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Time-dependent MHD Simulations of the Solar Wind Outflow Using Interplanetary Scintillation Observations

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Abstract. Numerical modeling of the heliosphere is a critical component of space weather forecasting. The accuracy of heliospheric models can be improved by using realistic boundary conditions and confirming the results with *in situ* spacecraft measurements. To accurately reproduce the solar wind (SW) plasma flow near Earth, we need realistic, time-dependent boundary conditions at a fixed distance from the Sun. We may prepare such boundary conditions using SW speed and density determined from interplanetary scintillation (IPS) observations, magnetic field derived from photospheric magnetograms, and temperature estimated from its correlation with SW speed. Here, we present the time-dependent MHD simulation results obtained by using the 2011 IPS data from the Solar-Terrestrial Environment Laboratory as time-varying inner boundary conditions and compare the simulated data at Earth with OMNI data (spacecraft-interspersed, near-Earth solar wind data).

Keywords: solar wind, interplanetary scintillation (IPS), inner heliosphere, MHD simulation.
PACS: 94.05.Sd, 96.50.Ci

INTRODUCTION

The Sun continuously emits a stream of charged particles called the solar wind (SW), which is the primary driver of space weather as it transports the Sun's energy and magnetic field more or less radially outward through interplanetary space. Besides its obvious influence on space missions, space weather has begun to have substantial impact on the daily functions of the modern civilization as well. Therefore, it is important to develop accurate and reliable forecasting tools. A key component of space weather forecasting involves numerical modeling of the SW outflow in interplanetary space between the Sun and the Earth. Since the SW parameters fluctuate considerably within each Carrington rotation, or sometimes due to transient events, it is necessary to use realistic boundary conditions that reflect such temporal and spatial variations as accurately as possible. Interplanetary scintillation (IPS) observations, which have long been used in three-dimensional (3D) reconstructions of the SW including coronal mass ejections and corotating structures [1, 2, 3], could provide such boundary conditions on a daily basis.

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There are several facilities around the world offering past and/or real-time IPS observations, but the Solar-Terrestrial Environment Laboratory (STEL) at Nagoya University currently operates the only multi-site IPS observatory dedicated to monitoring the SW. In addition to measuring the scintillation index (also called the g-level; see [1] for details) at each of its four stations in central Japan that may be used in estimating the SW number density, STEL can determine the SW speed from multi-site observations using the time lag for maximum cross-correlation of the spectra - with greater accuracy than that derived from single-site observations [4]. STEL IPS data are available for a relatively long period dating back to the early 1970's, and they have made significant contributions to various studies on the long-term evolution of the 3D SW structure [5, 6].

Unlike *in situ* spacecraft measurements, remote-sensing observations like IPS contain a line-of-sight (LOS) integration effect, so one must take great care in processing the data to obtain reliable SW speed and density maps in 3D. As of now, four types of computer-assisted tomography (CAT) methods have been developed to deconvolve the LOS integration effect in the IPS measurements: corotating tomography, time-sequence tomography, magnetohydrodynamics (MHD)-IPS tomography, and time-dependent tomography [7]. The corotating tomography method combines lines of sight (typically 30 or so per day) for one or more solar rotations in analyzing the SW structure, assuming temporarily stable SW conditions. Since corotating tomography is not suitable for the solar maximum periods, in one instance STEL developed the time-sequence tomography method, which can tolerate changes in the SW structure over a solar rotation. Developed by Hayashi et al. [3], the MHD-IPS tomography method combines the IPS CAT analysis (see [8] and [9] for details) with MHD simulation to provide multiple SW parameters, such as number density, velocity, magnetic field, and temperature, at various heliocentric distances. On the other hand, the time-dependent tomography method developed at the University of California in San Diego (UCSD) uses a purely kinematic model to propagate the SW from the source surface to Earth and beyond by assuming radial outflow and conservation of mass and mass flux [10, 11]. Inclusion of *in situ* measurements by near-Earth spacecraft in the time-dependent tomography considerably improves the SW speed [12] and density [13] reconstructions around Earth that are particularly useful for space weather forecasting purposes.

In general, the MHD-IPS tomography is quite successful at reproducing the SW parameters in the inner heliosphere that closely match the *in situ* spacecraft measurements, but its use of empirical correlations determined from the Helios data to estimate the boundary values (i.e., number density and temperature) apparently leads to overestimation of number density after around 2006 [5]. In contrast, the UCSD time-dependent tomography derives the SW number density from the IPS g-level and manages to do a remarkably good job at reproducing the SW parameters around Earth despite using a very simple kinematic model [1]. Hence, it would be interesting to see if the accuracy of SW reconstruction at Earth improves with use of time-dependent tomography results as boundary values in our MHD model.

