A Data-driven Model of the Solar Wind, Interstellar Pickup Ions, and Turbulence throughout Interplanetary Space

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Abstract

The outer heliosphere is an interesting region characterized by the interaction between the solar wind and the interstellar neutral atoms. Having accomplished the mission to Pluto in 2015 and currently on the way to the Kuiper Belt, the New Horizons spacecraft is following the footsteps of the two Voyager spacecraft that previously explored this region lying roughly beyond 30 AU from the Sun. We model the three-dimensional, time-dependent solar wind plasma flow to the outer heliosphere using our own software Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS), which, in addition to the thermal solar wind plasma, takes into account charge exchange of the solar wind protons with interstellar neutral atoms and treats nonthermal ions (i.e., pickup ions) born during this process as a separate fluid. Additionally, MS-FLUKSS allows us to model turbulence generated by pickup ions. We use MS-FLUKSS to investigate the evolution of plasma and turbulent fluctuations along the trajectory of the New Horizons spacecraft using plasma and turbulence parameters from OMNI data as time-dependent boundary conditions at 1 AU for the Reynolds-averaged MHD equations. We compare the model with in situ plasma observations by New Horizons, Voyager 2, and Ulysses. We also compare the model pickup proton parameters with those derived from the Ulysses-SWICS data.

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1. Introduction

Solar Wind

- A stream of charged particles originating from the Sun
- A medium in which the solar magnetic field and energy propagate outward
- Primary driver of space weather

Heliosphere

- A "bubble-like" structure formed by the pressure balance between the solar wind and the local interstellar medium (LISM) as illustrated in Figure 1
- Size and shape largely affected by fluctuations in the solar wind parameters
- Heliopause: the boundary between the solar wind and the LISM plasma
- Heliosheath: the region characterized by compressed, turbulent, subsonic plasma flow
- Termination shock: the boundary across which the supersonic solar wind slows down to subsonic speeds

Termination Shock Crossing by NASA Spacecraft

- *Voyager 1*: 94 AU, December 2004 (Stone et al., 2005)
- *Voyager 2*: 83.6 AU, August 2007 (Stone et al., 2008; Richardson et al., 2008)

Note: *New Horizons (NH)* passed Pluto at ~33 AU on July 14, 2015 and will be next.

