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Solar Variability Effects in the Outer Heliosphere and Heliosheath

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Abstract. We compare 3D results from the 3D HAFv2 forecasting kinematic model, the 3D MHD HHMS model, and in-situ observations. These comparisons provide insights on the 3D effects of interplanetary shocks. There is good agreement between results from our 3D models and spacecraft data. Voyager 1 and Voyager 2 continue to observe the effects of solar – induced shocks.

INTRODUCTION

At last year's IGPP meeting [1], we discussed the initial comparisons between the two 3D models - the 3D HAFv2 (Hakamada-Akasofu-Fry version 2 [2,3,4]) forecasting kinematic model and the 3D MHD HHMS (magnetohydrodynamic Hybrid Heliospheric Modeling System [5,1] - of the solar wind out to 6 AU with *in-situ* observations at the ACE spacecraft before and after the October/November (Halloween) 2003 solar events. At Solar Wind 11 [6] we extended these comparisons out to 10 AU, including comparisons between the two models and the in-situ Ulysses data. At the SHINE meeting [7] and then the Fall AGU 2005 meeting [8], we extended the types of comparisons between the two models and the data including discussions of the high correlation coefficients between the two 3D models' results for various solar wind and interplanetary magnetic field (IMF) parameters and the in-situ data at ACE and Ulysses for these events and for other time intervals, too.

In the present paper, we show examples of additional capabilities of our 3D models and the types of analyses to which they can contribute. We also revisit the HAFv2 prediction of the arrival of the Halloween 2003 events at Voyager 1 since McDonald 2006 [9] has recently identified the arrival of these events in the Voyager 1 CRS data. We also discuss the more recent Halloween 2004 events and the January-February 2005 events and our prediction at SHINE 2005 for a possible recrossing of the termination shock (TS) in the summer of 2005 at Voyager 1 due to the increased dynamic pressure in the outer heliosphere associated with these events.

When we were invited to discuss this topic, we assumed we would have to put in a correction factor for the arrival of the events at Voyager 1 when the spacecraft was in the heliosheath beyond the termination shock. To our surprise, we found that this was not necessary and that the termination shock did not appear to play a major role in the timing of the arrival of the shocks at Voyager 1.

It is important to have 3D models. The value of our 3D models or any 3D models is not only to correctly predict the timing of the arrival of an event or the profile of an event at the Voyager spacecraft or at other locations. Often more physics is revealed when model predictions do not agree with the observations. In our analyses to date we have found that the 3D HAFv2 model is accurate in predicting the arrival times of the events and the speed profiles of the events at various locations. To date using HAFv2 and HHMS the speed magnitudes and the magnitudes of other plasma and IMF parameters are more accurate <~ 10 AU than in the outer heliosphere. For example, the HAFv2 plasma speeds at Voyager 2 tend to be higher than the measured speeds.

3D HAFv2 Model and the HHMS

Many papers have been published on our 3D models, see [1-8, 10] and references therein. Both of our 3D models incorporate a global, pre-event, inhomogeneous, background solar wind plasma and IMF. They both use source surface models to drive a quasi-steady background solar wind. In both models transient events are superimposed on the background, stream/stream interactions, and corotating interaction region (CIR) buildup are included. At this time interstellar pickup ions are not included in the models, but we plan to include them in the future. Inclusion of the pickup ions in the models will make, for example, the HAFv2 predicted plasma speeds at Voyager 2 more consistent with the data. Both models have been benchmarked between the Sun and 10 AU and HAFv2 has been benchmarked out to Voyager 1 and Voyager 2 at distances of 96 AU and 76 AU, respectively. The HAFv2 kinematic model inputs data at 2.5Rs and has the longest track record in being used successfully to predict the "Fearless Forecasts" in space weather from the Sun to Earth [10] and beyond. In the 3D HHMS [1,3,6,7] the Wang-Sheeley-Arge source surface model plus HAFv2 provide the background boundary condition at 0.1 AU. Shock initiation at 0.1 AU is based on other solar observations. The capabilities of HAFv2 and HHMS complement each other and provide important insights into the 3D physical processes throughout the heliosphere and in the heliosheath.