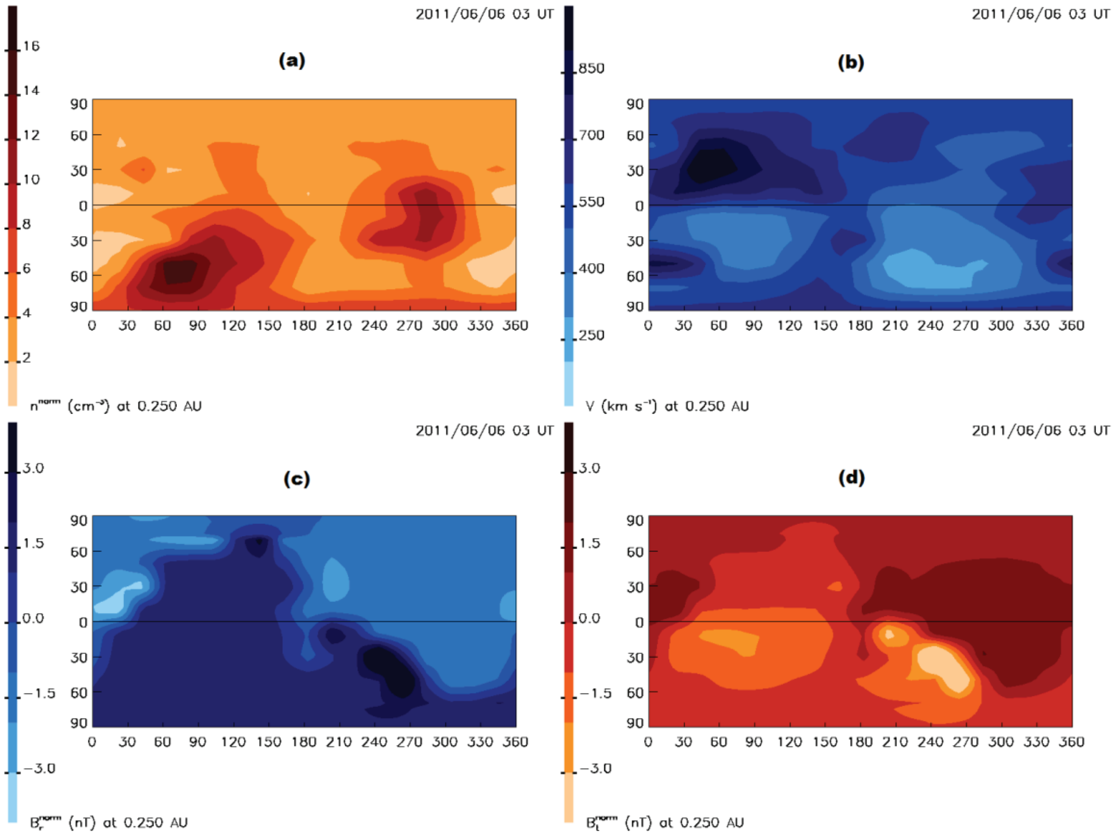

FIGURE 1. UCSD 3D time-dependent tomography results at 0.25 AU estimated from the STEL IPS observations and WSO magnetograms on June 6, 2011 (normalized to 1 AU).

BOUNDARY CONDITIONS

To simulate the SW outflow to Earth and beyond, we need boundary conditions at a source surface that is relatively close to the Sun and well beyond the critical point, where we can safely assume the SW to be supersonic everywhere. In this case, we use the SW speed and density data obtained by the UCSD time-dependent tomography at the heliocentric distance of 0.25 astronomical units (AU) to construct a set of time-dependent boundary conditions, assuming that the SW flow at this distance is entirely radial (zero azimuthal and latitudinal velocity components). Moreover, we estimate the magnetic field and temperature, which are also required for our calculations, from the Wilcox Solar Observatory (WSO) magnetograms and as a linear function of SW speed using an empirical correlation between speed and temperature [3], respectively.

The boundary conditions provided by the UCSD time-dependent tomography cover a period of 6 Carrington rotations from June 6, 2011 to November 16, 2011 with a temporal resolution of one day. Figure 1 shows the SW number density, speed (radial velocity), and radial and tangential components of magnetic field at 0.25 AU on June 6 in the heliographic inertial (HGI) coordinate system, which we have used to obtain the initial quasi-steady state solution. The corresponding temperature distribution is not shown here, but it closely resembles that of the SW speed.

