Simulations of Solar Wind Evolution

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CENTER FOR SPACE PLASMA AND AERONOMIC RESEARCH AND THE DEPARTMENT OF SPACE SCIENCE

New Horizons STM #54
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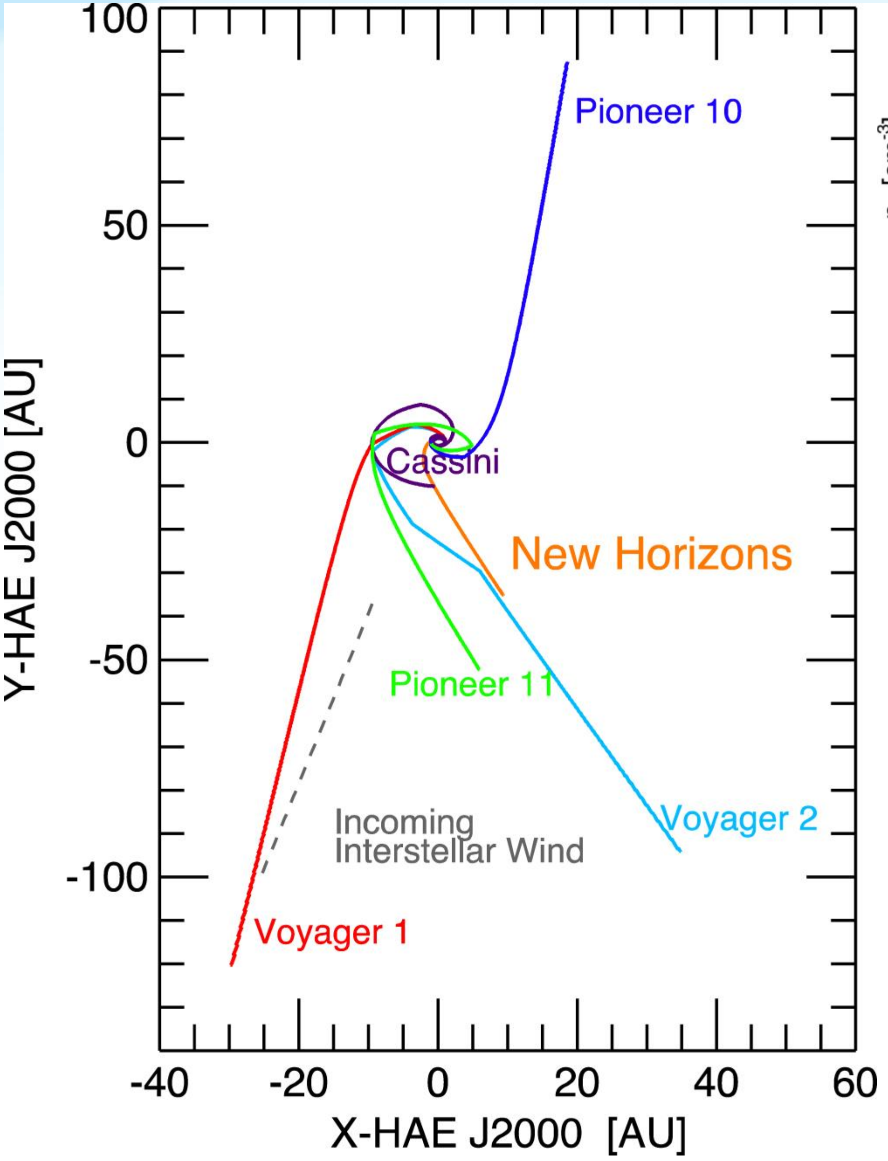
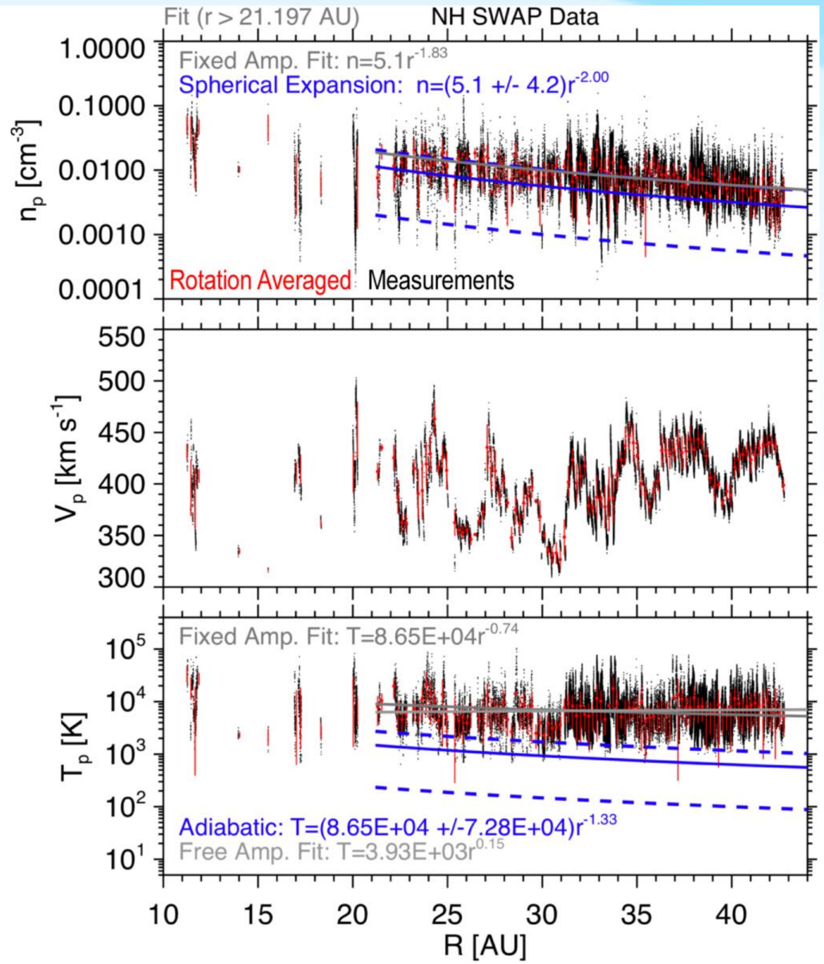
New Horizons in the Outer Heliosphere





Elliott et al. 2016, ApJS, 223, 19; 2019, ApJ, 885, 156

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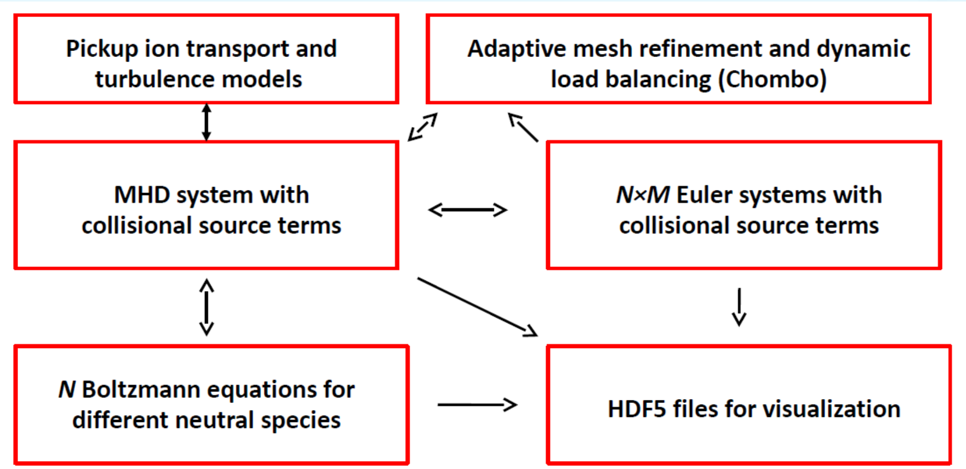
Modeling Software: Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS)