RESULTS

In Figure 1 we review the HAFv2 benchmarking at ACE and Ulysses for the Halloween 2003 events. We note the relatively high correlation coefficients between the HAFv2 predicted time series and the data (see figure caption). The HHMS benchmarking at these locations [1,6,7,8] also shows relatively high correlation coefficients between the HHMS predicted time series and the data.

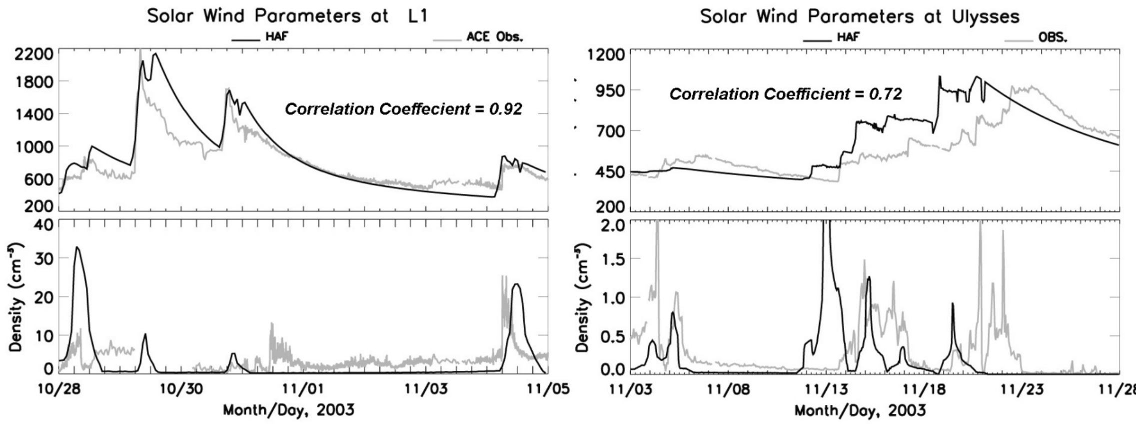
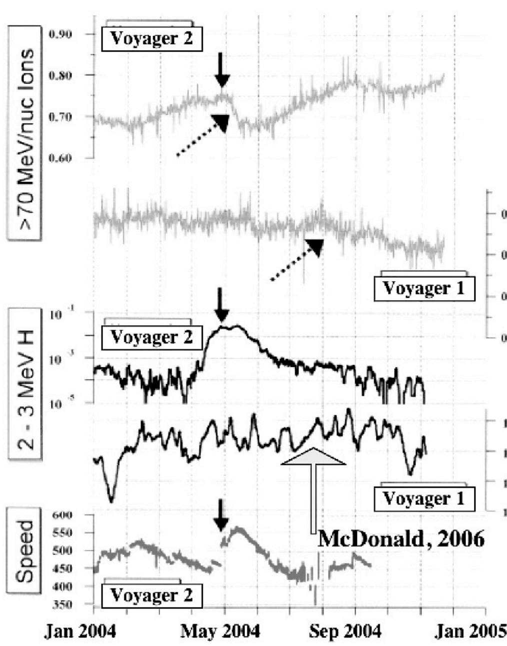