The Heliosphere

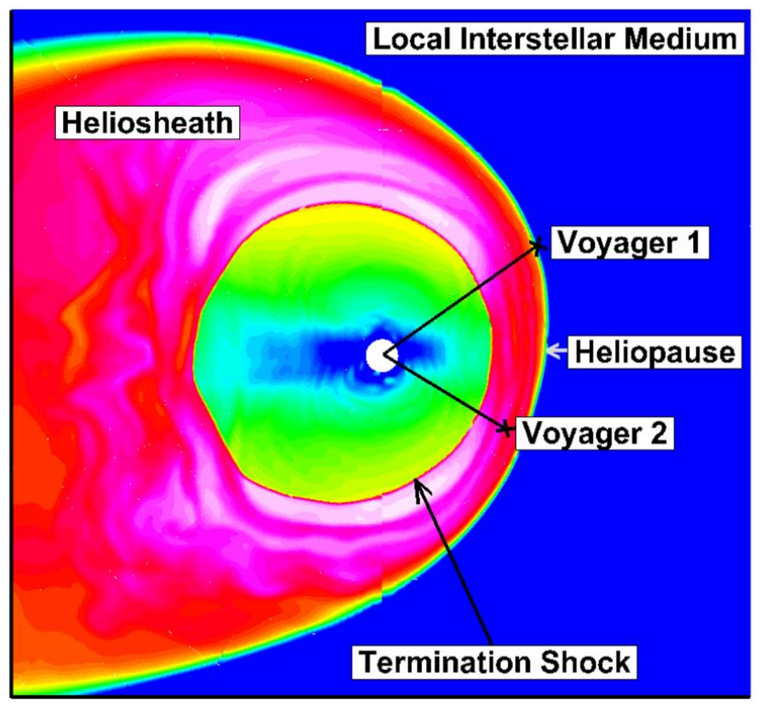

Figure 1. The heliosphere and the Voyager spacecraft trajectories

2. Modeling Software

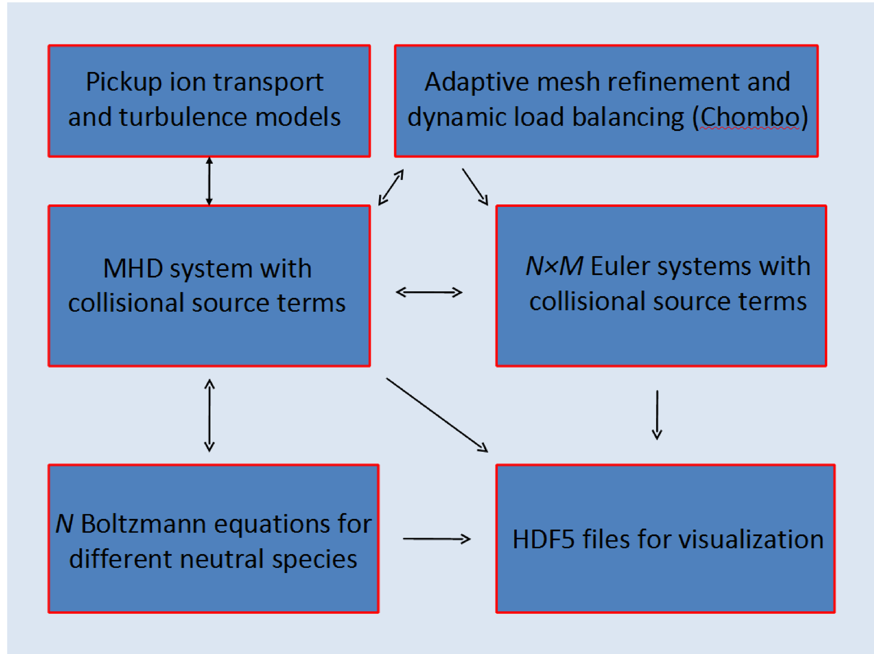

Figure 2. Block diagram of MS-FLUKSS (Pogorelov et al. 2011)

- **Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS)**
  - A package of numerical codes designed to model the heliosphere in multiple scales and high resolution
  - Adaptive mesh refinement based on Chombo architecture (Colella et al. 2007)
  - MHD treatment for solar wind / LISM plasma and fluid treatment for neutral hydrogen atoms (1, 2, 4, or 5 fluids) (Pogorelov et al. 2008)
  - MHD treatment for solar wind / LISM plasma and kinetic treatment for neutral hydrogen atoms (Pogorelov et al. 2008; Borovikov et al. 2008; Heerikhuisen et al. 2008)
  - Turbulence model for supersonic solar wind (Pogorelov et al. 2012; Kryukov et al. 2012)
  - Time-dependent boundary conditions from in situ measurements of the solar wind (e.g., Pogorelov et al. 2013; Kryukov et al. 2012; Kim et al. 2016, 2017)
  - Realistic 3-D time-dependent boundary conditions from remote-sensing observations of the solar wind (e.g., Kim et al. 2014a; 2014b)

3. 3-D Simulation Results

3-Fluid Model (MHD plasma, fluid LISM neutral H and PUI)

- Single-fluid plasma of solar and interstellar origins
- Fluid LISM neutral hydrogen atoms
- Fluid interstellar PUI and PUI-driven turbulence in the supersonic solar wind (e.g., Breech et al. 2008; Kryukov et al. 2012)
- 3-D time-dependent simulation between 1 and 80 AU