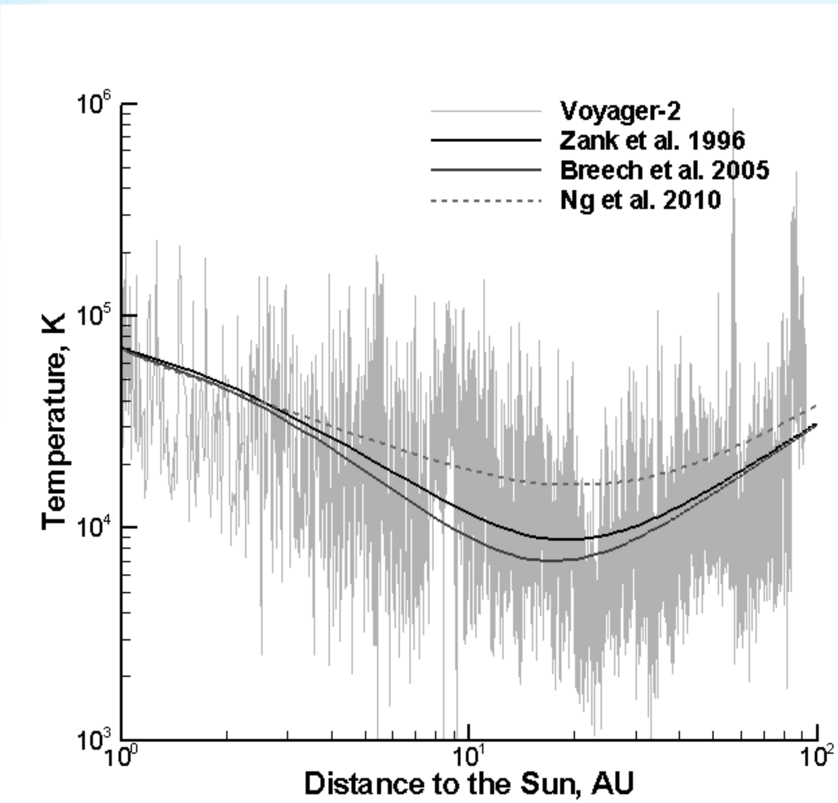
- A package of numerical codes designed at UAH/CSPAR to model the **heliosphere in multiple scales and resolution** (Pogorelov et al. 2014, XSEDE, 22)
- **Adaptive mesh refinement** based on Chombo architecture (Colella et al. 2007, JPCS, 78, 012013) for computational efficiency
- Scalable to >160,000 cores and portable across multiple computational platforms
- **MHD** treatment for solar wind/interstellar plasma and **fluid** treatment for neutral atoms (1, 2, 4, or 5 fluids) (Pogorelov et al. 2008, ASP, 385, 180)



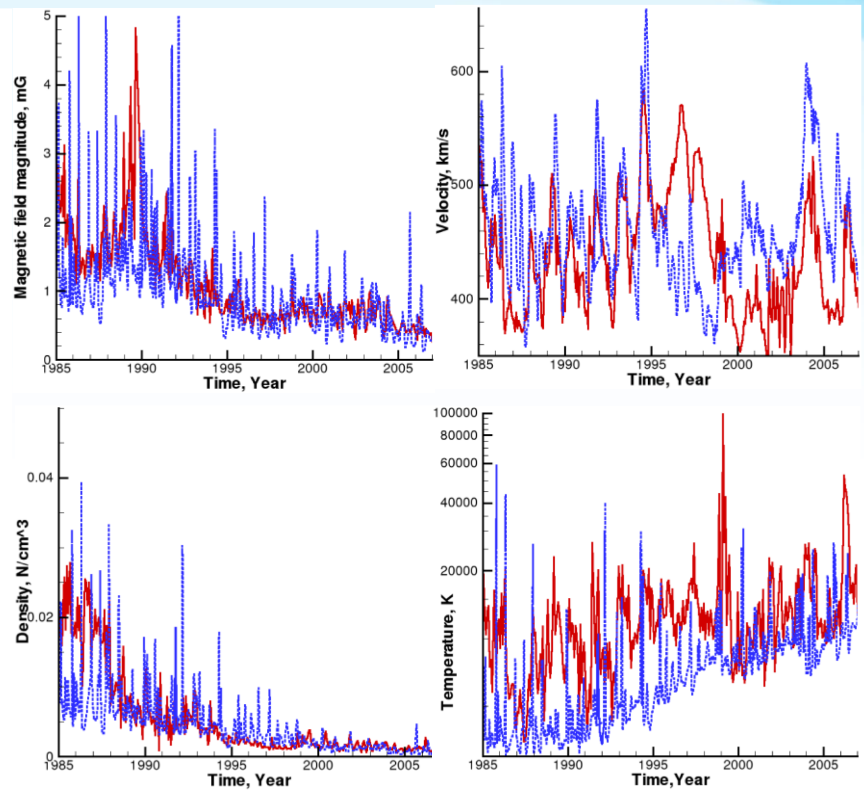
Block diagram of MS-FLUKSS

- **MHD** treatment for solar wind/interstellar plasma and **kinetic** treatment for neutral atoms (Pogorelov et al. 2008, ASP, 385, 180; Borovikov et al. 2008, ASP, 385, 197; Heerikhuisen et al. 2008, ASP, 385, 204; Fraternale et al. 2021, ApJL, 921, L24)
- **Turbulence** models for super-Alfvenic solar wind (Pogorelov et al. 2012, AIP, 1500, 134; Kryukov et al. 2012, AIP, 1436, 48)
- Data extraction at static points or along trajectories of spacecraft/planets
- Time-dependent solar wind model driven by realistic boundary conditions (Kim et al. 2014, JGR, 119, 7981; Kim 2016, ApJ, 832, 72; Kim et al. 2017, ApJL, 843, L32; Kim et al. 2020, ApJS, 246, 40)
- Observationally-constrained Flux-rope CMEs for space weather applications (e.g., Singh et al. 2020, Space Weather, 18, 2405)

Turbulence Models in MS-FLUKSS



Comparison of the solar wind temperature measured by *V*oyager 2 with MS-FLUKSS simulations using different turbulence models (Pogorelov et al. 2012, AIP, 1500, 134)



3D time-dependent MHD-plasma and fluid neutral H and pickup ions with Breech et al. (2008) turbulence model using spherically-symmetric OMNI data at the inner boundary of 1 AU compared with Voyager 2 data (Kryukov et al. 2012, AIP, 1436, 48)

