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A Time-dependent Heliospheric Model Driven by Empirical Boundary Conditions

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Abstract

Consisting of charged particles originating from the Sun, the solar wind carries the Sun's energy and magnetic field outward through interplanetary space. The solar wind is the predominant source of space weather events, and modeling the solar wind propagation to Earth is a critical component of space weather research. Solar wind models are typically separated into coronal and heliospheric parts to account for the different physical processes and scales characterizing each region. Coronal models are often coupled with heliospheric models to propagate the solar wind out to Earth's orbit and beyond. The Wang-Sheeley-Arge (WSA) model is a semi-empirical coronal model consisting of a potential field source surface model and a current sheet model that takes synoptic magnetograms as input to estimate the magnetic field and solar wind speed at any distance above the coronal region. The current version of the WSA model takes the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model as input to provide improved time-varying solutions for the ambient solar wind structure. When heliospheric MHD models are coupled with the WSA model, density and temperature at the inner boundary are treated as free parameters that are tuned to optimal values. For example, the WSA-ENLIL model prescribes density and temperature assuming momentum flux and thermal pressure balance across the inner boundary of the ENLIL heliospheric MHD model. We consider an alternative approach of prescribing density and temperature using empirical correlations derived from Ulysses and OMNI data. We use our own modeling software (Multi-scale Fluid-kinetic Simulation Suite) to drive a heliospheric MHD model with ADAPT-WSA input. The modeling results using the two different approaches of density and temperature prescription suggest that the use of empirical correlations may be a more straightforward, consistent method.

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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

Sun-Earth
- Earth is in the inner heliosphere, where the solar wind is the predominant component of interplanetary plasma
- Solar wind modeling is a critical component of space weather study

