Initial Comparison Between a 3D MHD Model and the HAFv2 Kinematic 3D Model: The October/November 2003 Events from the Sun to 6 AU

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Abstract. A first-generation 3D kinematic, space weather forecasting solar wind model (HAFv2) has been used to show the importance of solar generated disturbances in Voyager 1 and Voyager 2 observations in the outer heliosphere. We extend this work by using a 3D MHD model (HHMS) that, like HAFv2, incorporates a global, pre-event, inhomogeneous, background solar wind plasma and interplanetary magnetic field. Initial comparisons are made between the two models of the solar wind out to 6 AU and with *in-situ* observations at the ACE spacecraft before and after the October/November 2003 solar events.

INTRODUCTION

At last year's IGPP meeting, we began to discuss the possibility that effects from solar disturbances may have been in part responsible for the differences in the energetic particle measurements at Voyager 1 and Voyager 2 in August 2002. Our 3D HAFv2 results suggested that asymmetric propagation of solar events affect the dynamics of the outer heliosphere [1]. The 3D HAFv2 results suggested that in 2002, these effects - and not solely the proximity to the termination shock – contributed to the differences in the Voyager 1 and Voyager 2 energetic particle observations.

There were nineteen significant solar events between October 19, 2003 and November 20, 2003 (the "Halloween 2003" solar events). This complex system of Halloween 2003 events presents a challenge for modeling the interplanetary propagation of solar disturbances to the outer heliosphere. They also provide a special opportunity for benchmarking the interplanetary effects of these events and for determining their influence on the outer heliosphere. In Intriligator et al. [2], we used the HAFv2 model to study the propagation of these events throughout the heliosphere. We found that, while the HAFv2 model yielded many important results and insights, it would be helpful to compare its results with those of a full 3D MHD model.

In the present paper, we show some of the results from the full 3D MHD model within 6 AU. We show the time series results at ACE from both the HAFv2 model and the full 3D MHD model. In addition, we show ecliptic plane results out to 6 AU from both

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models for the “background” solar wind and interplanetary magnetic field (IMF) prior to the Halloween events and for the disturbed interplanetary medium after the Halloween events. Due to the limited page allowance here, in the next two sections, we discuss very briefly the HAFv2 model and then more completely the 3D MHD model. The results and conclusions are presented in the last two sections.

HAFV2 MODEL

The Hakamada – Akasofu - Fry version 2 model (Fry et al. [3, 4, 5] is a 3D kinematic simulation that inputs solar data at 2.5 Rs. The HAFv2 model is successfully used in the real time “Fearless Forecasts” from the Sun to Earth and Mars [6]. The HAFv2 model was used in real-time during the exceptional Bastille 2000 and Halloween 2003 storm intervals to predict shock arrival times at Earth (Dryer et al. [6, 7]). The model includes stream/stream interactions (Intriligator et al. [1, 2]). The details of this model are discussed in Intriligator et al. [1, 2] and references therein.

THE 3D MHD MODEL

The Hybrid Heliospheric Modeling System (HHMS) is a Sun to Earth system of coupled models designed primarily for real-time prediction of geomagnetic activity (Detman et al. [8]). The key features of the HHMS relevant to this paper are that it contains a set of empirical relationships (analogous to those in HAFv2) that translate the output of the Wang-Sheeley-Arge Source Surface (SS) model (Arge and Pizzo, [9]) into time- dependent lower boundary conditions for the IGMV (Interplanetary Global Model Vectorized) 3D MHD solar wind model ([10, 11]). The SS model is in routine daily operation at the NOAA Space Environment Center (SEC). Driven by daily solar magnetograms via the SS model, the HHMS gives the state of the slowly evolving background solar wind within the inner heliosphere from 45 degrees South latitude to 45 degrees North and for 365 degrees longitude, including stream-stream interactions and co-rotating interaction region (CIR) build-up. In addition to the time-dependent boundary condition driven by the SS model, the HHMS allows for interplanetary shock initiation at 0.1 AU based on other solar observations such as solar flares, Type II radio sweeps, and/or coronagraph observations of CMEs.

