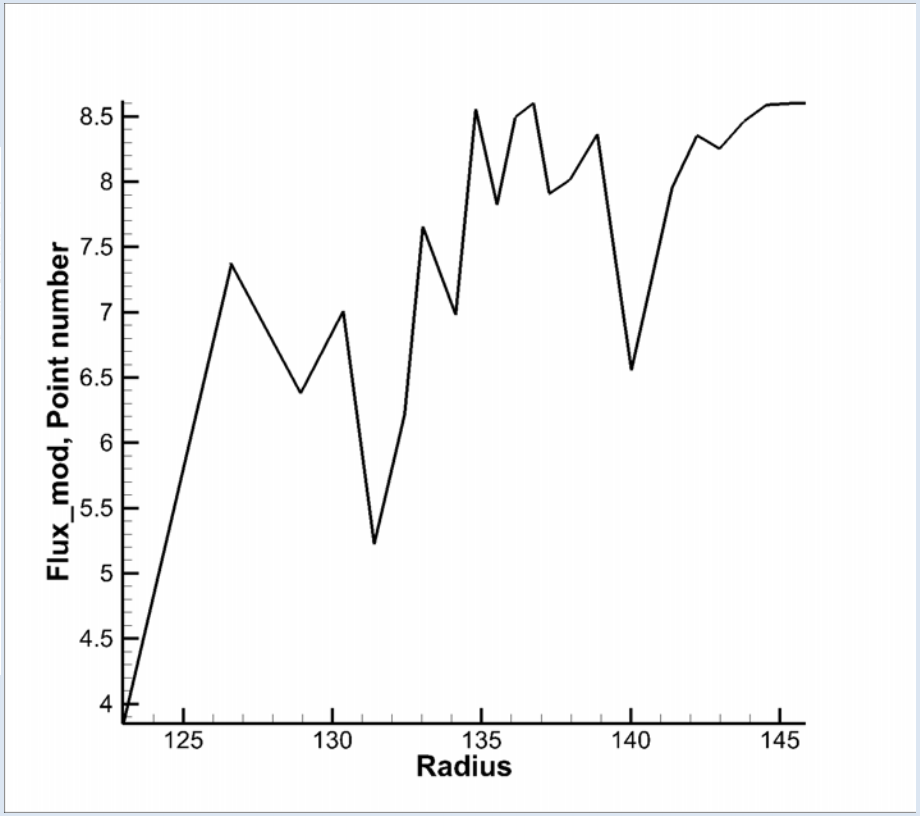
The heliopause – the boundary between the heliosphere and LISM – is unstable to KH and RT instabilities. Occasional magnetic reconnection is also possible.