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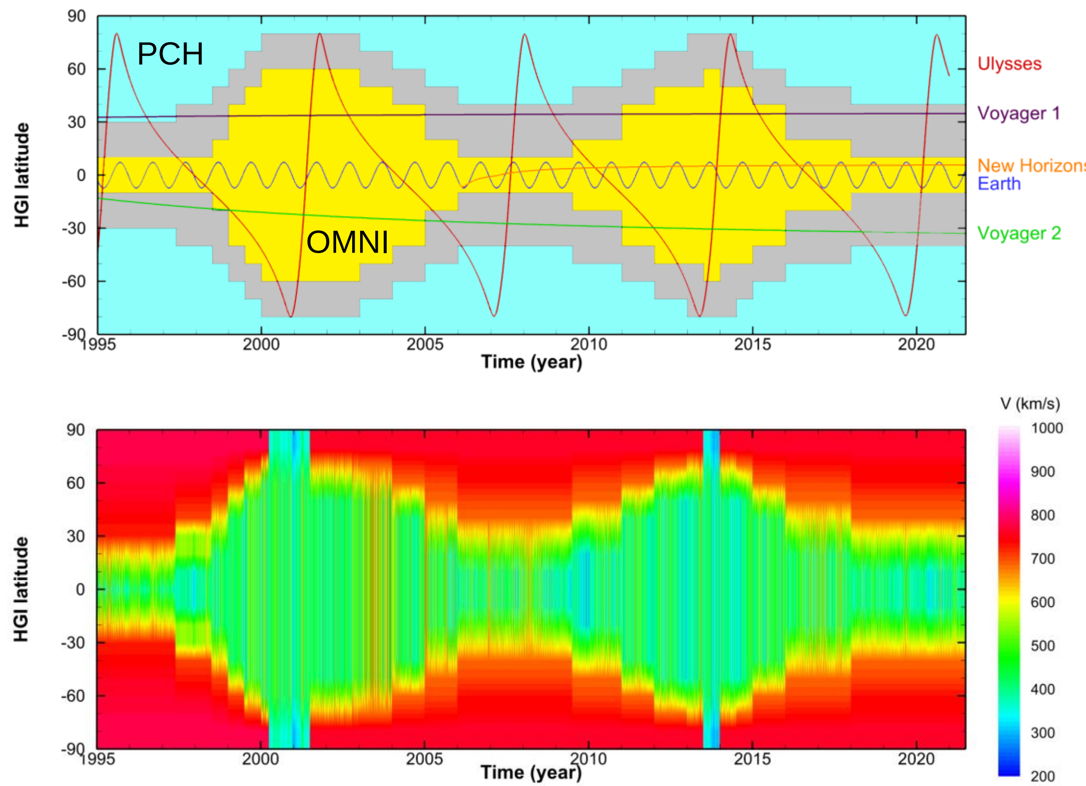
Time-varying Boundary Conditions at 1 AU

- Assumption of corotating solar wind using +/-13 days of OMNI data to fill the 360^o longitude space in the equatorial region whose latitudinal extent varies with time
- Polar coronal holes (PCHs) centered at the poles and varying in size with time are designed to best match Ulysses data at high latitudes
- Interplanetary magnetic field components estimated from OMNI |B| data in the form of a Parker spiral
- 27-day averaged tilt of the heliospheric current sheet (HCS) from the Wilcox Solar Observatory to construct a time-varying tilted dipole magnetic field configuration



(Top) Latitudinal extents of OMNI data and PCH regions shown as a function of time; (Bottom) Time series of the solar wind speed at different latitudes

Kim et al. 2016, ApJ, 832,72; 2017, ApJL, 843, L32;
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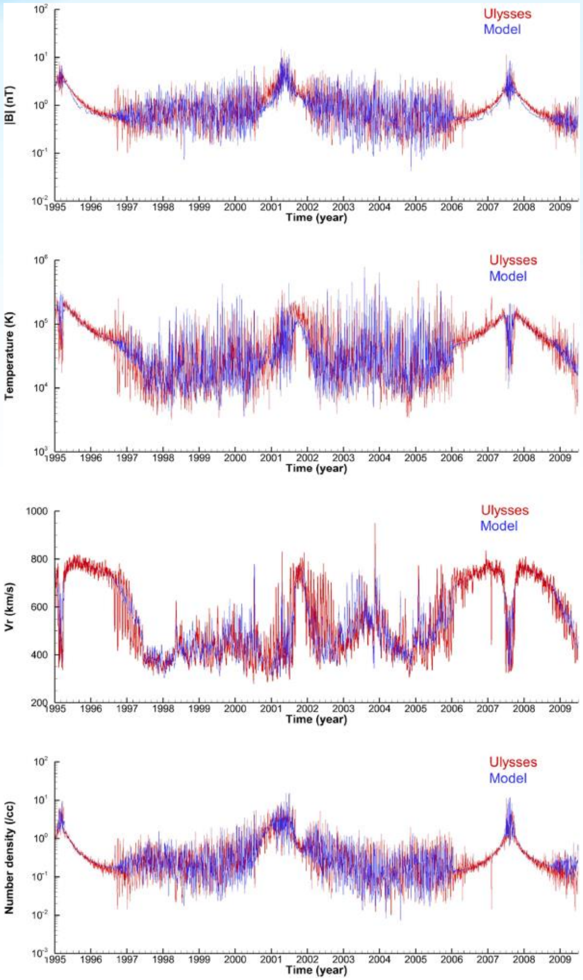
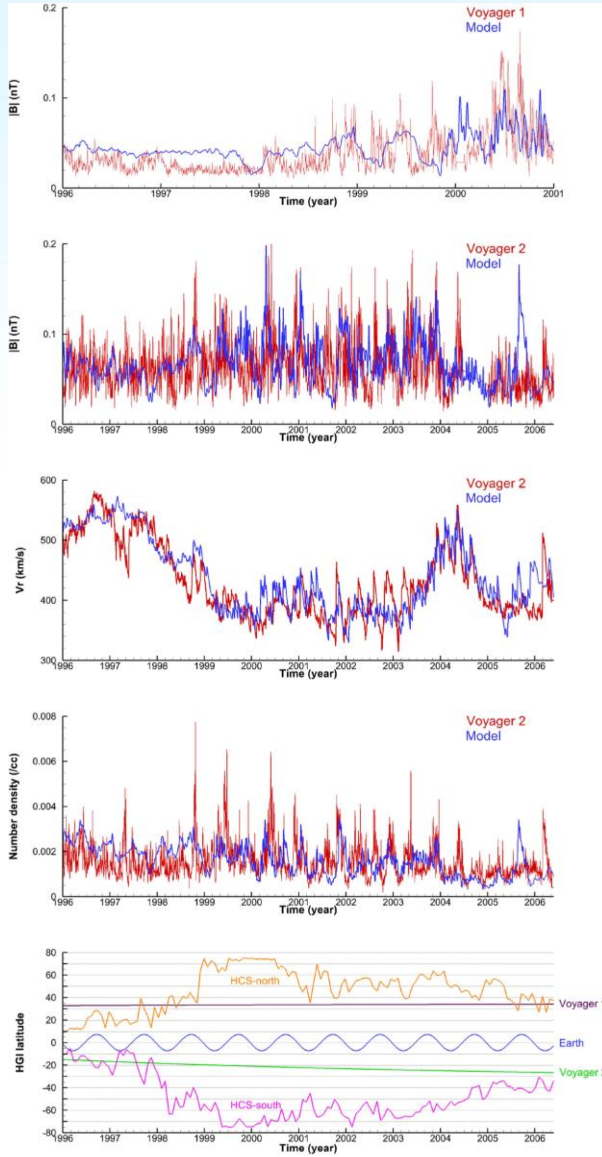
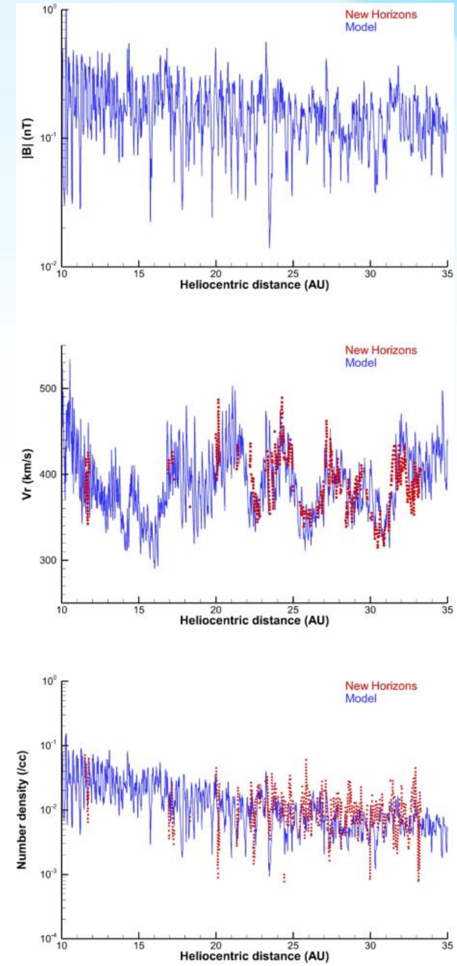
3D Time-dependent MHD-plasma and Fluid-Neutral Model