FIGURE 1 (LEFT). The arrival of the Halloween 2003 shocks at ACE (1 AU, 321deg HGI longitude, 4.5 deg latitude) on October 28, 29, 30, and November 4, 2003 are shown (upper panel) in the solar wind speed data and the HAFv2 results. The timings of the shock arrivals and the magnitudes of the associated speed jumps in the predictions of the HAFv2 model are very similar to the ACE speed observations at 1 AU. The Vs (shock speed) values at the sun in Table 1 of Intriligator et al. [3] are the tuned values from optimizing *only* the agreement between the interplanetary shock arrival times at ACE in the model results and in the ACE observations. The correlation coefficient of 0.92 is between the HAFv2 simulated solar wind speeds shown and the data. Before tuning, the correlation coefficient was 0.67. **FIGURE 1 (RIGHT).** Same as Fig. 1(left), but for Ulysses (5.2 AU, 80 deg HGI longitude, 5.8 deg latitude) using the same solar inputs as were used for the HAFv2 simulation for ACE and as shown in Table 1 of Intriligator et al. [3]. Note the large longitude (>90 deg) separation between Ulysses and ACE, yet the HAFv2 model, without any changing of the inputs, obtains a time series profile for the speed at Ulysses that is similar to that observed, but with the predicted shocks arriving a few days earlier. Note the correlation coefficient is 0.72 for this Ulysses speed comparison with the HAFv2 model results.



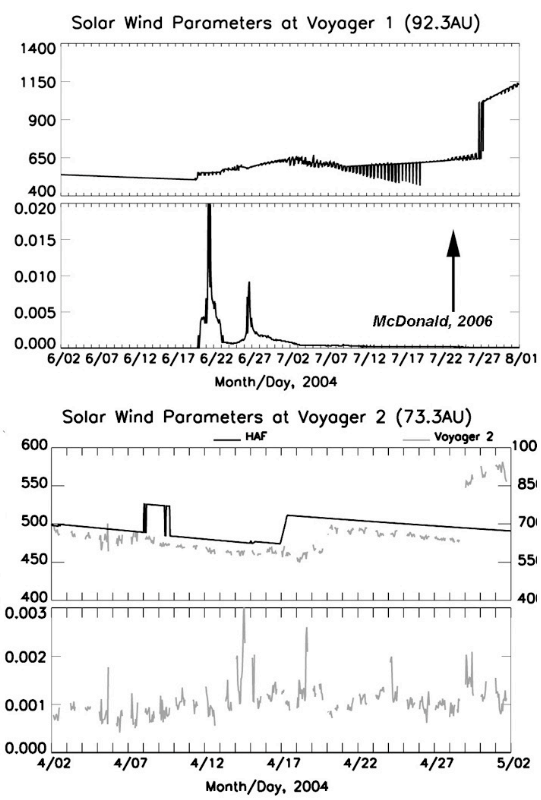


FIGURE 2 (LEFT). Voyager 1 and Voyager 2 data adapted from Intriligator et al. [3]. **Bottom panel:** Solar wind speed Voyager 2 data. **Middle panel:** CRS ~2 - 3 MeV/nuc ions. **Top panel:** CRS >70 MeV/nuc galactic cosmic rays. Vertical black arrows denote the arrival of the big shock from the Halloween 2003 solar events. Inclined dashed black arrows below the data denote the main Forbush decrease associated with the Halloween 2003 events. The large grey filled in arrow below data denotes identification by McDonald [9] of Halloween 2003 shock in Voyager 1 CRS data. **FIGURE 2 (RIGHT TOP)**. Solar wind speed and density parameters - predicted in February 2004 - at Voyager 1 adapted from Intriligator et al. [3]. The large vertical arrow denotes the recent identification by McDonald [9] of the Halloween 2003 shock in the Voyager 1 CRS data. **FIGURE 2 (RIGHT BOTTOM).** Solar wind parameters at Voyager 2 predicted in February 2004 (Intriligator et al. [3]).

Figure 2 shows the Voyager 1 and 2 data associated with the Halloween 2003 events and the HAFv2 predicted time series for these events. These predictions were made in February 2004 before the corresponding Voyager 1 and 2 data were acquired. The recent McDonald [9] identification of the Halloween event in the Voyager 1 CRS data is consistent with the HAFv2 predictions and also with our analyses in Intriligator et al. [3] where the dashed inclined arrow below the Voyager 1 CRS > 70 MeV/nuc data (Fig. 2 left) indicates our previous [3] identification of the probable Forbush decrease at Voyager 1 associated with the Halloween 2003 events.