Measured and simulated GCRs with E > 70 MeV

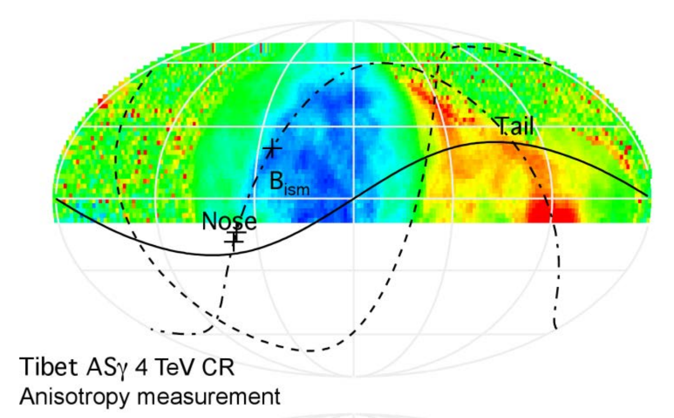


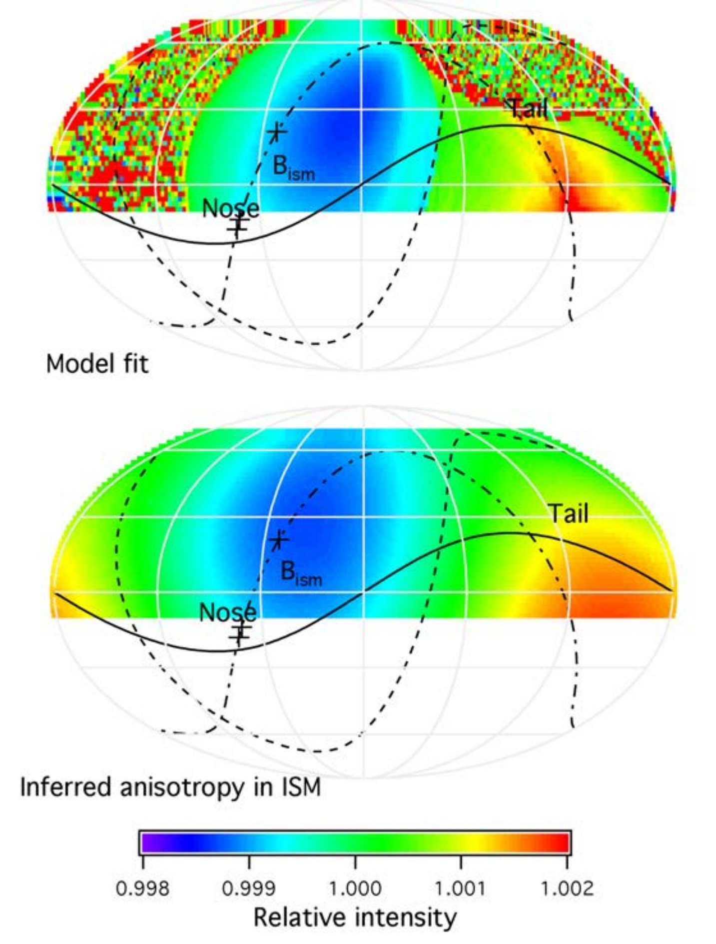
GCRs (predominantly protons)with energies exceeding 70 MeV measured by Voyager 1 (red lines). [From Stone et al., 2013)



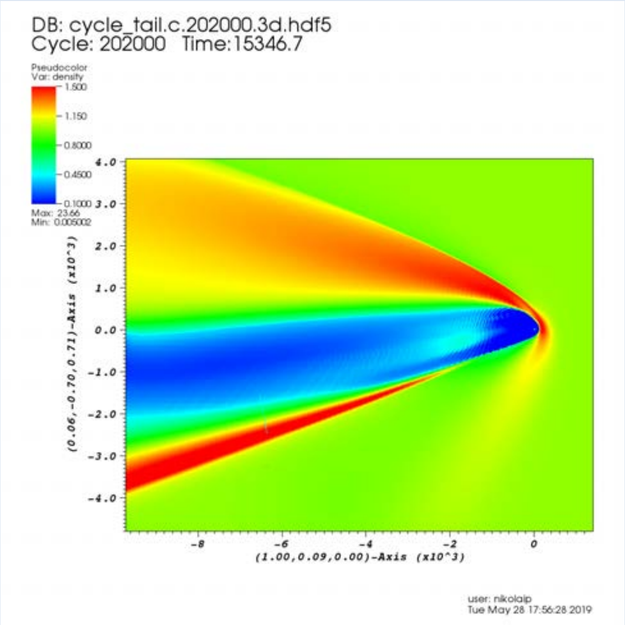
Simulations demonstrate that the changes in the GCR flux may be due to instabilities near the heliopause.

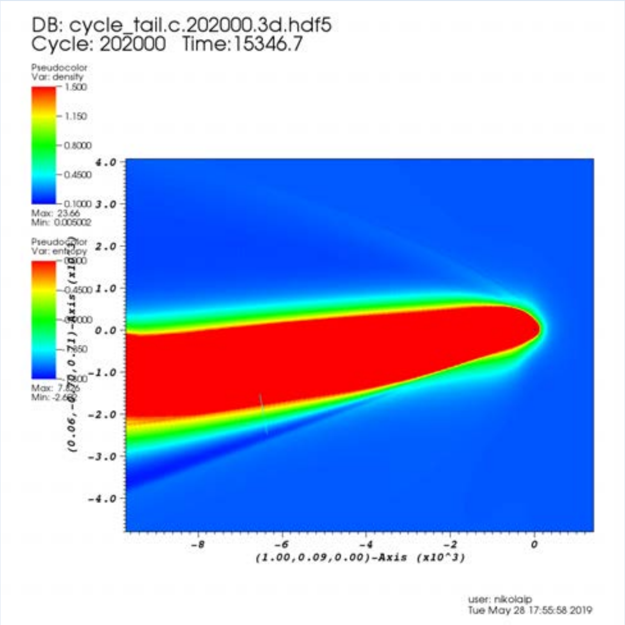
TeV Cosmic Rays Anisotropy





The heliosphere clearly affects the flux of 1-10 TeV cosmic rays. This feature has been overlooked by astrophysicists for years. It appears that the heliotail and the B-V plane are prominently seen on the all-sky maps.





New discontinuities have been identified on the B-V plane.

The particles spread from the source primarily along the magnetic field while experiencing a nearly isotropic pitch-angle scattering by its fluctuations. The heliosphere generates small-scale anisotropies off the dipole, contributing a significant fraction of high-order multipoles that make up complex patterns in the observations.