COMPARISON OF THE MODELS

The HAFv2 and HHMS models are quite different in their internal methods. The HAFv2 model is essentially a 2D (latitude, longitude) array of 1D (radial) computations; it operates by emitting pseudo particles from a grid of points fixed in Carrington coordinates. In inertial coordinates, however, the pseudo particles act like beads on a string. Their properties and interactions are designed to give conservation of mass, momentum, and magnetic flux. Also, their interaction parameters are tuned to agree with 1D MHD in the propagation of shocks. In contrast, the HHMS takes a continuum approach. It approximates the partial differential equations of MHD using the two-step Lax-Wendroff scheme [10]. It conserves mass, momentum, magnetic flux, and energy.

The HAFv2 and HHMS also have differences in their specification of lower boundary conditions. These differences, however, are not fundamental; both models have a background solar wind driven by SEC's SS maps, and both models superimpose shock inputs on their background boundary conditions based on the Fearless Forecast inputs. For HAFv2 this process uses the estimated metric Type II shock speed as a parameter in an exponential plasma speed profile that is superimposed upon the background SS model. HHMS, on the other hand, uses the Type II shock speed to compute the sonic Mach Number, hence, the Rankine-Hugoniot jump conditions of velocity, etc., at 0.1 AU for a time period suggested by the proxy piston driving time [2]. The Fearless Forecast information is shock time, flare location on the solar disk, shock speed (derived from Type II frequency sweep speed), and piston driving duration (derived from GOES X-ray flare time profile).

RESULTS

Figure 1 shows the HAFv2 results at 1 AU (Intriligator et al., [2]). The times of the simulated shock arrivals have been tuned [2] to optimize agreement with the observed (Skoug et al., [12]) shock arrivals at ACE. To begin using the HHMS for the study of shock propagation to the outer heliosphere, we focused on the October and November 2003 (Halloween) events and iteratively fine-tuned the shock inputs for agreement with ACE observations. Figure 2 shows comparisons of the HHMS simulated time series of solar wind proton speed (V), density (n), temperature (T), entropy (S), and IMF magnetic field magnitude (/B/) with corresponding ACE observations. ACE Level 2 science data with 96s resolution was combined with solar wind plasma velocity by Skoug et al. [12] for the large October 29th shock. Note the gap in density at this time due to energetic particle bombardment of the SWEPAM. These data were block averaged to 15-minute resolution, a rough match to the time step of the HHMS. ACE observations are plotted as blue symbols, the HHMS output as red, and differences are filled in green to guide the eye. The HHMS was then extended and the simulated shocks were tracked to 6 AU.

Comparison of the observed plasma speed (Figures 1 and 2) with the two models is quite good despite the unusually extreme conditions during the 10/28 to 11/05 period. The post 10/29 shock's plasma speed (HAFv2) exceeds the observed speed due to the initialization parameter used at 2.5Rs. We also note that the otherwise reasonable temperature comparison (Figure 2, panel c) of HHMS with the observations has several extreme excursions to low values. This, we believe, is due to the omission in the HHMS' ideal 3D MHD code of thermal conduction and Alfven wave damping.

Figure 3 shows the solar wind magnetic field in the ecliptic plane as calculated using the HAFv2 model out to 6 AU before (October 12, 2003) and after (November 06, 2003) the Halloween 2003 events. For comparison with the HHMS, the polarity of the field is color-coded (blue toward the Sun, red away from the Sun), and the density of the magnetic field lines is proportional to the plasma density.

