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3D modeling and turbulence: from the Sun to Voyager 1

Devrie S. Intriligator [1], Adam Rees[2], Timothy Horbury[2], Wei Sun[3], Thomas Detman[4,5], Murray Dryer [4,5], Charles Deehr[3], and James Intriligator [1,6]

1. Carmel Research Center, P.O. Box 1732, Santa Monica, CA 90406 USA
2. Imperial College, London, England, UK
3. Geophysical Institute, University of Alaska, Fairbanks, AK 99775, USA
4. Exploration Physics International, Inc., Huntsville, AL 35806, USA
5. NOAA/Space Environment Center, 325 Broadway, Boulder, CO 80305 USA
6. University of Wales, Bangor, Wales, LL572AS, UK

Abstract. We compare in-situ observations at ACE and Ulysses with simulation results obtained from two different 3D models. Specifically, we look at results from the time dependent full 3D MHD HHMS model and also from the quick-look tool: the 3D HAFv2 kinematic model. These comparisons provide insights into the 3D propagation of interplanetary shocks. We find excellent agreement between results from our 3D models and spacecraft data. Our results also suggest that Voyager 1 and Voyager 2 continue to observe the effects of solar–induced shocks. The presence of planar magnetic structures is found from ACE to Voyager 1 in association with the Halloween 2003 events. These results are consistent with large-scale compressions and may have possible consequences for cosmic ray modulation. The results of our models, along with numerous in-situ observations, illustrate several aspects of interplanetary shock propagation that have implications for future modeling efforts. First, only continuous 3D models can accurately capture the dramatic asymmetries that often evolve over time. Second, although in-situ observations (at Earth, L_1. etc.) are unquestionably valuable (e.g., for helping to refine or "tune" a model), because shock-induced effects may sometimes miss a location entirely, any model (1D, 2D, or even 3D) that relies only on such observations can often make seriously erroneous predictions. Third, along the same lines, any attempt to model the propagation of solar phenomena must begin this propagation at the source – the Sun. And, finally, because such propagation is going to be heavily dependent on the state of the medium through which it is propagating, models must incorporate this pre-event state. Thus, we emphasize the importance of using these primary solar source data as continuous inputs into models that extrapolate in three dimensions phenomena from the solar surface throughout the heliosphere and into the heliosheath.

Keywords: solar variability effects, solar wind plasma & fields, interplanetary magnetic fields, discontinuities, energetic particles, cosmic rays, turbulence.
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INTRODUCTION

At last year's IGPP meeting [1], we discussed comparisons between the two 3D models - the time dependent full 3D MHD HHMS (magnetohydrodynamic Hybrid Heliospheric Modeling System [6,1]) and the quick-look tool, the 3D HAFv2 (Hakamada-Akasofu-Fry version 2 [1-5]) forecasting kinematic model, of the solar wind out to 10 AU with *in-situ* observations. All of our results from our two 3D models - that continuously input solar data and then propagate the background and disturbed solar wind and interplanetary magnetic field (IMF) throughout the 3D heliosphere - provide a basis for a deeper understanding of the effects of solar events and of their 3D propagation to the outer heliosphere. We reported the surprising result that Voyager 1 observations in the heliosheath confirmed the HAFv2 predictions of the time of arrival of shocks

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associated with the January 2005 solar events and the Halloween 2004 solar events. This agreement was unexpected since the quick-look tool, HAFv2, does not contain any corrections for the presence of the termination shock. Based on these agreements between the HAFv2 predictions for the timing of the arrival in the heliosheath of the shocks associated with the solar events, we concluded that it did not appear that the termination shock played a major role in the timing of the arrival of these shocks in the heliosheath. We also reported on the confirmation of our HAFv2 predictions for the arrival of these events in the outer heliosphere at Voyager 2 and for the arrival of the Halloween 2003 solar events at Voyager 1 in the outer heliosphere. We also presented some of the results from the full 3D MHD HHMS that showed the heliospheric asymmetries in latitude and longitude associated with the propagation of the Halloween 2003 events to the outer heliosphere.

In the present paper, we show examples of additional capabilities of our 3D models and the types of analyses to which they can contribute. Our time dependent full 3D MHD HHMS can be tuned and the grid size adjusted to obtained better agreement between the model predictions and ACE and Ulysses data. Examples of latitude and longitude variations from the HAFv2 quick-look tool emphasize the importance of employing 3D models with continuous solar inputs for studying the effects of the propagation throughout the heliosphere of disturbances originating with solar events. We also begin our examination of the turbulence associated with these events by investigating the presence of planar magnetic structures (PMS) associated with the propagation of the Halloween 2003 events from ACE to Voyager 1.