The Heliosphere

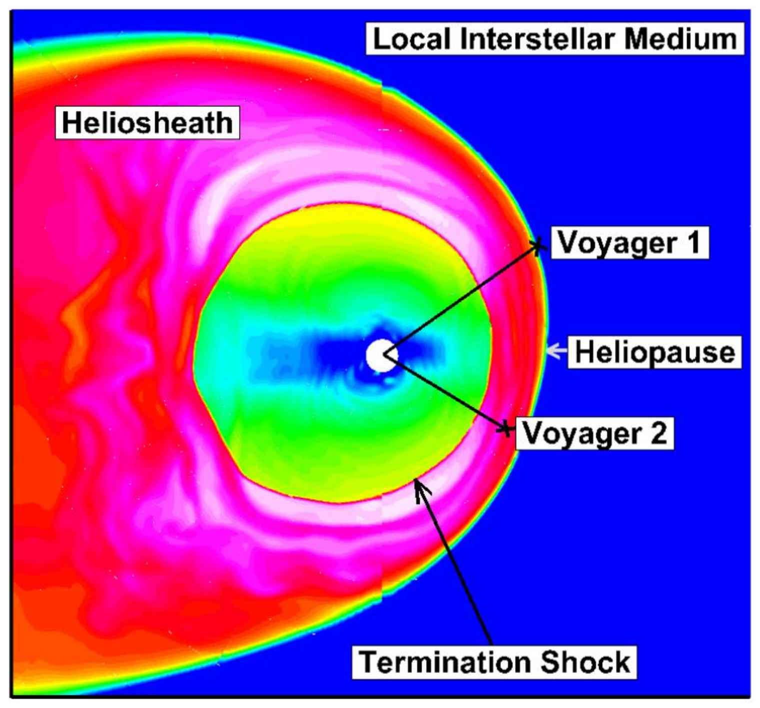

Figure 1. The heliosphere and the Voyager spacecraft trajectories

2. Modeling Software

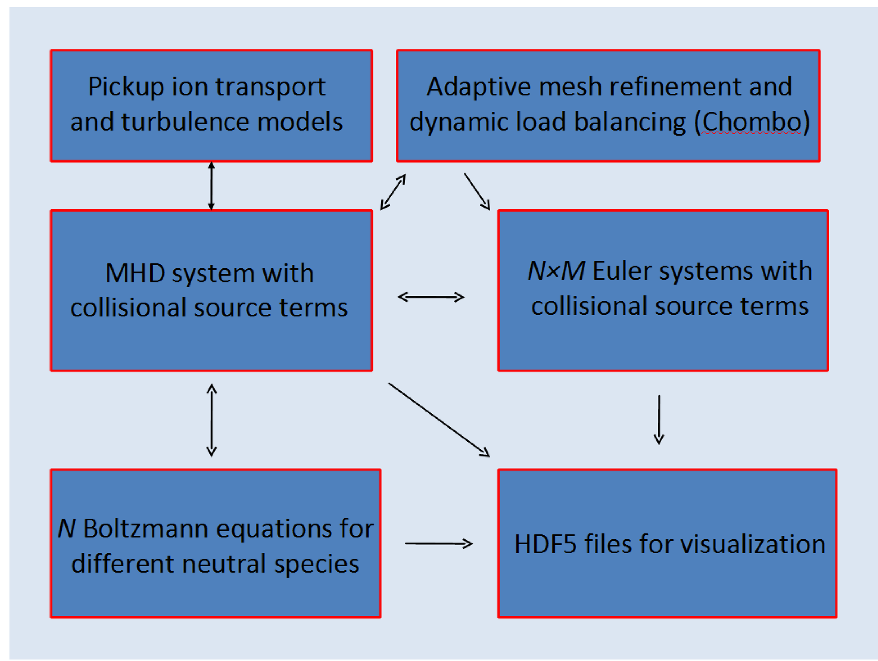

Figure 2. Block diagram of MS-FLUKSS (Pogorelov et al. 2011)

- **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. Simulation Results

Boundary Conditions from the Wang-Sheeley-Arge (WSA) model
- WSA: semi-empirical coronal model for the ambient solar wind (Arge et al. 2003, 2004)
- Potential field source surface (PFSS) model + current sheet model
- Input from synoptic magnetograms or Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model at the Sun’s surface (Arge et al. 2010, 2012, 2013)
- Solar wind speed estimated as a function of the flux expansion factor and the distance to the nearest coronal hole boundary (Arge et al. 2003, 2005)
- Coupled with heliospheric MHD models such as ENLIL and MAS as part of CORHEL

MS-FLUKSS Heliospheric 3-D MHD Model
- Single-fluid ideal MHD solar wind flow from 0.1 to 1.5 AU
- Input from ADAPT-WSA model output (interplanetary magnetic field and solar wind speed) at 0.1 AU
- **Density and temperature at the inner boundary estimated using either ad hoc assumptions (labeled as Model 1) or empirical correlations (labeled as Model 2)**

Estimation of Density and Temperature at 0.1 AU
- Ad hoc prescription assuming momentum and thermal pressure balance:
  e.g., WSA-ENLIL v2.7: $nV^2 = 300 \times 650^2$ (constant kinetic energy) and $nT = 300 \times 0.8$ (constant pressure) at 21.5 R_s, where n is number density in cm^{-3}, V is radial velocity in km/s, and T is temperature in MK.
- Density-speed and temperature-speed correlations from Ulysses data up to 2009 (Pogorelov et al. 2013):

Solar Cycle 23

- Slow wind ($v_R < 450$ km/s)

$$T = 10^5 R^{-0.68} [0.80 + 0.0217 \times (v_R R^{-0.048} - 388)],$$

$$n = R^{-1.93} [6.37 - 0.0292 \times (v_R R^{-0.048} - 388)],$$

- Fast wind ($v_R > 450$ km/s)

$$T = 10^5 R^{-0.95} [2.21 + 0.000233 \times (v_R R^{-0.06} - 668)],$$

$$n = R^{-1.93} [2.27 - 0.0085 \times (v_R R^{-0.06} - 668)],$$

where T, n, v_R, and R represent the proton temperature (K), number density (cm^{-3}), radial velocity (km/s), and the heliocentric distance (AU), respectively.
- Density-speed and temperature-speed correlations from OMNI data (Elliott et al. 2016):