The GCR density gradient points towards Vela as an astrophysical source of the anisotropy.

Why Blue Waters?

To analyze the stability of the heliopause and magnetic reconnection in turbulent plasma, we should perform simulations with the local resolution 5 – 6 orders of magnitude smaller than the size of our typical computational region.

Heliotail simulations additionally require very large computational regions, while Monte Carlo modeling produces very large data sets (each ~ 2-5 Tb) in time-dependent MHD-kinetic simulations.

Broader impacts

The development of codes that embrace “coupling complexity” via the self-consistent incorporation of multiple physical scales and multiple physical processes in models is viewed as a pivotal development in the different plasma physics areas for the current decade.

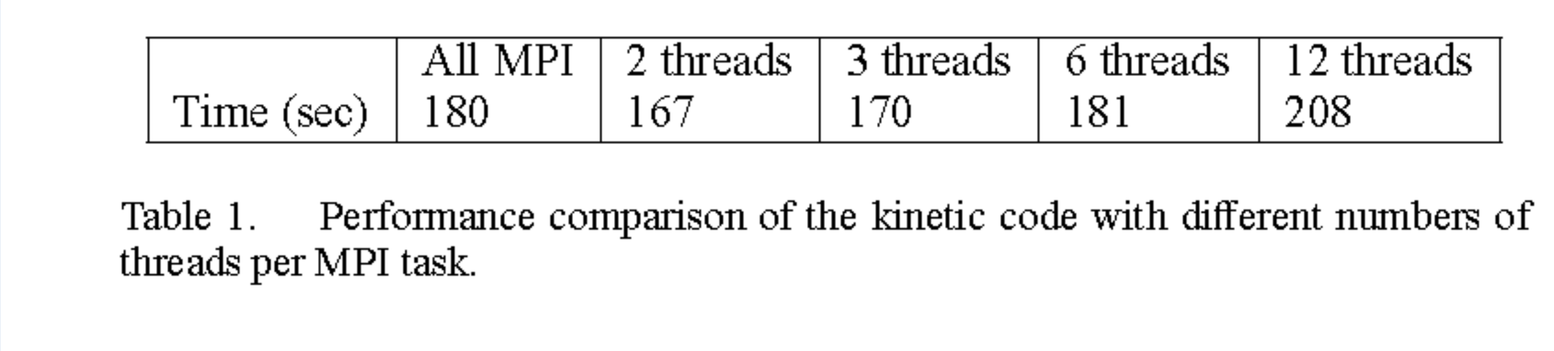
Blue Waters support

We greatly acknowledge support from all people on the Blue Waters team. BW pioneered an individual approach to users’ needs. We got help with code porting, scaling, and even occasional debugging. Whether it was a scheduling or visualization support, it was always provided in a highly professional and efficient manner. The experience of BW will always be an example for future supercomputing centers.

THANK YOU GUYS!

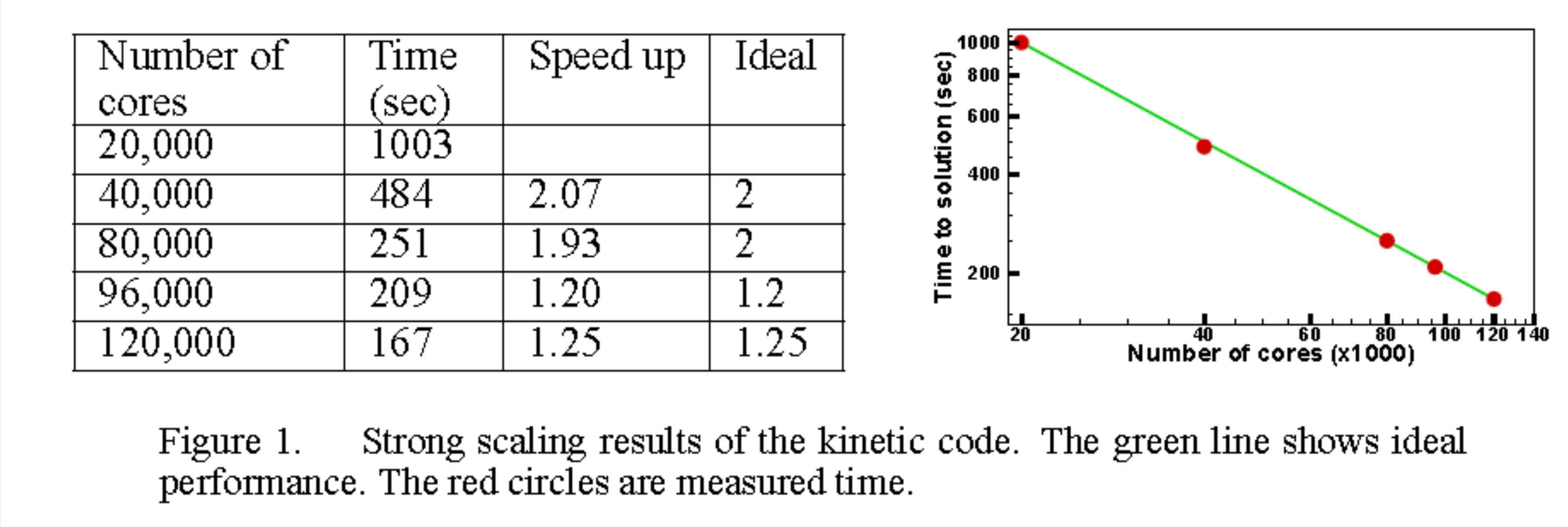
SEE YOU SOON AT OTHER SUPERCOMPUTING AND MODELING MEETINGS!