Figure 3 shows the HHMS latitude plots (+/- 45 deg) of the solar wind speed, Vr, from the Sun to 10 AU along the Sun-Earth line for three different times associated with the Halloween 2003 events. The left (10/08/03) plot shows the quiescent configuration before the events. Note, between the Sun and ~4 AU, that the high speeds associated with the northern coronal hole extend from 45 deg north (the top of the plot) down to the equator. Similarly, between 4 to ~ 7.5 AU, the high speeds associated with the southern coronal hole extend from 45 deg south (the bottom of the plot) toward the equator and near 6 AU they extend almost up to 20 deg north. Beyond ~8 AU the high speeds from a northern coronal hole extend toward the equator. The middle plot (11/08/03) shows the speed variations associated with some of the Halloween shocks, as indicated by the arrows. In contrast to the quiescent configuration, note the almost uniform vertical regions of speed extending across all latitudes from +/- 45 degrees. Some of these speed slabs extend along the Sun-Earth line for ~ 1 AU. In the third plot (11/28/03) near the Sun (<~3 AU) the quiescent coronal hole configuration is beginning to return. Beyond ~3AU the 11/17 shock front is seen. Similar HHMS latitude plots are available for the IMF and other plasma parameters.

Figure 4 shows a different diagnostic of the solar wind and IMF provided by HHMS. In this case the solar wind speed (Vr) is shown in four simultaneous meridian "slices" - similar to medical magnetic resonance imaging (MRI) views - on November 24, 2003 following the Halloween 2003 events. In Fig. 4 the +/- 45 deg slices extend from the Sun to 10 AU along the Sun-Voyager 1 longitude line, the Sun-Voyager 2 line, the Sun-Cassini line, and the Sun-Earth line. The speed variations in the V1 and V2 slices in the direction of the respective spacecraft, which are relatively close in longitude, are similar. The variations in these slices are quite different from the other slices, particularly in the directions of Cassini and Earth.

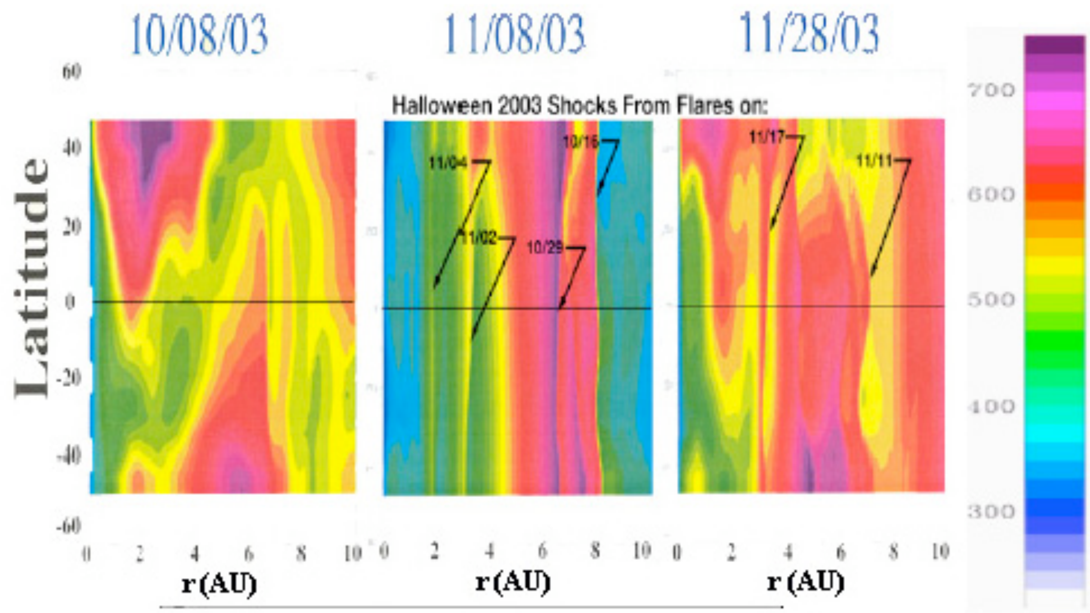


FIGURE 3. HHMS latitude plots (+/- 45 deg) along the Sun-Earth line of the solar wind speed (Vr) from the Sun to 10 AU for three different time intervals associated with the Halloween 2003 solar events. The dates and arrows indicate the time and location of some of the specific shocks listed in Table 1 in Intriligator et al. [3].