The four panels in Figure 4 show solar wind plasma radial velocity (Vr) and IMF polarity before (October 12, 2003) and after (November 06, 2003) the Halloween 2003 events. In the ecliptic plots of Figure 4 the changes are evident in the configuration of the

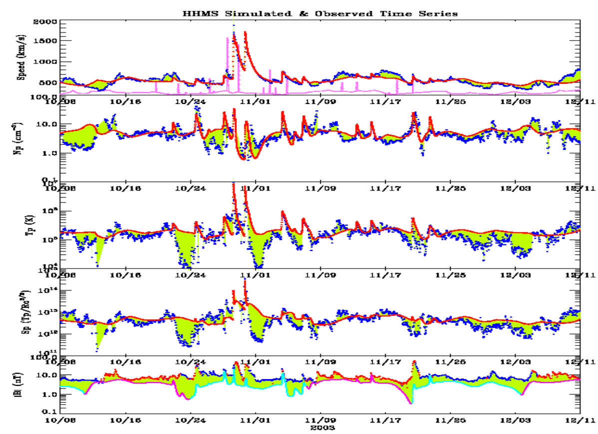

FIGURE 1. The arrival of the Halloween 2003 shocks at ACE on October 28, 29, 30, and November 4, 2003 are shown in the solar wind data and the HAFv2 results. The timings of the shock arrivals and the magnitudes of the associated speed jumps in the predictions of the HAFv2 model are very similar to the ACE speed observations at 1 AU. The Vs values in Table 1 of Intriligator et al. [2] were tuned to optimize *only* the agreement between the shock arrivals in the model results and in the ACE observations.

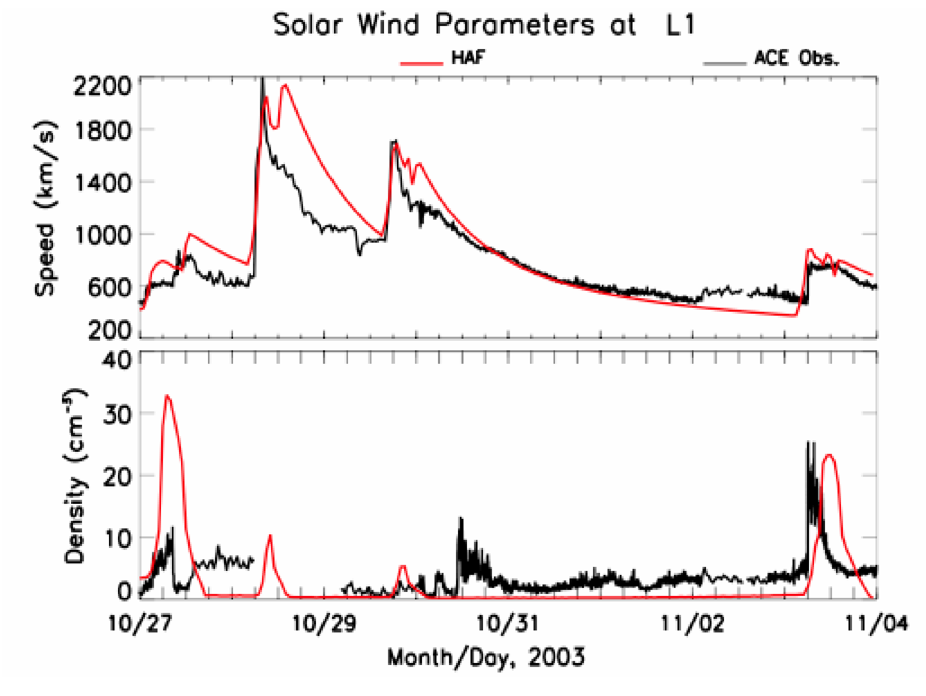

FIGURE 2. Comparison of HHMS simulated time series with ACE observations. ACE data are plotted as blue symbols, these represent 15-minute block averages as described in text. HHMS simulation output is plotted as red dots, one for each time step. Differences are filled in green to guide the eye. (a) Speed, (b) Density, (c) Temperature,(d) Entropy, (e) Magnetic field strength. Panel (a) also shows (in magenta) the model sub-Earth boundary condition speed at 0.1 AU. Panel (e) also indicates the IMF polarity changes in the red-to-blue (and vice versa) colors.