Simulation Grid

- Spherical grid: 980 x 128 x128 (r, φ, θ)
- Non-uniform radial grid: Δr ≈ 0.05, 0.08, and 0.13 AU at 1, 33, and 80 AU, respectively
- Δθ ≈ 1.4º, Δφ ≈ 2.8º

Boundary Conditions at 1 AU

- Based on the work by Kim et al. (2016) who used daily averaged OMNI data for a time-dependent two-fluid simulation
- Assumption of corotating solar wind using daily averaged solar wind parameters in the OMNI-driven equatorial region whose latitudinal extent varies with time (see Figure 3)
- Polar coronal holes (PCHs) centered at the poles and varying in size with time are designed to best match Ulysses data at high latitudes (see Figure 3)
- Interplanetary magnetic field components computed 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
- Previous Applications
  - Modeling shock propagation at Voyager 1 in the very local interstellar medium (Kim et al. 2017)
  - Modeling support for remote observations of aurorae at Uranus and Neptune using the Hubble Space Telescope (e.g., Lamy et al. 2017)

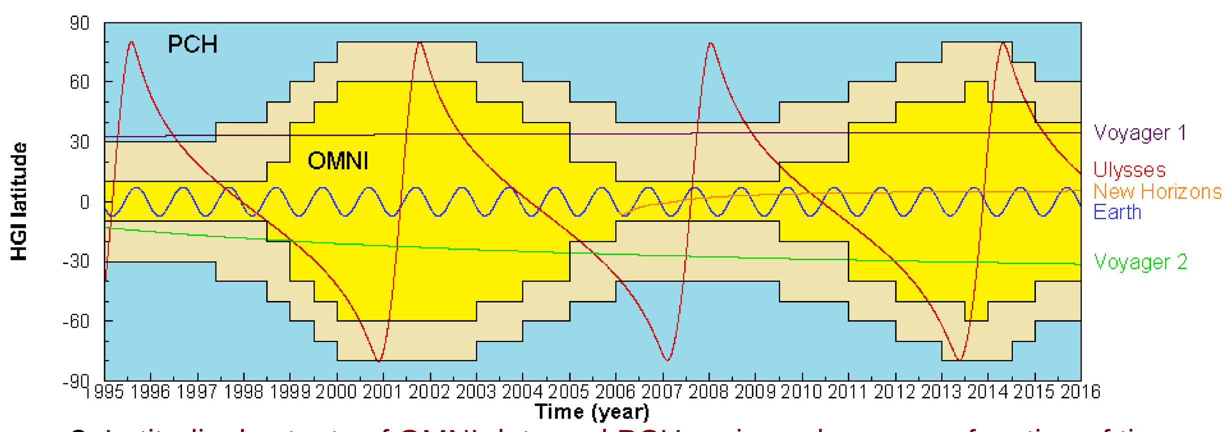

Figure 3. Latitudinal extents of OMNI data and PCH regions shown as a function of time

LISM Parameters at 80 AU

- LISM H density: 0.09 cm^{-3} (Bzowski et al. 2009)
- LISM inflow speed and direction: 25.4 km/s, 75.7º and 5.1º ecliptic inflow longitude and latitude, respectively (McComas et al. 2015)
- LISM H temperature: 7500 K (McComas et al. 2015)