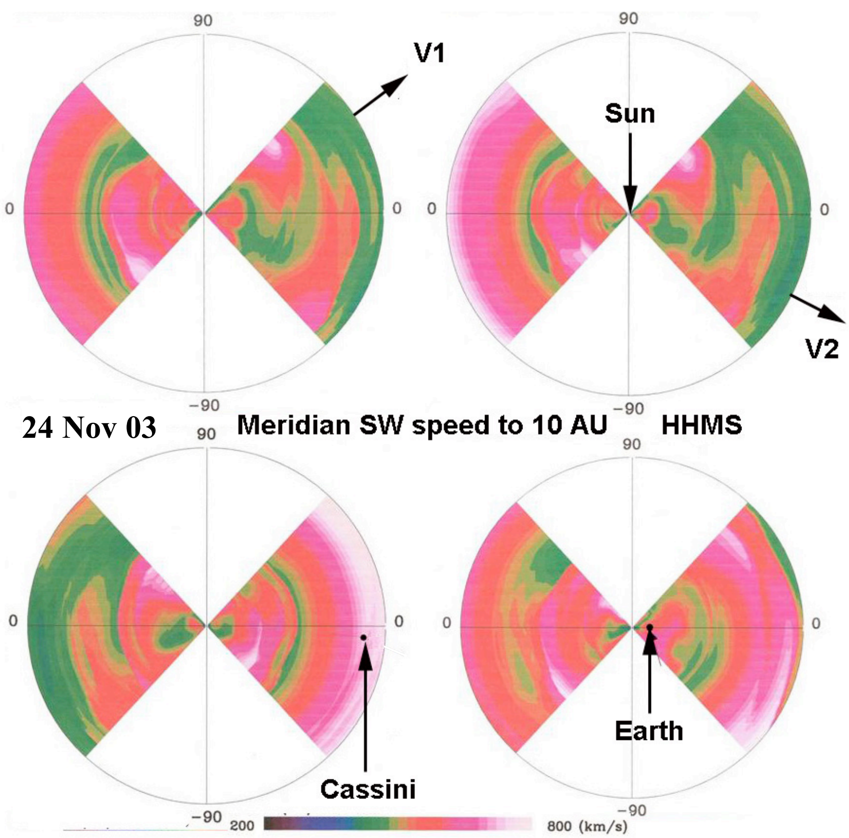


FIGURE 4. Four simultaneous HHMS MRI-like meridian plots on November 24, 2003 following the Halloween 2003 solar events showing the latitude (+/- 45 deg) variation of the solar wind speed out to 10 AU along four different longitudinal slices: the Sun-Voyager 1 line, the Sun-Voyager 2 line, the Sun-Cassini (Saturn) line, and the Sun-Earth line.

At the SHINE 2005 meeting [7] we predicted, on the basis of HAFv2 simulations, that the termination shock might re-cross Voyager 1 during Aug/Sept 2005 due to an increase in solar wind dynamic pressure from the Halloween 2004 (not 2003) events. To date the available Voyager 1 data do not appear to indicate that this second TS crossing occurred. If this is in fact the case, we suggest that an increase in the heliosheath magnetic field may have been able to "stand off" the TS as it moved outward toward Voyager 1. The timing of the arrival of this solar-induced event at Voyager 1 in the heliosheath appears to be consistent with our prediction [7].

SUMMARY

Statistical analyses between data (1 - 10 AU) and both 3D model results show high correlation coefficients between the predicted time series and the data. All spacecraft (1 - 96 AU) are observing the effects of solar-induced shock waves. Voyager 1 and Voyager 2 data comparisons with the results from both 3D models lead to better understanding of the 3D dynamics of the outer heliosphere and heliosheath.

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