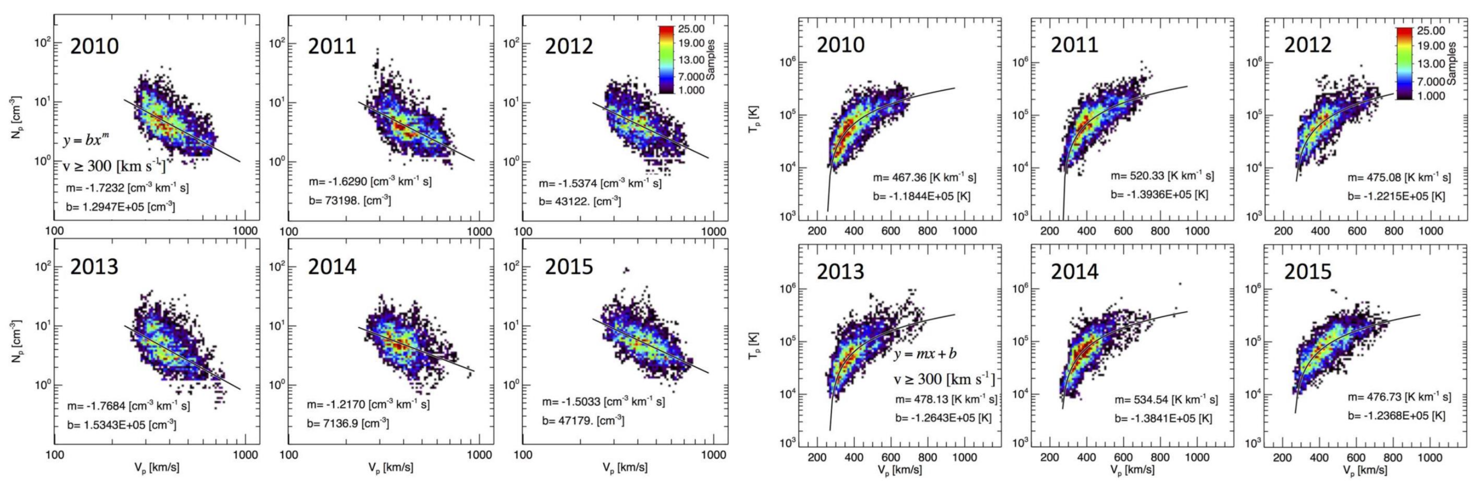

Figure 3. Density–speed distribution plots (top two rows) and temperature-speed plots (bottom two rows) spanning from 2010 to 2015. After removing the ICMEs, the remaining hourly OMNI T_p–V_p observations are placed in 2D bins, and color coded by the number of points per bin. The fits are performed to all the hourly samples with the ICMEs removed, but without any binning. The black curves show linear fits over most of the energy range, and the fitting procedure is the same as those in Elliott et al. (2012), where the measurements with speeds from 330 to 850 km/s were fit. Taken from Elliot et al. (2016).