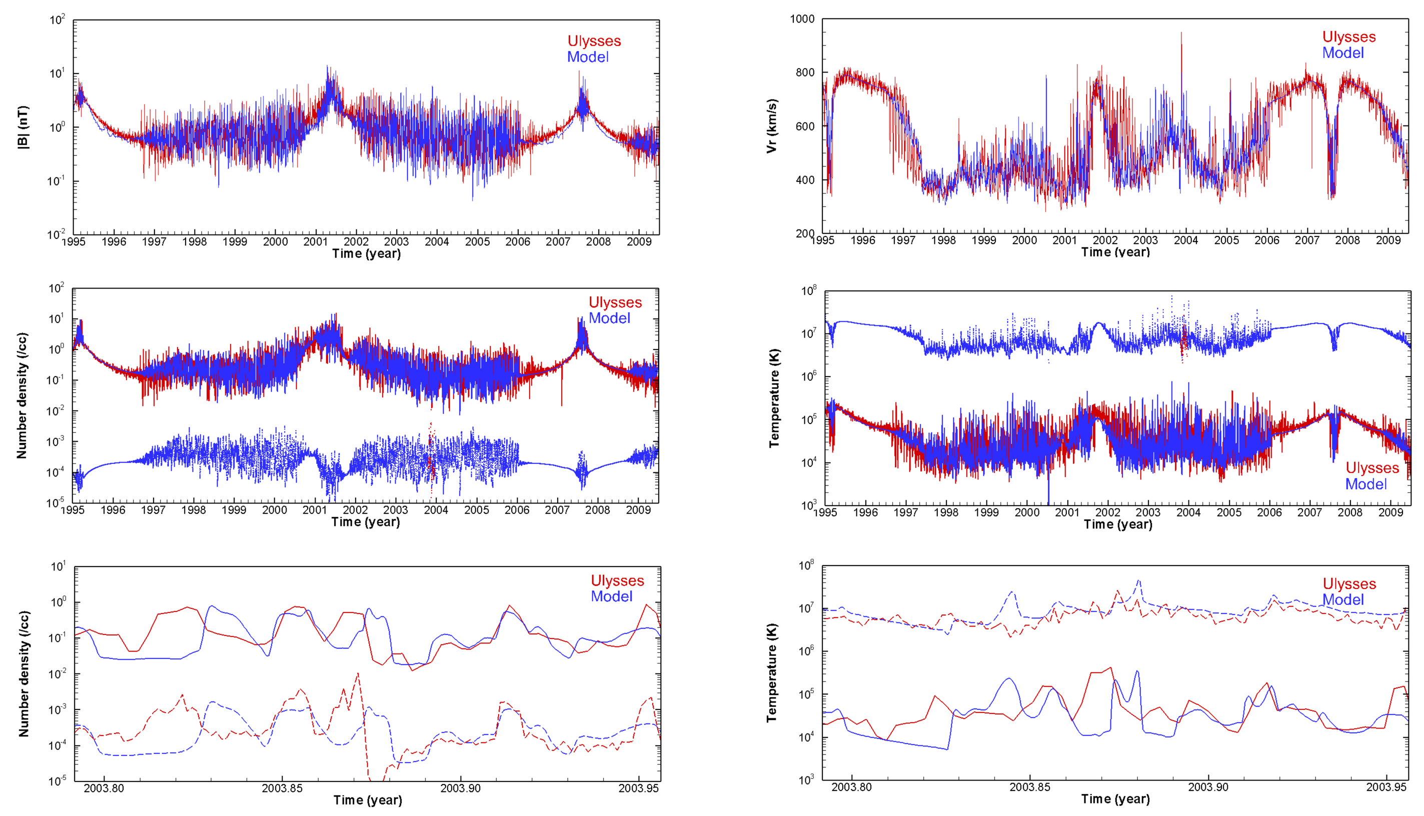

Figure 4. Model interplanetary magnetic field strength, radial velocity, solar wind and interplanetary pickup proton number density, and temperature compared with *Ulysses* data from 1995 to 2009.5 in the top two rows. The bottom two plots compare the model densities and temperatures with *Ulysses/SWOOPS* and *SWICS* data (e.g., Intriligator et al. 2012) around the 2003 Halloween event.