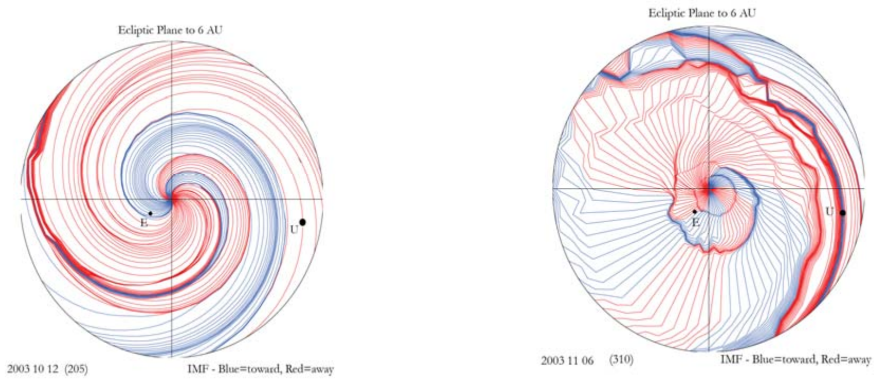

FIGURE 3. Showing the solar wind magnetic field in the ecliptic plane as calculated using the HAFv2 model out to 6 AU before (October 12, 2003) and after (November 06, 2003) the Halloween 2003 events. E and U indicate Earth's and Ulysses' locations.

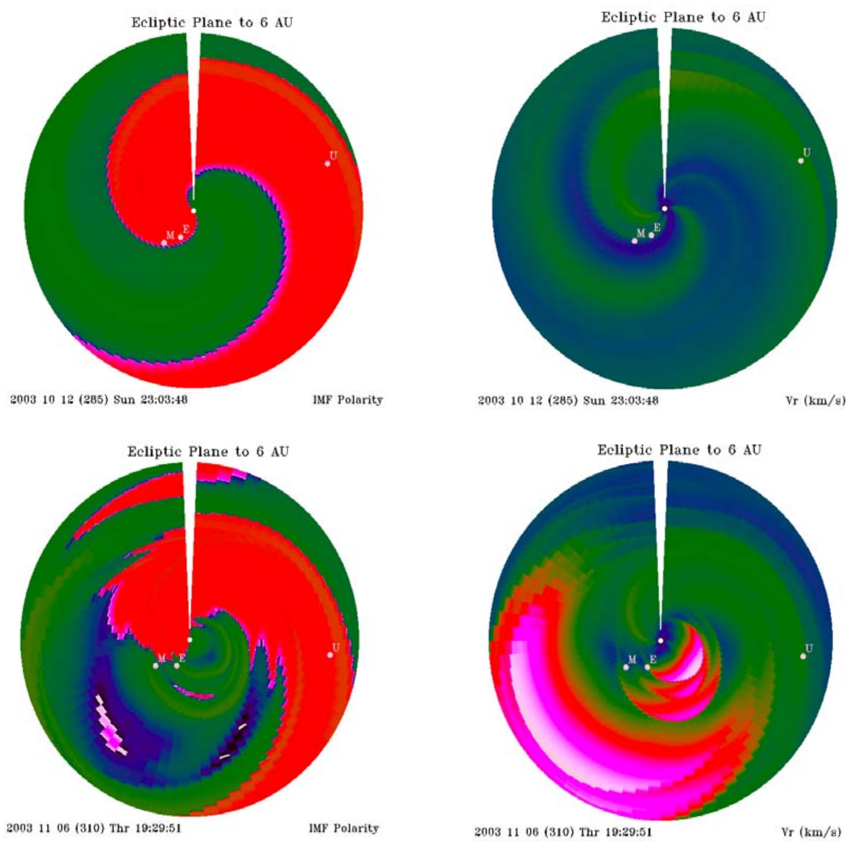

FIGURE 4. Ecliptic plane HHMS plots of the solar wind IMF polarity (left panels) and radial velocity (Vr) (right panels). Before/after the Halloween 2003 events: upper panels (October 12, 2003) and lower panels (November 06, 2003). The small circles show the locations of Earth, Mars, and Ulysses (at 5.23 AU).