3D MHD HHMS and the 3D HAFv2 Model

Both of our 3D models have a continuous input of solar parameters, see [1-9, 11] and references therein. Both of our 3D models incorporate a global, pre-event, inhomogeneous, background solar wind plasma and IMF. They both use solar source surface models to drive a quasi-steady background solar wind. In both models transient events are then superimposed on this background. These models also incorporate the buildup of corotating interaction regions (CIRs). We have proposed extending the continuous time dependent 3D full MHD HHMS from 10 AU to >100 AU. To this end, we have been making numerous improvements to the HHMS [6]. We have been tuning a 1 AU version of HHMS designed for expansion to >100 AU. Specifically, we optimized the parameter agreement with ACE data, incorporated a polytropic index, ? = 1.6, more appropriate for the outer heliosphere - instead of 1.5 (Totten et al., [12]); and we use the sonic and Alfven Mach numbers as empirical boundary condition tuning parameters [6]. At this time interstellar pickup ions are not included in the models, but we plan to include them in the future. We believe that 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. We have benchmarked both models between the Sun and 10 AU and HAFv2 has been benchmarked out to Voyager 1 in the heliosheath at distances >100 AU. The HAFv2 kinematic model inputs data at 2.5Rs and has the longest track record in being used successfully to predict the "Fearless Forecasts" for shock arrival times (SATs) from the Sun to Earth [11] and beyond. It is currently being used by the U.S. Air Force for real time predictions of the solar wind for space weather purposes.

RESULTS

In Figure 1 we show the full 3D MHD HHMS benchmarking at ACE for the Halloween 2003 events. Note the excellent agreement with the HHMS 1 AU solar wind speed and the data. The full 3D MHD HHMS also was used to obtain comparisons of additional parameters over a longer time interval at ACE (Figure 2). Here again the benchmarking shows relatively high correlation coefficients between the HHMS predicted time series and the data. The close agreement between the HHMS simulation and observations shown in Figures 1 and 2 is at 1 AU (ACE observations), and is for a

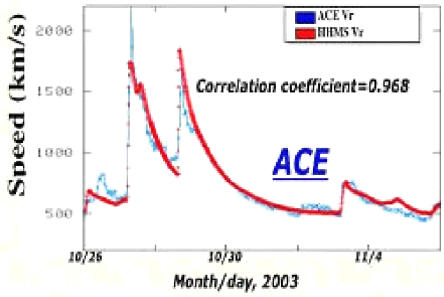

Figure 1. HHMS and ACE solar wind speed with high correlation coefficient (0.968) for the Halloween 2003 solar events. HHMS is a time dependent full 3D MHD modeling system with continuous solar inputs.

powerful series of shock waves. The shock strength inputs (at the 0.1 AU inner grid boundary) for each shock were carefully tuned to produce agreement between the simulated shock and the observed shock arrival times at ACE. These large-scale features dominate the appearance of Figures 1 and 2. Although the smaller turbulent fluctuations of Vr, Np, and (By-Bx) are not as well reproduced in the simulation, this is not surprising given the scale of these fluctuations and our current grid size (5 x 5 degree angular resolution). We hope to explore improved grid resolution in future work.

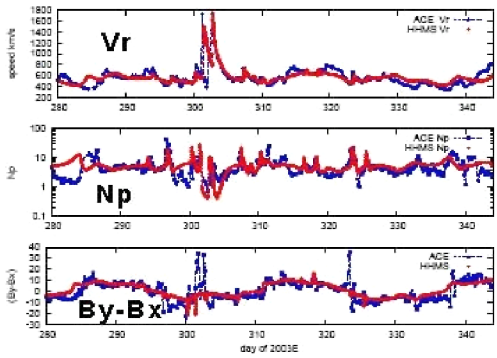

Figure 2. HHMS and ACE data comparisons for Halloween 2003 solar events: speed (Vr), density (Np), and IMF By - Bx.

Figure 3 shows some HHMS results at Ulysses, which was separated by >90 deg from Earth. The correlation coefficient (0.808) for the speed comparison is excellent at this longitudinal separation and distance of 5 AU. Also, the coefficients for the density

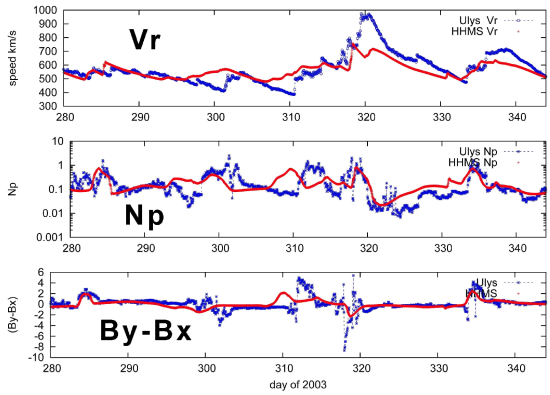

Figure 3. Same as Fig. 2, at Ulysses.