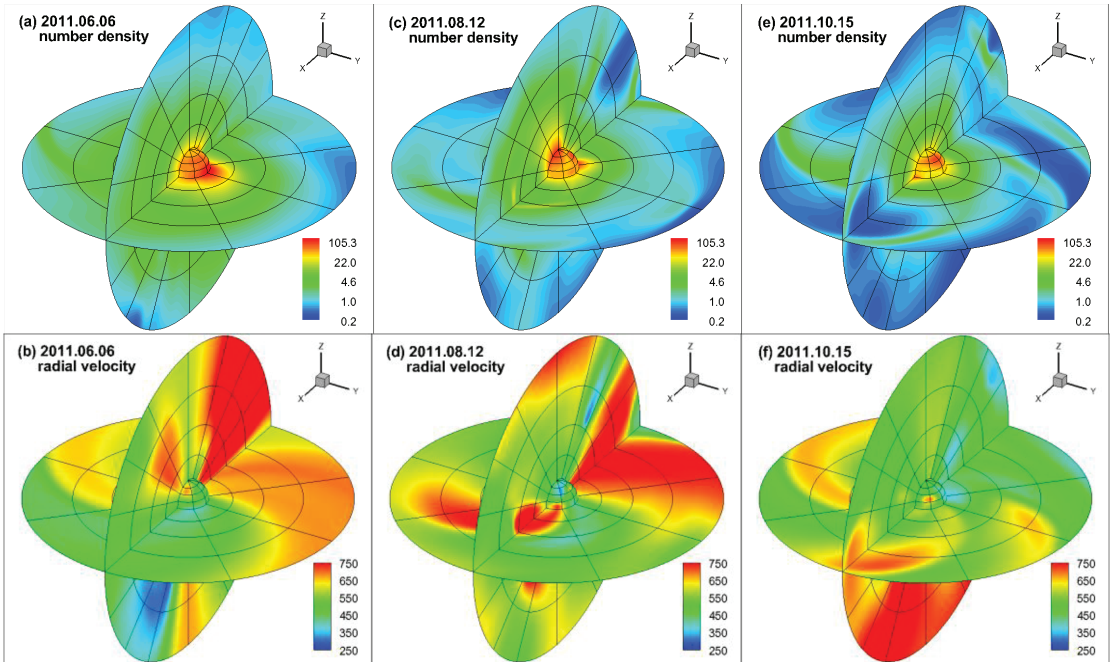

FIGURE 2. SW number density (top row, in cm^{-3}) and radial velocity (bottom row, in km/s) shown in the equatorial and meridional planes from 0.25 AU out to 2 AU at three different times.

MODELING THE SW FLOW WITH MS-FLUKSS

We implement the time-dependent tomography results discussed in the previous section as time-varying boundary conditions in Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS). Developed by the Center for Space Plasma and Aeronomic Research at the University of Alabama in Huntsville, MS-FLUKSS is a package of numerical codes frequently used for modeling the plasma flow and plasma-neutral interactions in the heliosphere [14, 15]. In the recent past, we have successfully analyzed the plasma parameters in the outer heliosphere using the MHD-IPS tomography results by Hayashi et al. [5] as time-varying inner boundary conditions in MS-FLUKSS [16]. In this study, we perform an MHD simulation of the SW flow from the source surface at 0.25 AU out to a distance of 2 AU using the time-dependent tomography data as inner boundary conditions in MS-FLUKSS. The simulated plasma parameters at Earth's location are compared with *in situ* measurements by near-Earth spacecraft.

SIMULATION RESULTS

After reaching a quasi-steady state (see Figure 2(a) and 2(b)) by rotating the June 6, 2011 data shown in Figure 1 with the solar rotational period, we apply the time-varying boundary conditions to investigate the evolution of the SW parameters during the noted period. Figure 2 displays some of the results plotted in 3D, namely number density and radial velocity, at three different times during the period. To avoid confusion, we must note that MS-FLUKSS employs a slightly different coordinate system from the HGI system, in which the nose (the x-axis) is rotated about the solar