interplanetary medium resulting from these Halloween events. This initial global comparison of the two models is encouraging. The HAFv2 model is shown to be an invaluable space weather tool with the HHMS model providing a more detailed examination of plasma and field conditions.

CONCLUSIONS

This work presents the first comparison of the HAFv2 3D kinematic model with a 3D MHD solar wind model. The IMF structure simulated by the HAF and HHMS models is remarkably consistent both with the ACE observations and between the simulations. In addition, the changing and asymmetric distribution of shocked solar wind is well represented by both models. The asymmetric propagation of solar events affects the dynamics of the outer heliosphere. Voyager 1 and Voyager 2 data comparisons with the 3D HAFv2 kinematic simulations and the 3D MHD simulations will enable us to achieve greater understandings of the 3D dynamics of the outer heliosphere and its interaction with the interstellar medium.

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REFERENCES

1. Intriligator, D. S., M. Dryer, W. Sun, C.D. Fry, C. Deehr, and J. Intriligator, *Physics of the Outer Heliosphere*, AIP, V. Florinski, N. Pogorelov, and G. Zank, editors (2004).
2. Intriligator, D.S., W. Sun, M. Dryer, C. Fry, C. Deehr, and J. Intriligator, *J. Geophys. Res*., in press (2005).
3. Fry, C.D., W. Sun, C.S. Deehr, M. Dryer, Z. Smith, S.-I. Akasofu, M. Tokumaru, and M. Kojima, *J. Geophys. Res.* **106**, 20,985-21,001 (2001).
4. Fry, C. D., W. Sun, C. S. Deehr, M. Dryer, Z. Smith, and S.-I. Akasofu, in *Solar-Terrestrial Magnetic Activity and Space Environment*, (H. Wang and R. Xu, Eds.), *COSPAR Colloquia Series on Physics and Astronomy*, 401-407 (2002).
5. Fry, C. D., M. Dryer, Z. Smith, W. Sun, C. S. Deehr, and S.-I. Akasofu, *J. Geophys. Res*. **108**, 1070, doi:10.1029/2002JA009474 (2003).
6. Dryer, M., Z. Smith, C.D. Fry, W. Sun, C. S. Deehr, and S.-I. Akasofu, *Space Weather* **2**, S09001, doi:10.1029/2004SW000087 (2004).
7. Dryer, M., C. Fry, W. Sun, C. Deehr, Z. Smith, S.-I. Akasofu, and M. Andrews, *Solar Phys*. **204**, 267-286 (2001).
8. Detman, T., C. Arge, V. Pizzo, Z. Smith, M. Dryer, and C. Fry, submitted *J. Atm. Solar Terr. Phys*. (2004).
9. Arge, C.N. and V.J. Pizzo, *J. Geophys. Res*. **105** (A5), 10465-10480 (2000).
10. Han, S.M., S.T. Wu, and M. Dryer, *Computers and Fluids* **16**(1), 81-103 (1988).
11. Detman, T.R., M. Dryer, T. Yeh, S. Han, S.T. Wu, and D.J. McComas, *J. Geophys. Res.* **96**, 9531-9540 (1991).
12. Skoug, R.M., J.T. Gosling, J. T. Steinberg, D. J. McComas, C.W. Smith, N. F. Ness, Q. Hu, and L.F. Burlaga, *J. Geophys. Res.* **109**, A09102, doi:10.1029/2004JA010494 (2004).