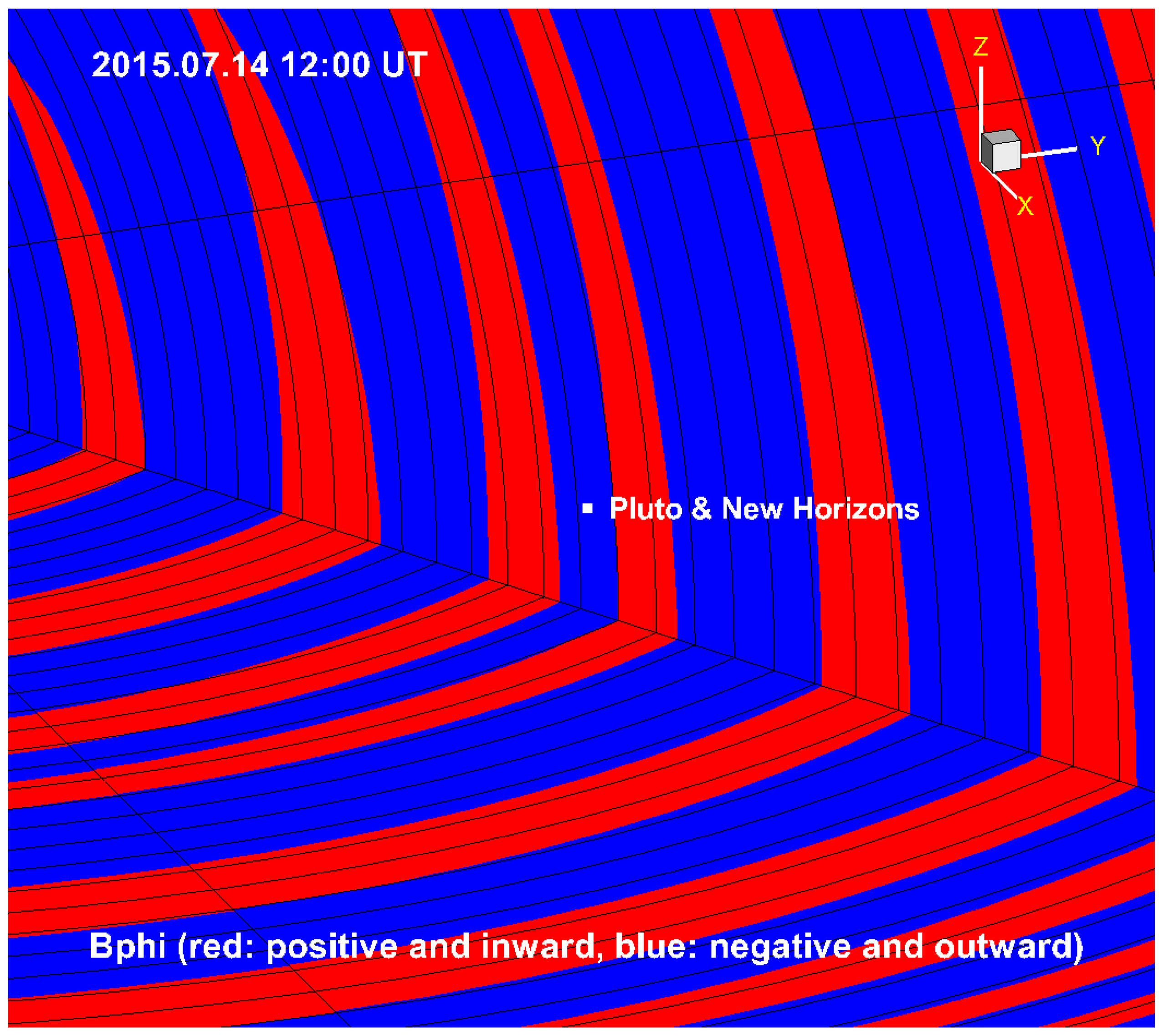

Figure 6. Model interplanetary magnetic field direction shown on the equatorial plane and on a vertical plane formed by the solar rotation axis and the Sun-Pluto line at the time of *NH*'s closest approach to Pluto