Code parallelization



	All MPI	2 threads	3 threads	6 threads	12 threads
Time (sec)	180	167	170	181	208

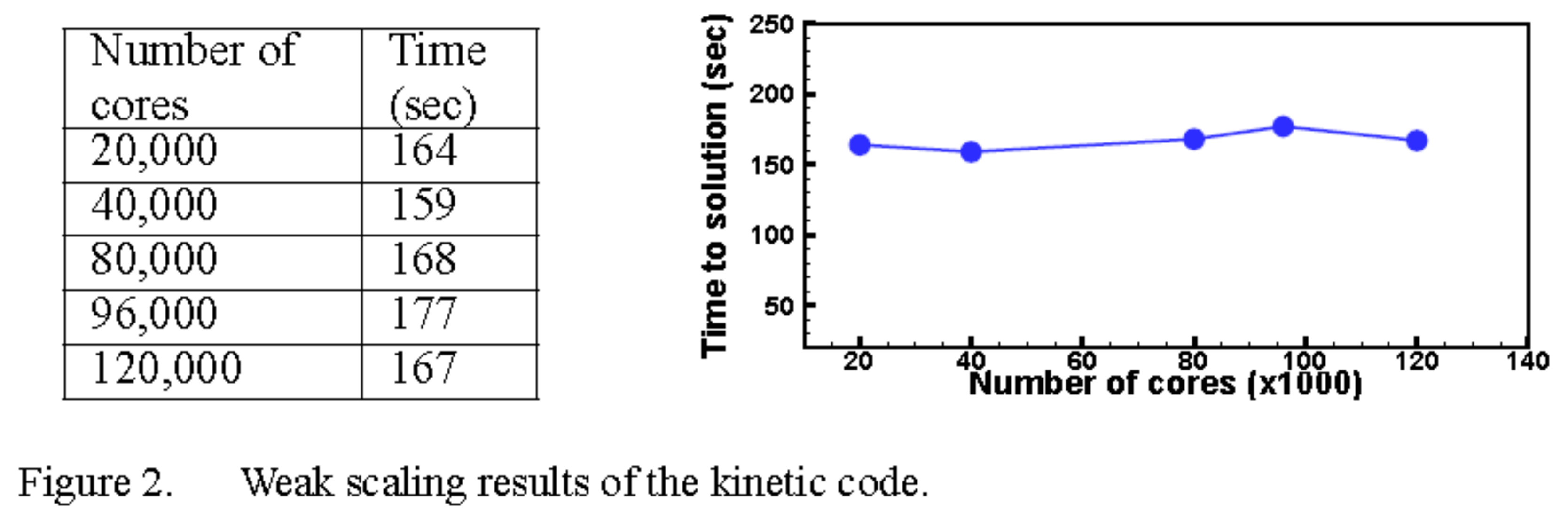
Table 1. Performance comparison of the kinetic code with different numbers of threads per MPI task.



Number of cores	Time (sec)	Speed up	Ideal
20,000	1003		
40,000	484	2.07	2
80,000	251	1.93	2
96,000	209	1.20	1.2
120,000	167	1.25	1.25

Figure 1. Strong scaling results of the kinetic code. The green line shows ideal performance. The red circles are measured time.

Parallelization (continued)



Number of cores	Time (sec)
20,000	164
40,000	159
80,000	168
96,000	177
120,000	167

Figure 2. Weak scaling results of the kinetic code.

A 650Gb data file containing 10 billion particles (full 64-bit support is necessary) can be written as fast as 32 seconds on Lustre file system if it is striped over 100 Object Storage Targets (OSTs).