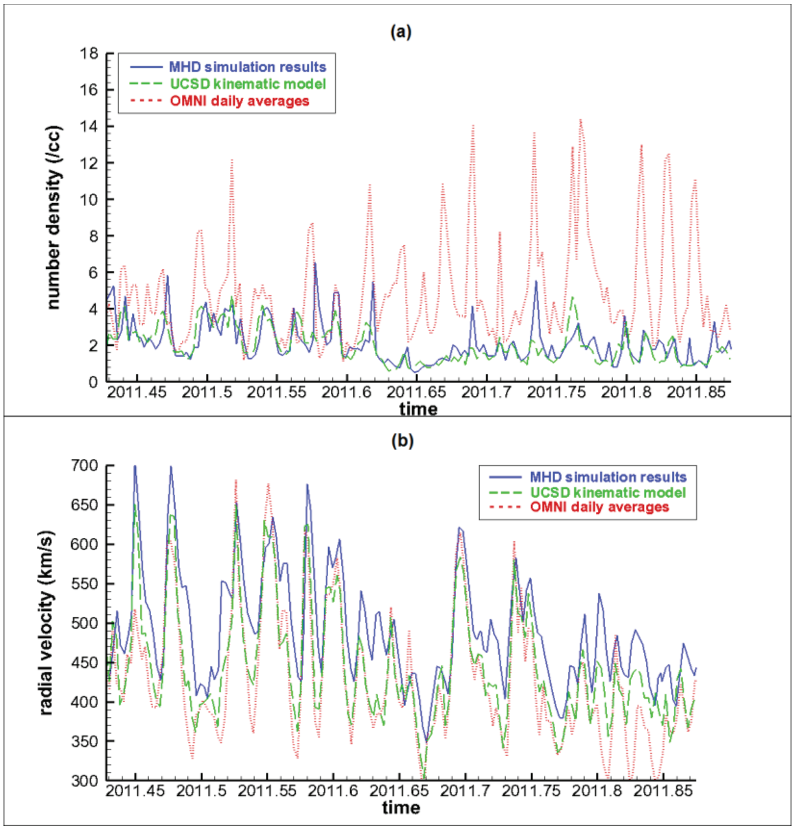

FIGURE 3. Comparisons of the MHD simulation results at Earth with the OMNI daily averaged data and the UCSD kinematic solutions.

rotational axis (the z-axis) by a certain angle such that the y-component of the local interstellar medium velocity vector disappears. In other words, the meridional plane shown in Figure 2 is somewhat different from that of the HGI system. After extracting the SW parameters at Earth, we compare them with OMNI daily averaged data as shown in Figure 3. The number density and radial velocity comparisons show reasonably good agreements between the simulated and *in situ* data at least until mid-August 2011. However, the differences grow relatively large from then on, particularly in number density. For additional reference we have included the UCSD kinematic solutions in the same figure.

SUMMARY AND CONCLUSIONS

Using the UCSD time-dependent tomography results derived from STEL IPS observations as time-varying inner boundary conditions, we have simulated the SW flow from 0.25 AU to 2 AU for the latter half of 2011. Though our MHD simulation results at Earth compare fairly well with *in situ* measurements in general, there are some notable discrepancies as mentioned in the previous section. For example, the fluctuation in the SW number density is considerably smaller in the simulated data than in the near-Earth spacecraft measurements from mid-August to early November 2011. While the UCSD kinematic model manages to reproduce the SW radial velocity at Earth with remarkably good accuracy - which is more or less expected because *in* *situ* velocity measurements from the Advanced Composition Explorer (ACE) are integrated into the time-dependent tomography - it, too, struggles to accurately reproduce the number density as displayed in Figure 3(a). This is most likely due to the fact that the IPS g-level measurements are matched to ACE Level 0 data, which gradually lose amplitude during this period, whereas OMNI data are primarily made up of Wind and ACE Level 2 data that retain higher amplitude. On the other hand, the radial velocity comparison between the MHD simulation results and OMNI daily averaged data is much better, but still not quite as good as that between the UCSD kinematic solutions and OMNI data. In other words, the SW speed map reconstructed at 0.25 AU by the UCSD time-dependent tomography - which produces excellent results at Earth using the kinematic model - does only a marginally respectable job when used as boundary conditions in the MHD model, thereby raising suspicion in the accuracy of the tomography results. However, it is difficult to question the accuracy of a model with data comparisons at only a single point in space for such a limited period of time. Therefore, our next step would be to continue our analysis using additional sets of boundary conditions, preferably pre-2009 data so that we may compare the MHD simulation results with Ulysses data as well. In addition, we will also attempt to analyze our density results with IPS data matched to Wind and CELIAS (the Charge, Element, and Isotope Analysis System on the Solar and Heliospheric Observatory) densities.

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