Kim et al. 2016, ApJ, 832,72

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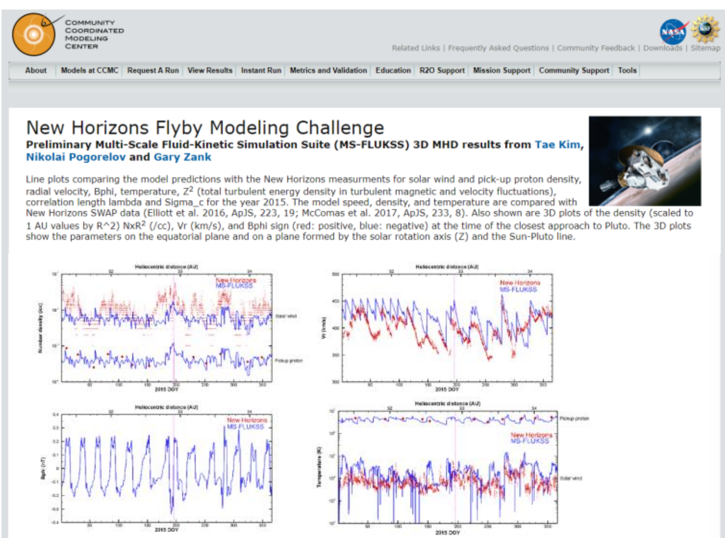
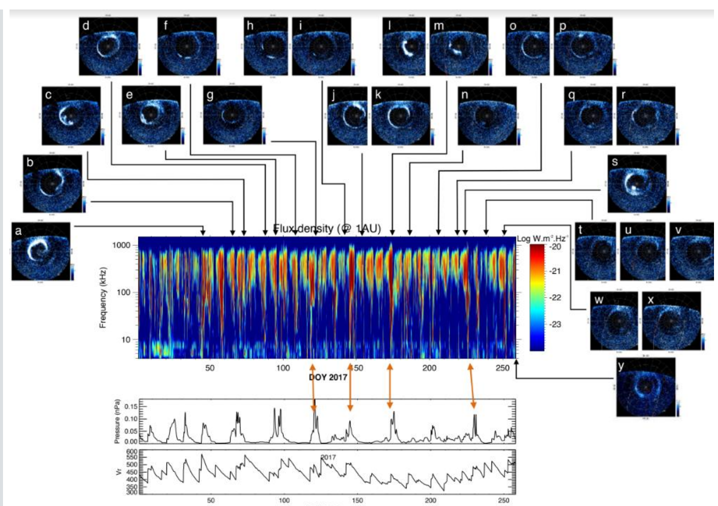
3-Fluid Model (MHD Plasma, Fluid Neutral H and PUI) with Turbulence

- Single-fluid plasma of solar and interstellar origins; Fluid LISM neutral hydrogen atoms
- Fluid interstellar PUI with stream-shear and PUI-driven turbulence in the supersonic solar wind (e.g., Breech et al. 2008, JGR, 113, A08105; Kryukov et al. 2012, AIP, 1436, 48)
- 3D time-dependent simulation between 1 and 80 AU
- First results posted on CCMC New Horizons Flyby Modeling Challenge (bottom left plot) and also shown at the 2017 AGU Fall Meeting (Abstract SH23C-2671, https://doi.org/10.1002/essoar.b60497724eca58de.7c985d5380f54d2b.1)
- High-resolution simulation to predict the arrival of interplanetary shocks at Saturn (bottom right plot) and Uranus to support UV observations of aurorae using the Hubble Space Telescope (Lamy et al. 2017, JGR, 122, 3997; 2018, GRL, 45, 9353)





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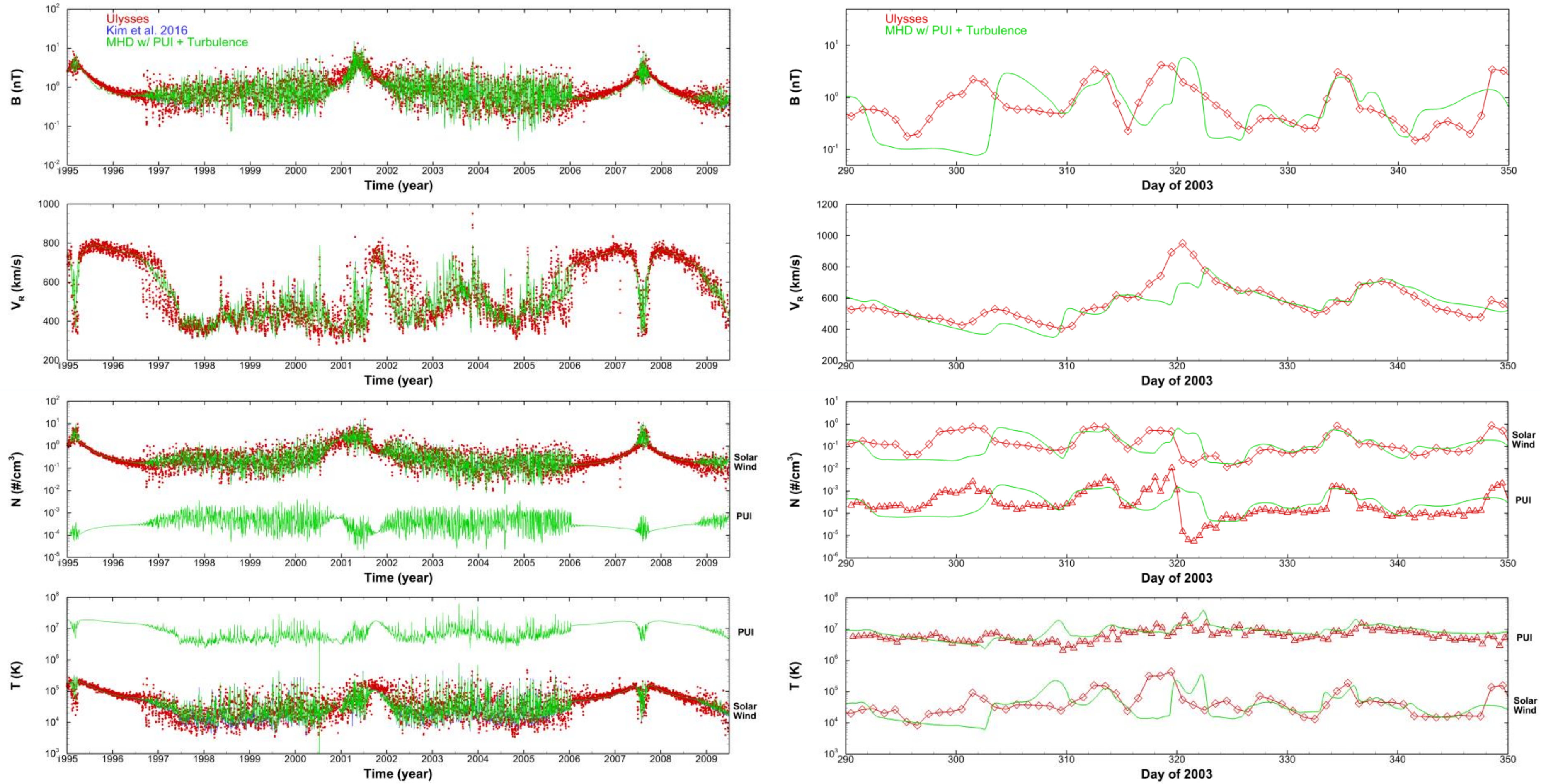
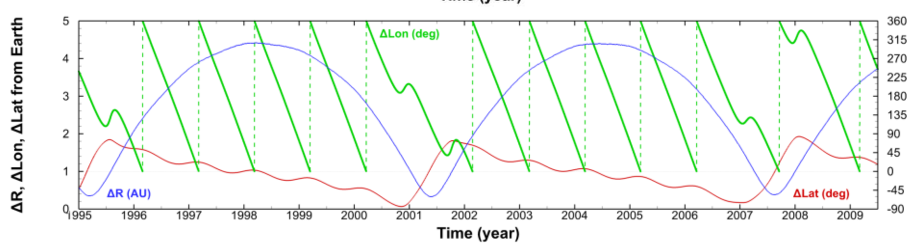
Comparison at Ulysses