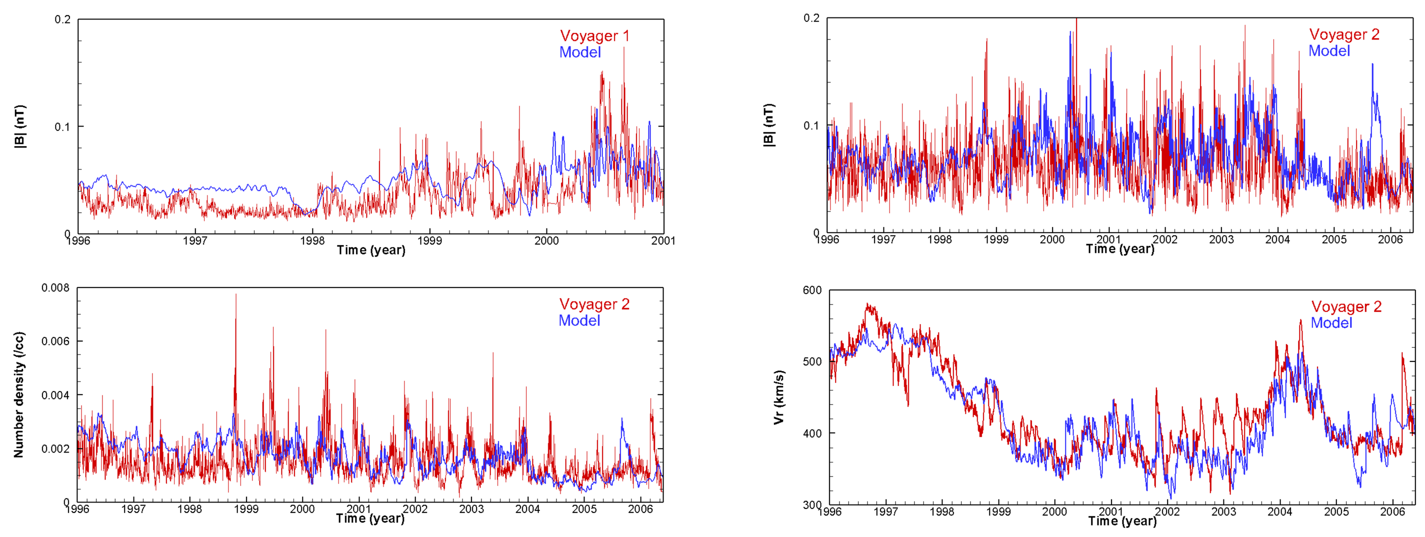

Figure 5. Model interplanetary magnetic field strength (nT) compared with *Voyager 1* and *2* data (top row), number density (cm^{-3}), and radial velocity (km/s) compared with *Voyager 2* data (bottom row)