(0.324) and IMF polarity (By-Bx; 0.403) are considered reasonably satisfactory given the nature of this comparison. Richardson et al. [13] used a 1D MHD model and input data measured at 1 AU but failed to obtain structures like those observed at Ulysses. In contrast, both our HHMS (see Figure 3) and our HAFv2 model (see Figure 1 in [1]) input continuous solar data and obtain structures more similar to those observed at Ulysses [1-9]. At Voyager 2, using our quick-look tool, HAFv2, we obtained the arrival in April 2004 of two shocks with the correct spacing between them. In contrast, Richardson et al. predicted only the arrival of one shock, and their results had to be time shifted 14 days.

Figure 4 shows the line of sight (LOS) densities associated with the Halloween 2003 events obtained with our 3D HAFv2 model looking back toward the Sun from Earth on October 28, 2003. This figure illustrates two important points. First, the strong latitude asymmetries emphasize the need for using 3D modeling. Second, frequently, as in the case depicted here, much of the activity propagating outward from the Sun may bypass

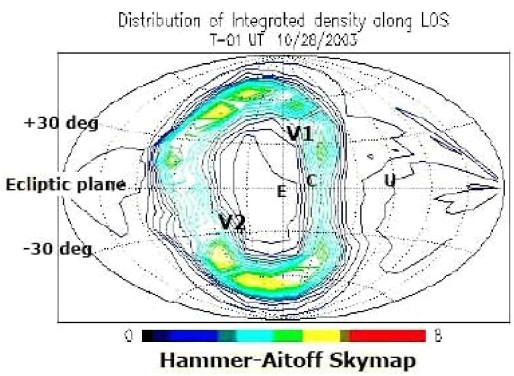

Figure 4. HAFv2 line-of-sight (LOS) densities from Earth (E) looking toward the Sun (and toward Voyagers - V1 & V2) for Halloween 2003 events. Locations of Cassini (C) and Ulysses (U) are shown. Note the large asymmetric mass distribution. Note also that if you were to input the mass distribution at Earth into models, you would not get the correct mass distributions at V1, V2, or C.

the Earth, and thus any attempt to use 1D or even 3D models to extrapolate measurements taken at Earth to other locations in the heliosphere could be drastically misleading.

Similarly, Figure 5 shows the large longitudinal asymmetries and distortions from the spiral IMF in the ecliptic plane out to 10 AU on October 31, 2003 obtained by the 3D HAFv2 model, which originates at the Sun and uses continuous solar inputs. The locations of Earth, Ulysses, Cassini, Mars, Jupiter, and Saturn are shown in Figure 5. In this reference frame, Voyager 1 would be located in the direction of 172 deg at 93 AU

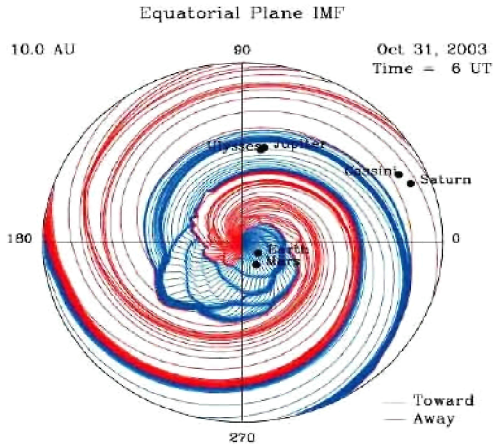

Figure 5. HAFv2 ecliptic plane plot from Sun (origin) to 10 AU with IMF lines showing the asymmetric longitudinal compressions and distortions from the spiral field configuration due to the Halloween 2003 solar event transients.

and Voyager 2 would be at ~215 deg at 73 AU. Here again the large IMF asymmetries shown in the figure emphasize the need for 3D modeling originating at the Sun. As we saw in the LOS data (Figure 4), here again it is obvious that one would obtain a very inaccurate view if he/she were to input IMF data at Earth into any model and extrapolate to other locations.