Model interplanetary magnetic field strength, radial velocity, solar wind and interplanetary pickup proton number density, and temperature compared with *Ulysses* data from 1995 to 2009.5 in the left column. The plots in the right column compare the model with *Ulysses/SWOOPS* and *SWICS* data (e.g., Intriligator et al. 2012, JGR, 117, A06104) around the 2003 Halloween event. **Note that the new model assumes the most recent estimate of the interstellar neutral hydrogen density of 0.127 cm^{-3} at the termination shock (Swaczyna et al. 2020, ApJ, 903, 48), in contrast to the 2016 model that assumed 0.09 cm^{-3} at the outer boundary at 80 AU.**

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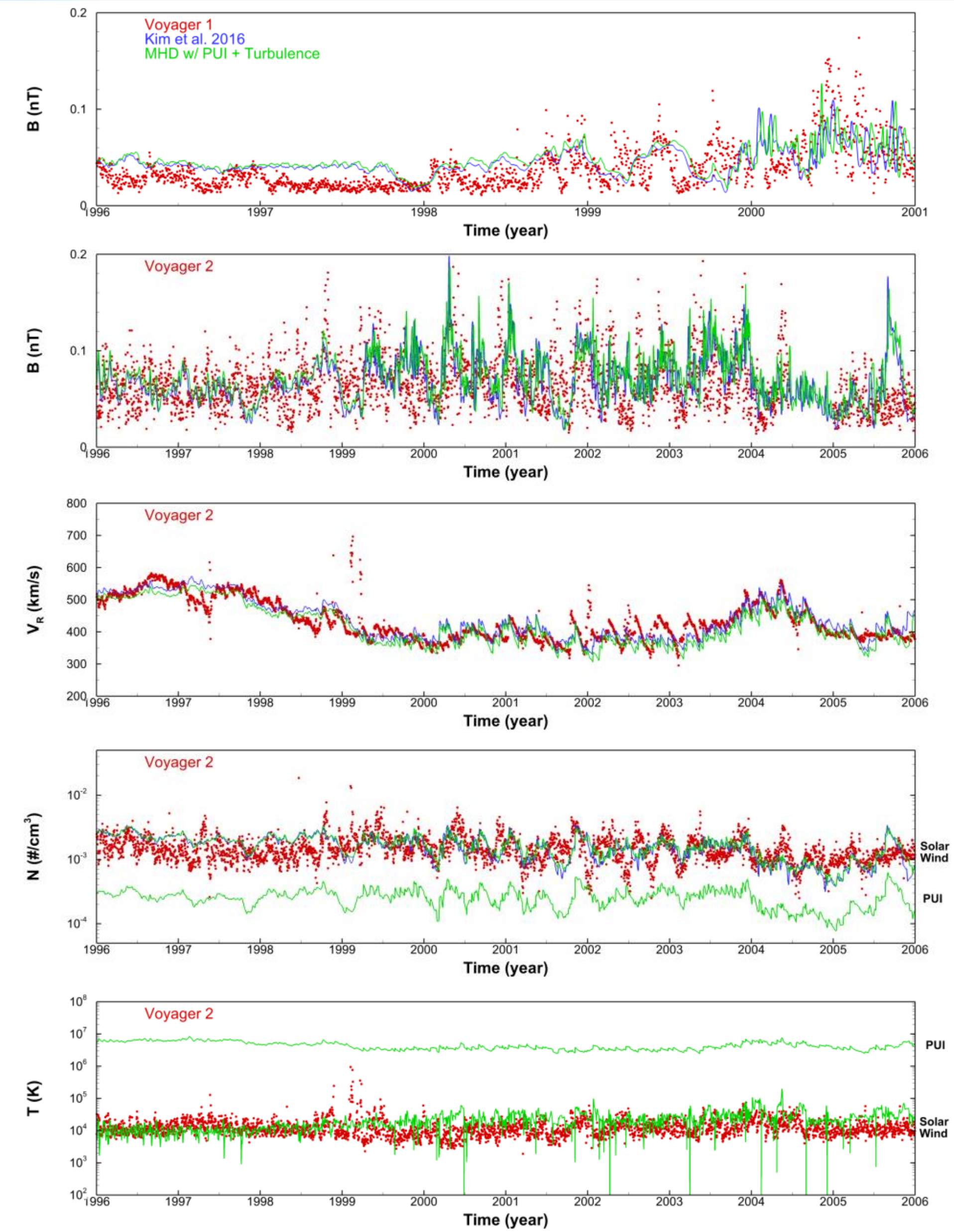
Comparison at Voyager 1 and 2



Simulated interplanetary magnetic field strength (nT) compared with *Voyager 1* and *2* data, proton number density (cm^{-3}), radial velocity (km/s), and temperature (K) compared with *Voyager 2* data

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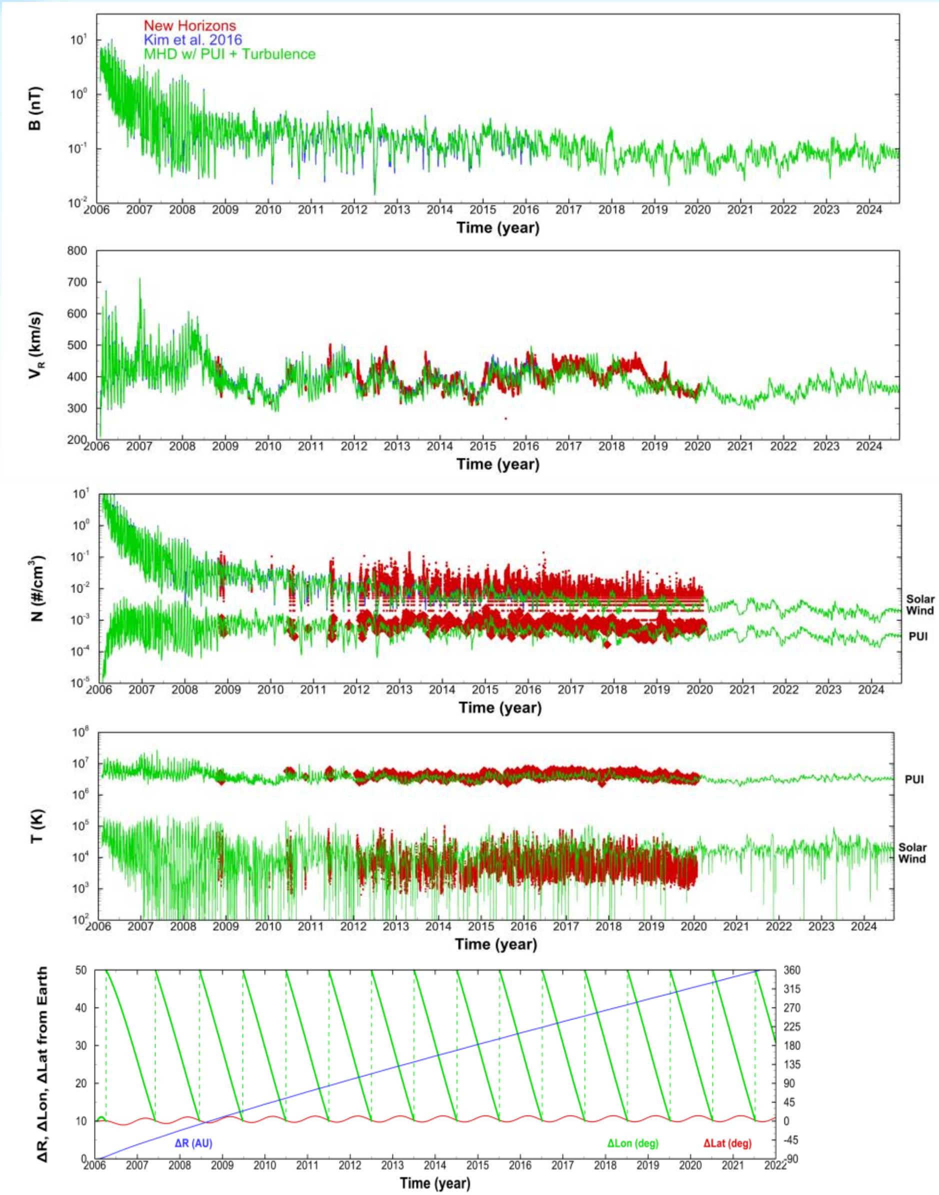
Comparison at New Horizons



