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The space environment of Mercury at the times of the second and third MESSENGER flybys

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ABSTRACT

The second and third flybys of Mercury by the MESSENGER spacecraft occurred, respectively, on 6 October 2008 and on 29 September 2009. In order to provide contextual information about the solar wind properties and the interplanetary magnetic field (IMF) near the planet at those times, we have used an empirical modeling technique combined with a numerical physics-based solar wind model. The Wang–Sheeley–Arge (WSA) method uses solar photospheric magnetic field observations (from Earth-based instruments) in order to estimate the inner heliospheric radial flow speed and radial magnetic field out to 21.5 solar radii from the Sun. This information is then used as input to the global numerical magnetohydrodynamic model, ENLIL, which calculates solar wind velocity, density, temperature, and magnetic field strength and polarity throughout the inner heliosphere. WSA-ENLIL calculations are presented for the several-week period encompassing the second and third flybys. This information, in conjunction with available MESSENGER data, aid in understanding the Mercury flyby observations and provide a basis for global magnetospheric modeling. We find that during both flybys, the solar wind conditions were very quiescent and would have provided only modest dynamic driving forces for Mercury's magnetospheric system.

1. Introduction

Recent years have seen a dramatic improvement in the comprehensive modeling of solar wind conditions throughout the inner heliosphere (e.g., Arge et al., 2004; Odstrcil et al., 2004). Much of this work has been motivated by the goal of providing forecasts of ambient solar wind conditions at Earth's location. The methods – which will be described in this paper – utilize photospheric magnetic field observations of the Sun from Earth-based instruments combined with empirical and physics-based (forward) numerical modeling tools. Present-day modeling is holding out new and improved prospects of "space weather" prediction capability.

In a previous paper (Baker et al., 2009) we described the solar wind conditions as modeled – and as observed – for the first Mercury planetary flyby by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft in January 2008. In that work we discussed the limitations of having only the single-point measurements at the MESSENGER location in the inner heliosphere. A much broader and more informative context is set for the spacecraft flyby results if one can provide a global inner heliospheric map of solar wind plasma and magnetic field conditions. From the previously noted state-of-the-art modeling efforts, one can have a clearer and more comprehensive picture of high-speed solar wind streams, corotating interaction regions, interplanetary magnetic field (IMF) sector boundaries,

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and heliospheric current sheet properties throughout the inner solar system.

Since MESSENGER's first Mercury flyby (M1), the spacecraft has completed two further Mercury encounters. The second flyby (M2) on 6 October 2008 was fully successful from the standpoint of MESSENGER data collection (e.g., Slavin et al., 2009). During the third flyby (M3) on 29 September 2009, MESSENGER experienced a safe-hold anomaly shortly before the time of closest approach, and scientific data collection was stopped until the anomaly could be diagnosed and the spacecraft restored to operational mode. Nonetheless, remarkable new data were obtained on the M3 inbound trajectory (Slavin et al., 2010; Vervack et al., 2010).

In this paper, we first summarize our modeling technique and then review briefly our results for M1. The main goal of this paper is to provide detailed new results for M2 and M3. In each case, we use the available data from near 1 AU to test and validate the solar wind modeling for consistency and overall validity. In particular, *in situ* measurements from the Advanced Composition Explorer (ACE) and the Solar TErrestrial RElations Observatory (STEREO) pair of spacecraft provide the basis to assess our model results. We then compare the model results directly with available MESSENGER measurements. Finally, we discuss plans for modeling efforts as MESSENGER enters the Mercury orbital phase of the mission in March 2011.

2. Model description and prior results

As described by Baker et al. (2009), the Wang–Sheeley–Arge (WSA) model is a combined empirical and physics-based description of the global solar wind flow (Arge et al., 2004; Arge and Pizzo, 2000). It is widely used to predict the solar wind speed and IMF polarity at Earth (as well as other points in the inner heliosphere) and is an extension of the original Wang and Sheeley (1992) model. The model begins with ground-based observations of the solar surface magnetic field as input to a magnetostatic potential-field source surface (PFSS) model (Schatten et al., 1969) and yields estimates for the current sheet properties between 2.5 and 5 R_S (Fig. 1), where R_s is the solar radius. Updated solar field maps are used four times per day (6-h cadence). The outward flows in the corona, which are not explicitly contained in this PFSS formulation, are approximated by the imposition of radial field boundary conditions at the source surface and by an empirical relation that relates expansion factors to initial solar wind speeds at this point. This surface is a Sun-centered sphere of radius 2.5 R_s.