To begin our study of turbulence throughout the heliosphere in association with the Halloween 2003 solar events we follow up on our paper Intriligator, Jokipii, Horbury, et al. [14] where we found evidence of planar magnetic structures (PMS) in association with the stream interface in corotating interaction regions (CIRs) and in association with the entire CIR. Intriligator, Jokipii, Horbury, et al. [14] also showed that there was reduced cross transport for energetic particles near the stream interface in CIRs consistent with the energetic particle profiles in CIRs (Intriligator and Siscoe, [15]; Intriligator et al., [16]) and with the expectations of Intriligator and Siscoe [17]. Intriligator et al. [4] showed that, for example, at Voyager 2 the largest shock associated with the Halloween 2003 solar events was a prolific producer of 2-3 MeV/nuc energetic particles. Intriligator at al. [4] also indicated that somewhat later there was modulation of the >70 MeV/nuc galactic cosmic rays (GCRs).

Planar magnetic structures (PMS) were first reported by Nakagawa et al. [18]. Figure 6, adapted from Jones and Balogh [19], is a conceptual drawing of PMS. PMS can be

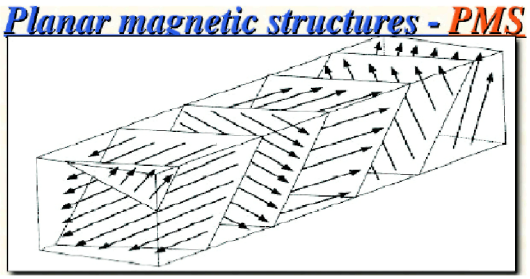

Figure 6. Planar magnetic structures (PMS) adapted from Jones and Balogh [19]. The IMF field vectors in neighboring regions, although oriented in various directions are all parallel to a fixed plane. Planar regions are separated by discontinuities, which also are parallel to the same plane.

formed in regions of compression such as CIRs and CMEs, in which case the magnetic field vectors lie on a great circle in the location of the compression [14]. In this case, the magnetic field minimum variance vector lies perpendicular to the large-scale compression plane and can, therefore, be used to deduce its orientation. We investigated the presence of PMS in association with the Halloween 2003 solar events in the spacecraft data at ACE, Ulysses, Cassini, Voyager 2, and Voyager 1. Generally, we found that PMS were present at each location, consistent with compression at the leading edges of these structures. For example, Figure 7 uses 1-hour resolution IMF data and shows a scatter plot of IMF latitude theta versus IMF longitude, phi, to indicate the orientation of the PMS at Voyager 1: the dashed line indicates the plane perpendicular to the maximum variance vector, on which most of the field vectors lie. Figure 7 indicates that a planar magnetic structure is present at Voyager 1 in association with the Halloween 2003 solar events.

In the future we plan to continue our investigation of turbulence and to examine, for example, the power associated with fluctuations in the various components of the IMF and the implications for cross-field transport and the modulation of galactic cosmic rays. This already was shown [14] for locally accelerated particles at CIRs.

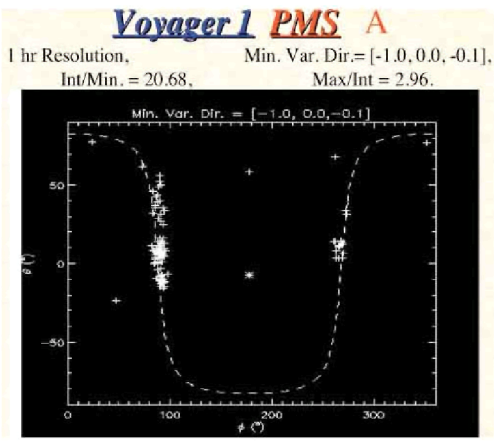

Figure 7. PMS scatter plot of theta versus phi for the Voyager 1 time interval associated with the Halloween 2003 solar events. In a PMS (in solar ecliptic coordinates) the IMF latitude theta is a single-valued trigonometric function of the IMF longitude phi.

Our 3D models with continuous solar inputs are essential for the interpretation of in-situ data at diverse heliospheric and heliosheath locations. Statistical analyses between data (1-10 AU) and our full 3D MHD HHMS results show high correlation coefficients. The strong latitude and longitude asymmetries in the solar wind and IMF in association with solar events emphasize the importance of using 3D models with continuous solar inputs. Planar magnetic structures are present in the interplanetary data from ACE to Voyager 1 in association with the Halloween 2003 solar events.

SUMMARY

Our 3D models with continuous solar inputs are essential for the interpretation of in-situ data at diverse heliospheric and heliosheath locations. Statistical analyses between data (1-10 AU) and our full 3D MHD HHMS results show high correlation coefficients. The strong latitude and longitude asymmetries in the solar wind and IMF in association with solar events emphasize the importance of using 3D models with continuous solar inputs. Voyager 1 and Voyager 2 continue to observe the effects of solar–induced shocks. Planar magnetic structures are present in the interplanetary data from ACE to Voyager 1 in association with the Halloween 2003 solar events.

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