Simulated solar wind V_R, N, and T are compared with *NH/SWAP* observations (Elliott et al. 2019, ApJ, 885, 156). Model interstellar pickup proton density and temperature are also compared with *NH/SWAP* observations (McComas et al. 2021, ApJS, 254, 19). Solar wind predictions for late 2023 to mid 2024 were made based on OMNI data at the end of September 2023.

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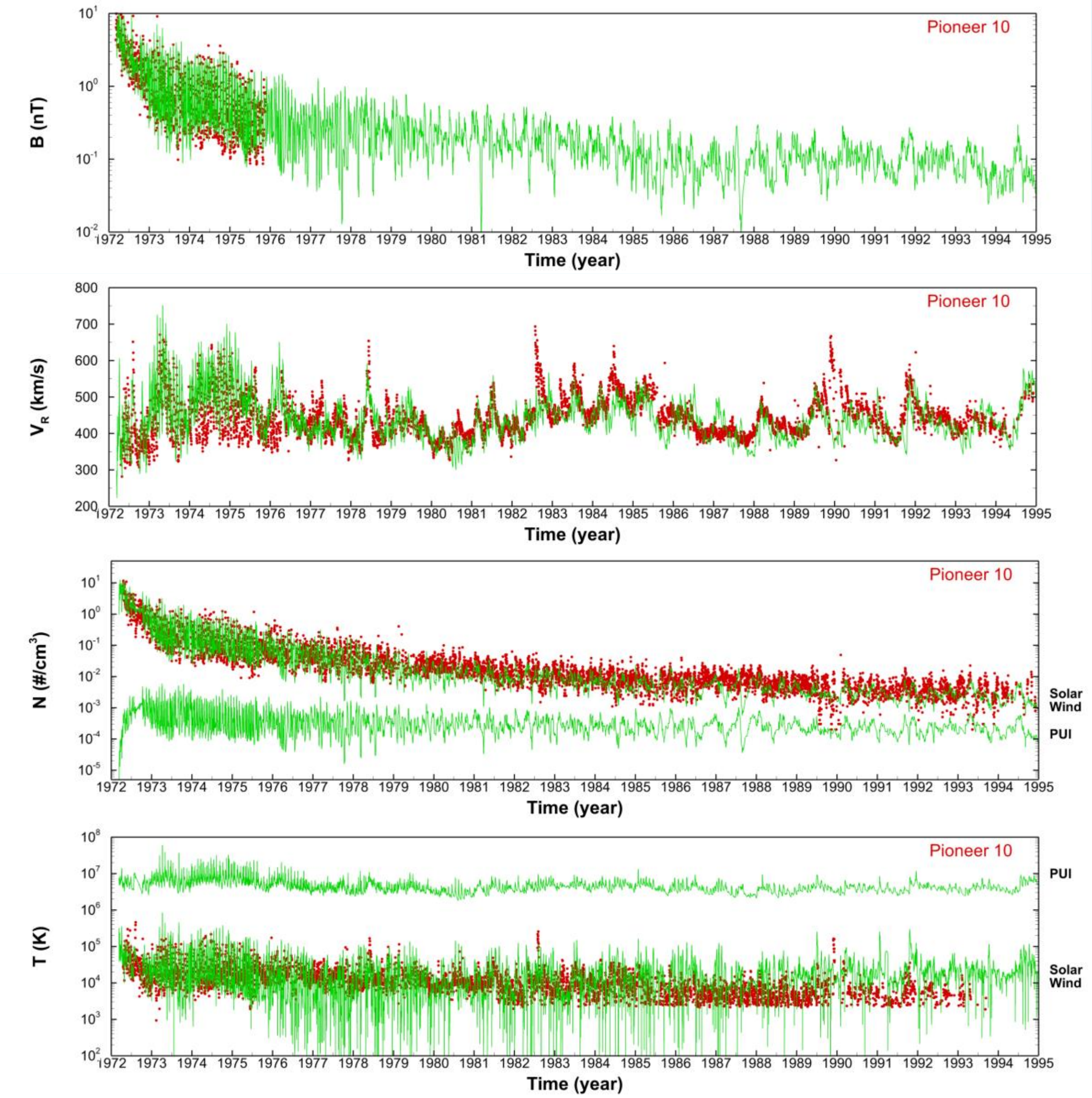
Extended Results at Pioneer 10



Simulated B and solar wind V_R, N, and T (green) are compared with *Pioneer 10* observations (red) from 1972 to 1995. Model interstellar pickup proton density and temperature are also shown in the bottom two plots.

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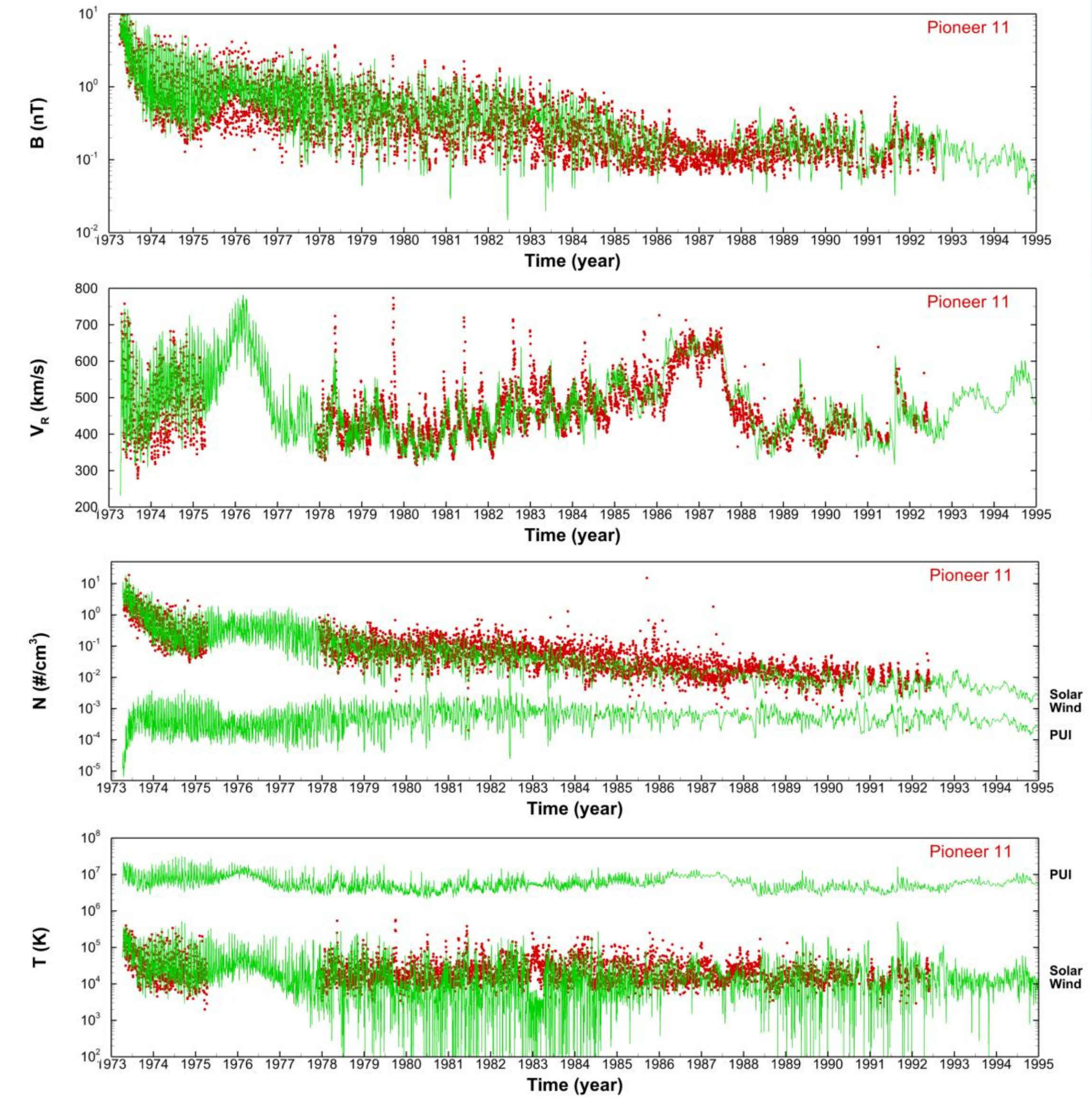
Extended Results at Pioneer 11