The photospheric field observations are the basic properties used to drive the computations. They serve as a key input to our coronal and solar wind models. Updated photospheric field synoptic maps (i.e., magnetic maps incremented regularly with new data) are constructed with magnetograms from the National Solar Observatory's Global Oscillation Network Group (GONG) system. The line-of-sight field measurements from these data sources are converted to the radial field component (see Arge et al., 2004). This radial field is the basis of our standard "forecast" version of the models. As described further below, in this paper we have used data from several different ground stations updated at a 6-h cadence and have scaled model parameters separately for the two encounters (M2 and M3).

From WSA results for the region near the Sun, an ideal magnetohydrodynamic (MHD) simulation, ENLIL (Odstrcil et al., 2004), is then used to model the solar wind flow outward to distances beyond 1 AU. The computational domain is a uniform grid occupying the sector of a sphere. The position of the inner boundary is set at 0.1 AU (≈ 21.5 R_s), and the outer boundary is set at 1.1 AU. The meridional and azimuthal extents span 30–150° in heliospheric colatitude and 0–360° in longitude, respectively. The inner boundary lies in the supersonic flow region, near the outer field of view of the Large-Angle and Spectrometric Coronagraph (LASCO) C3 instrument on the Solar Heliospheric Observer (SOHO) spacecraft. The outer boundary at 1.1 AU allows comparison of simulated temporal profiles of solar wind properties at and near the Earth position with spacecraft measurements at ACE or other platforms (Odstrcil et al., 2004).

The combined WSA-ENLIL modeling is a specification of the solar wind flow speed, plasma density, solar wind mean plasma temperature, and magnetic field strength throughout the inner part of the heliosphere. A color representation of the radial flow speed (V_r) in the heliospheric equatorial plane computed for the entire inner heliosphere on 14 January 2008 is shown in Fig. 2a. The model results demonstrate that a broad solar wind stream region was present near the ecliptic plane during this time. The modeled solar wind speed enhancement (up to speeds of $\sim$600 km/s) at $\sim$1 AU was primarily in the longitude sector "trailing" the azimuthal location of the Earth (i.e., 0–90°E longitude). According to the model, the stream enveloped STEREO-B at the time of the snapshot but had not yet quite reached STEREO-A (Baker et al., 2009).

MESSENGER and Mercury were essentially collocated at the time shown in Fig. 2a and were subjected to nearly identical solar wind flow conditions. From a Mercury magnetospheric perspective, there was only a modest solar wind speed enhancement expected on the day of the flyby. The high-speed stream noted above would have passed over MESSENGER several days prior to the flyby with the highest-speed (600 km/s) stream features expected to rotate over the Mercury location several days earlier.

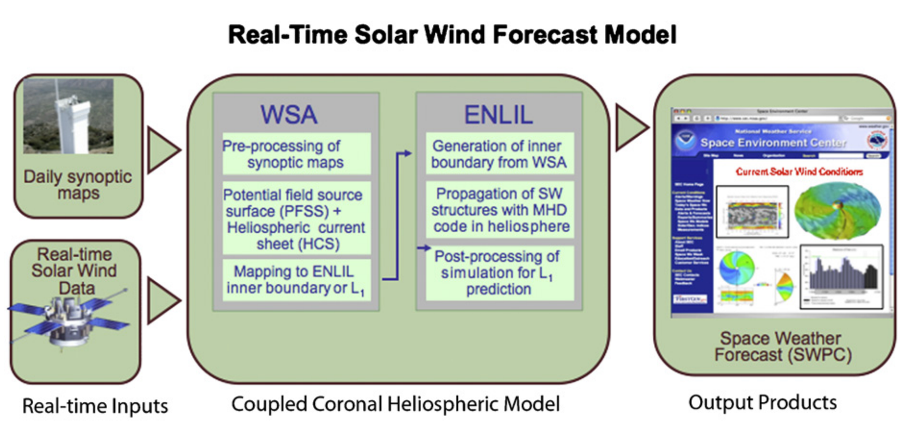

Fig. 1. Elements of the real-time coupled coronal-heliospheric model used in the present study. GONG data are used as input for the synoptic maps, and forecast outputs are given at the testbed site (http://swpc.noaa.gov/enlil/evolution). Definitions and abbreviations are described in the text.