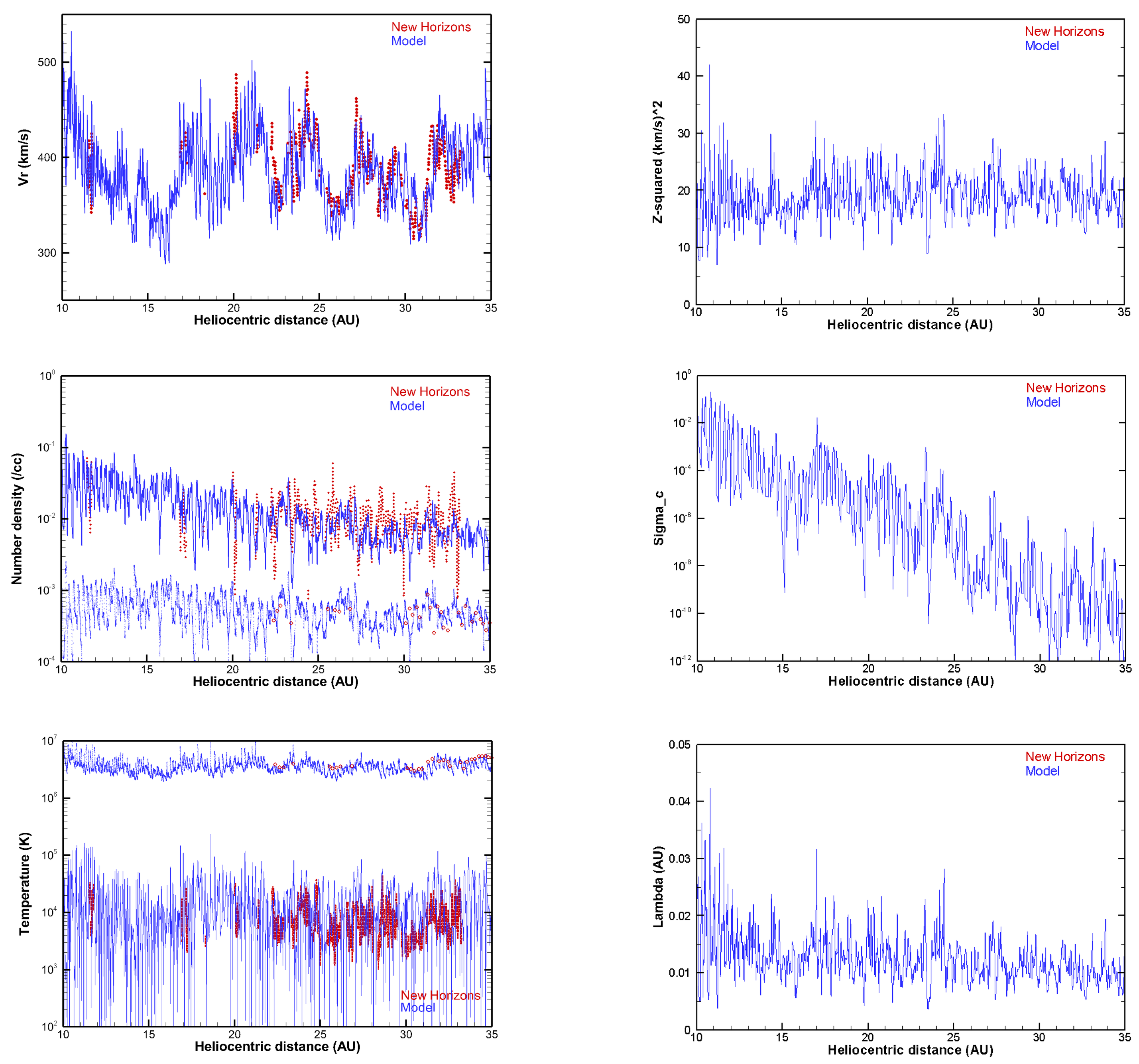

Figure 7. Model solar wind radial velocity, number density, and temperature are compared with *NH/SWAP* observations (Elliott et al. 2016) in the left column. Model interstellar pickup proton density and temperature are marked by open circles and compared with *NH/SWAP* observations (McComas et al. 2017). Turbulence parameters such as Z^2 (total turbulent energy density in turbulent magnetic and velocity fluctuations), σ_c (cross helicity), and λ (correlation length) are shown in the right column.

4. Summary and Discussions

- 3-D multi-fluid simulation of the solar wind, interstellar pickup ions, and turbulence between 1 and 80 AU
- Time-dependent 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
- Model compares favorably with in-space observations of the solar wind and interstellar pickup ions by Ulysses, Voyager, and NH.
- Model applications include forecasting of interplanetary shock arrival at the outer planets such as Uranus and Neptune.
- Potential sources of uncertainty include symmetric PCHs and HCS tilt, and radial outflow with a spiral magnetic field at 1 AU.
- Alternate sources of time-varying boundary conditions (e.g., WSA, IPS tomography) may complement the OMNI-based approach.
- Future work will consider kinetic treatment of interstellar pickup ions as an alternate, more realistic approach to the fluid model.

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