Simulated B and solar wind V_R, N, and T (green) are compared with *Pioneer 11* observations (red) from 1973 to 1992. Model interstellar pickup proton density and temperature are also shown in the bottom two plots.

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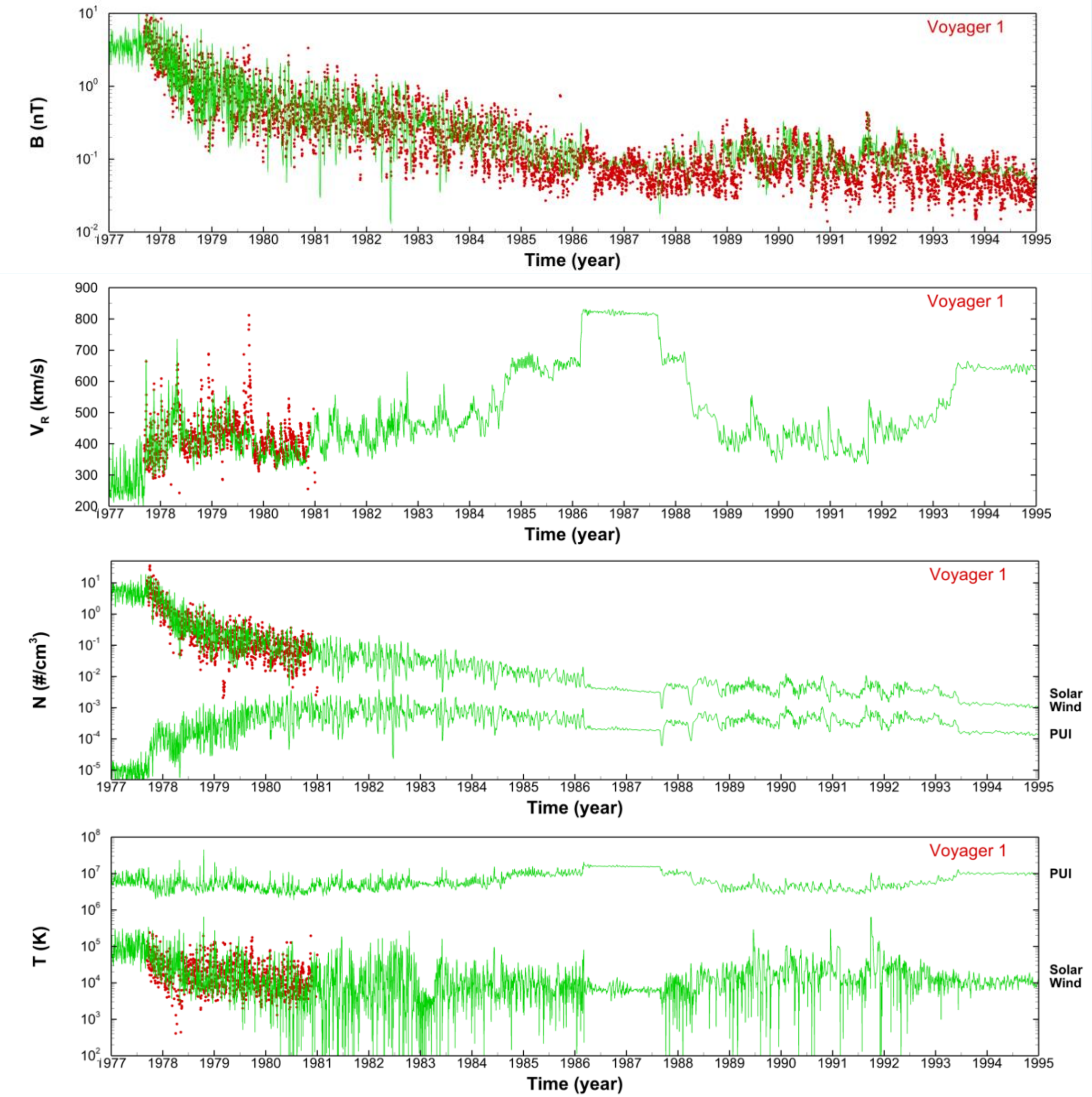
Extended Results at Voyager 1



Simulated B and solar wind V_R, N, and T (green) are compared with *Voyager 1* observations (red) from 1977 to 1995. Model interstellar pickup proton density and temperature are also shown in the bottom two plots.