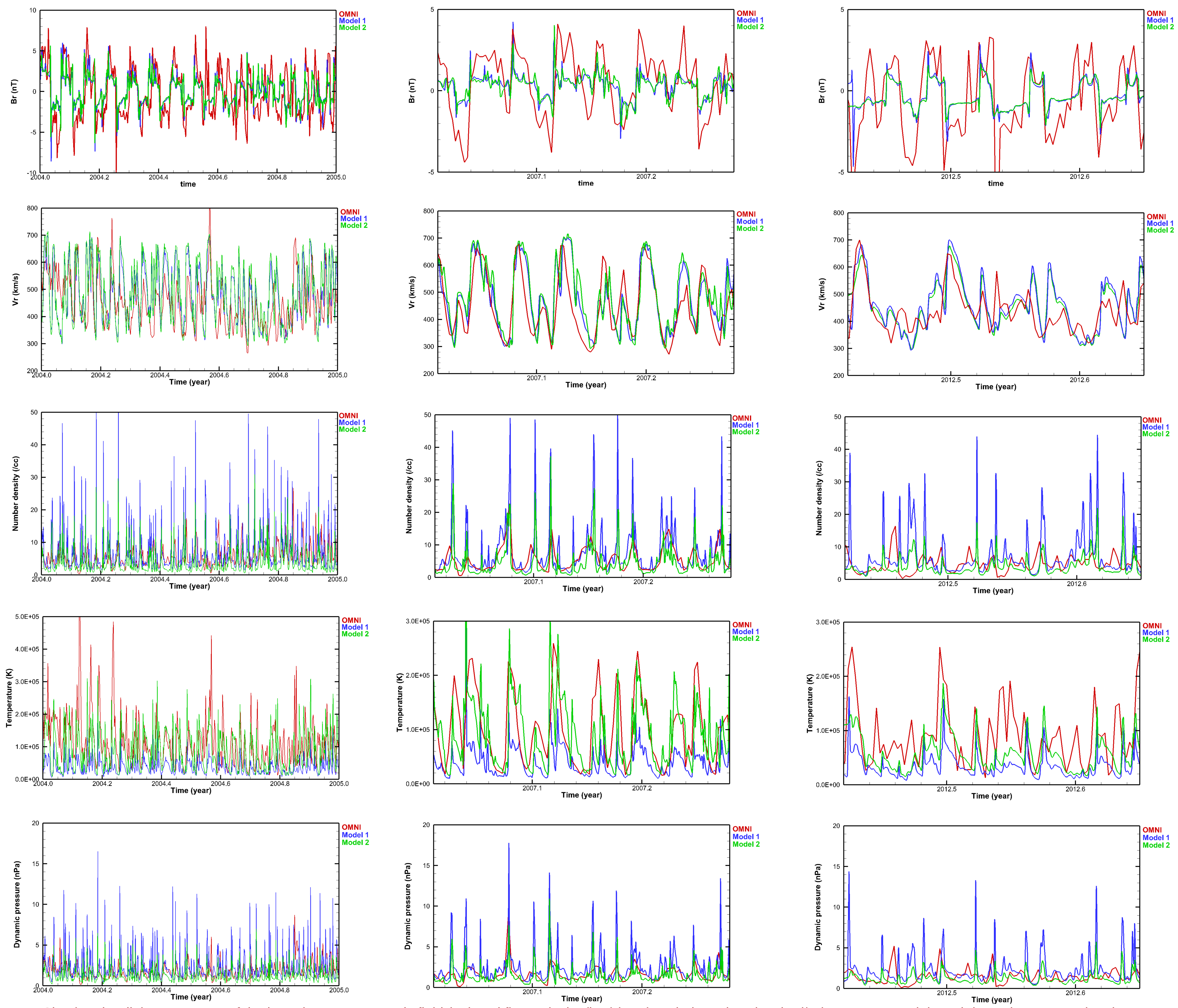

Figure 4. Simulated radial components of the interplanetary magnetic field (nT) and flow velocity (km/s), solar wind number density (/cc), temperature (K), and dynamic pressure (nPa) compared with OMNI data at Earth for three different periods

4. Summary and Discussions

- MS-FLUKSS 3-D heliospheric model coupled with ADAPT-WSA coronal model
- Simulation of time-dependent flow of the ambient solar wind from 0.1 to 1.5 AU
- Magnetic field and velocity at 0.1 AU from ADAPT-WSA model
- Density and temperature at 0.1 AU estimated using ad hoc assumptions (Model 1) or empirical correlations (Model 2)
- Models output compared with OMNI data at Earth for three different periods: 2004, 2007, and 2012
- Magnetic field and velocity nearly identical for Model 1 and 2
- Density and temperature for Model 2 agree more favorably with OMNI data
- Ad hoc assumptions of density and velocity may be tweaked to possibly improve Model 1 (e.g., WSA-ENLIL v2.8)
- No tweaking required for the Model 2 approach, which should be considered as an alternate, more consistent approach

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Acknowledgments

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