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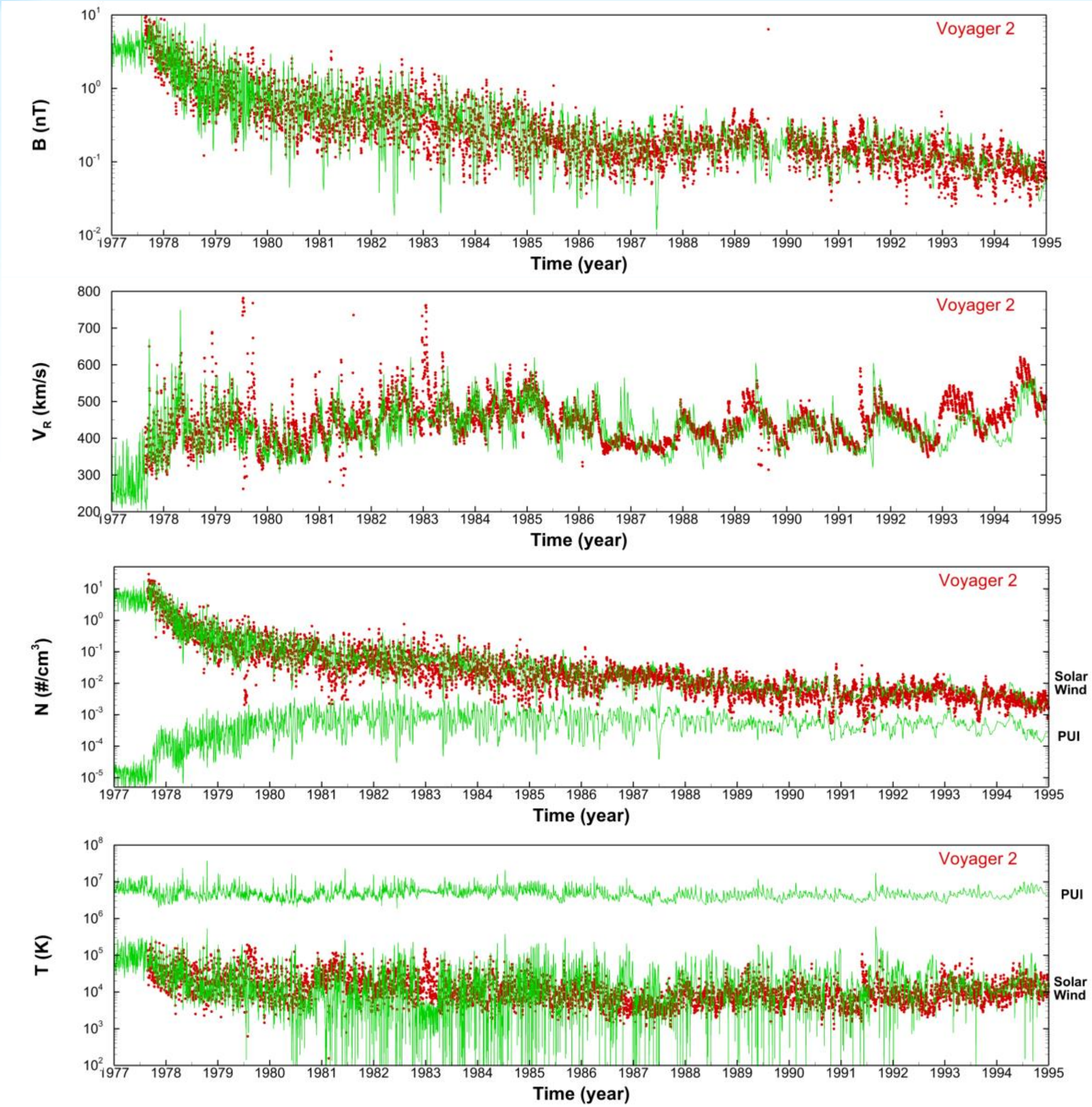
Extended Results at Voyager 2



Simulated B and solar wind V_R, N, and T (green) are compared with *Voyager 2* observations (red) from 1977 to 1995. Model interstellar pickup proton density and temperature are also shown in the bottom two plots.

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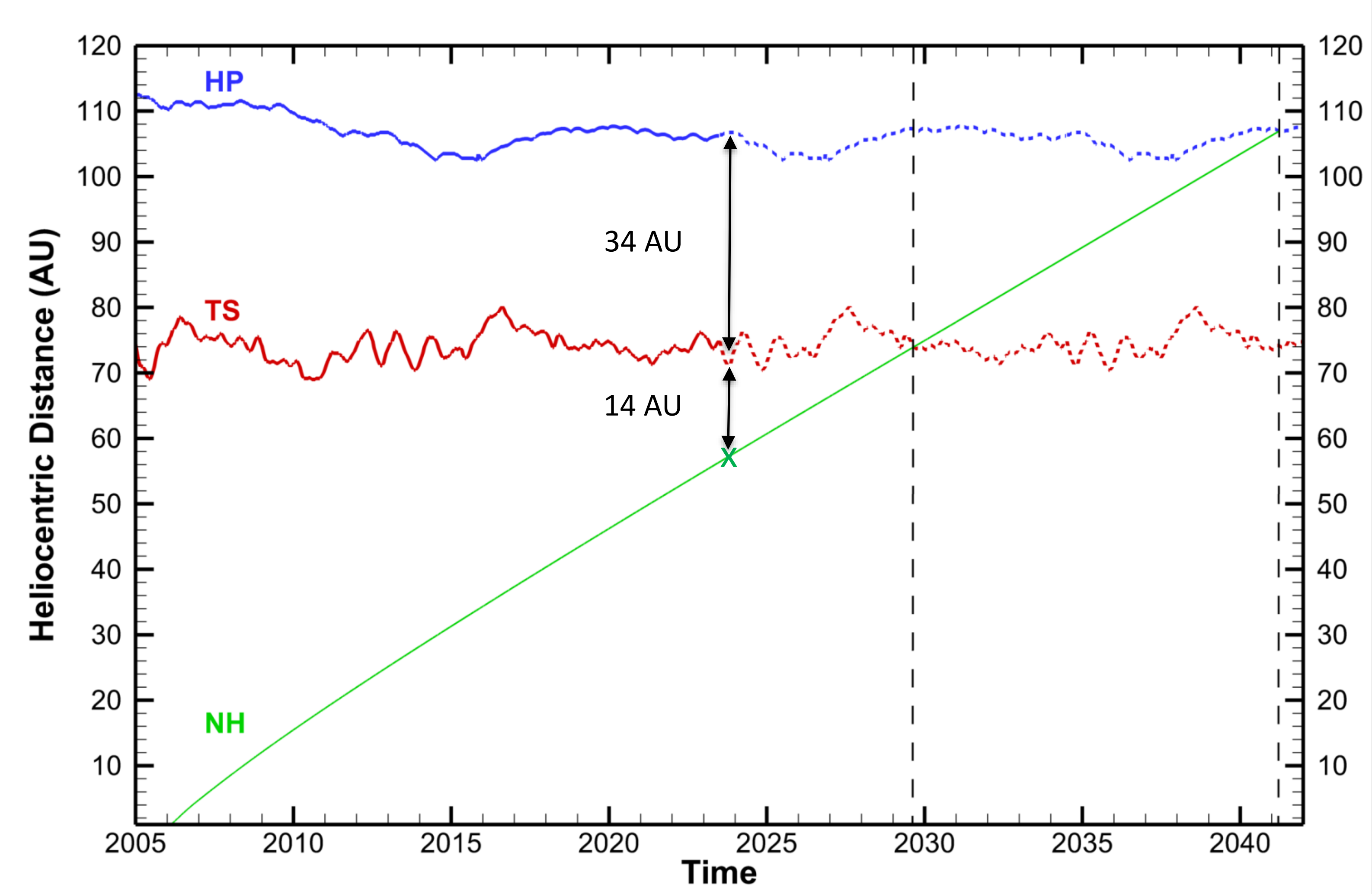
When will NH reach the TS?



TS and HP positions on the Sun-NH line shown as a function of time, based on the Kim et al. (2017) model. The dashed lines after 2023 assume recurring solar wind conditions for the next two solar cycles.

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Summary and Discussion

- 3D multi-fluid simulation of the solar wind, interstellar pickup ions, and turbulence between 1 and 80 AU by solving the Reynolds-averaged MHD equations
- Time-varying boundary conditions from OMNI data at low-to-mid heliographic latitudes
- Latitudinal extent of the OMNI-driven boundary conditions varying as a function of time
- Interstellar neutral hydrogen density of 0.127 cm^{-3} at the outer boundary of 80 AU
- Model compares favorably with in situ observations of the solar wind (and interstellar pickup protons) by Ulysses, Voyager, Pioneer, and New Horizons.
- The accuracy of the simulation generally is best around opposition with each spacecraft.
- New Horizons expected to reach the TS at 74 AU in 2029 and the HP at 105 AU in 2040, based on the Kim et al. (2017) model
- Model applications include forecasting of interplanetary shock arrival at the outer planets to support observations.
- Potential sources of uncertainty include N-S symmetric PCHs and HCS tilt, and radial outflow with a spiral magnetic field at 1 AU.
- Alternative sources of time-varying boundary conditions (e.g., WSA, IPS) may complement the OMNI-based boundary conditions.
- MHD solar wind with kinetic PUI and turbulence model currently under development
- Comments and suggestions to **tae.kim@uah.edu**

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