Three-Dimensional Simulations of Shock Propagation in the Heliosphere and Beyond

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Abstract. Continuous input of solar data to time-dependent 3D models is necessary for the study of shock propagation in the solar wind. We have performed time-dependent 3D simulations using two different models, the full MHD based HHMS model and the kinematic HAF model, to study turbulence, particle acceleration and transport, cosmic ray modulation, and other physically significant phenomena. The continuous solar inputs to these models include solar data from source surface maps, Wang-Sheeley-Arge parameters, and information on solar events such as coronal mass ejections, flares, etc. Model output options include the time series at any location of specific solar wind and magnetic field parameters, entropy, momentum flux, shock propagation, longitude and latitude distributions of parameters, meridian slices at any orientation for any parameter throughout the 3D heliosphere, flux ropes, interplanetary coronal mass ejections, corotating interaction regions, merged interaction regions, etc. Through comparisons with in-situ spacecraft data we are continuing our benchmarking of these models throughout the heliosphere and beyond. Comparisons of the results of these models with our analyses of planar magnetic structures associated with the October/November 2003 solar events provide additional insights into particle transport processes, shock propagation, and the modulation of cosmic rays. These efforts contribute to our understanding some of the physical mechanisms responsible for particle acceleration and transport.

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

Three-dimensional (3D) simulations starting at the Sun can provide important insights into particle acceleration and transport throughout the heliosphere and beyond. They can indicate locations of interplanetary shocks, regions of compression, merged interaction regions, and longitudinal and latitudinal asymmetries. While it is better to perform simulations originating at the Sun than those originating at another location (e.g., L1 or Ulysses), and while it is better to perform 3D simulations rather than 1D or 2D simulations, it is best to perform *continuous* 3D simulations originating at the Sun in the context of the solar events preceding and following them [1-11]. We will show that even performing a 3D simulation originating at the Sun in isolation, that is, not in the context of the preceding and following solar events, can lead to erroneous conclusions concerning the event's interplanetary propagation and the asymmetries associated with its propagation throughout the heliosphere. To illustrate this we will present our results for

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the January 2005 solar events, since there has been so much interest in these events at this conference. We also will summarize the evolution of the December 2006 solar events, because of the number of papers at this conference concerning these last events of solar cycle 23. Finally, we will discuss the planar magnetic structures [1, 12] associated with the propagation of the Halloween 2003 events and how they become more perpendicular to the radial direction as they propagate farther out in the heliosphere. In Intriligator, Jokipii, Horbury, et al. [13] we showed that the compressions associated with these structures in corotating interaction regions could lead to reduced particle transport.

3D MHD HHMS and the 3D HAF Model

As shown in the schematic in Figure 1, both of our 3D models employ continuous inputs of solar parameters, see [1-11] 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 are in the process of incorporating pickup ions into the time dependent 3D full MHD Hybid Heliospheric Modeling System (HHMS) [7]. After various model distributions for the pickup ions are incorporated into HHMS and the HHMS simulations compared with spacecraft data, we will determine the optimum incorporation of pickup ions in HHMS. Following this we will extend HHMS from 10 AU to > 100 AU. We then will incorporate

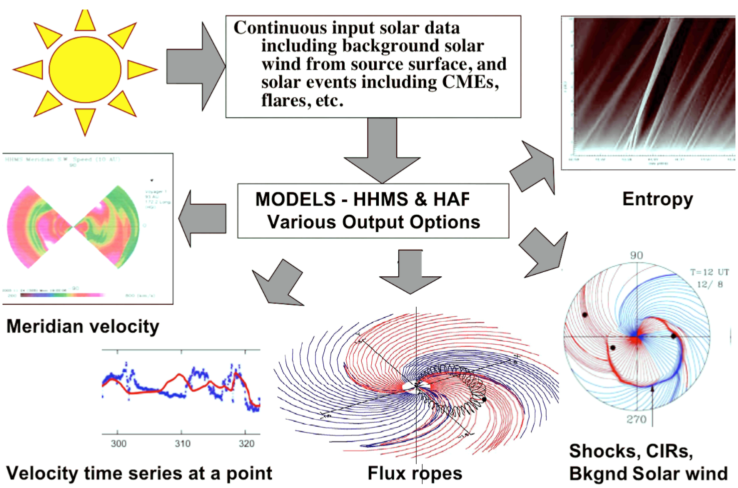

FIGURE 1. Schematic showing the continuous inputs of solar parameters into both of our 3D models - the full MHD HHMS and the kinematic HAF – and the models' multiple outputs for studying various aspects of shock propagation throughout the heliosphere.

pickup ions in HAF by comparing the results for various solar events from the new HHMS that incorporates pickup ions with spacecraft data at various locations throughout the heliosphere for these same events and with HAF results at these multiple locations for these same events. Through this iterative process of comparisons we will be able to determine how to adjust the HAF output to accurately take into account the pickup ions. The HAF model was originally developed at the Geophysical Institute of the University of Alaska. This empirical model is appealing since it runs relatively fast and we have been successful in extending and improving it so that it can provide simulations to heliospheric distances >100 AU.

RESULTS

Table 1. summarizes the solar events from January 1 through February 1, 2005 in the same format as our previous tables [5] and indicates the input data for our improved HAF model. Once these data are input into the model nothing is changed and the model runs from the Sun out in 3D going past the Earth and ACE and Wind, out to Ulysses and then Cassini, and then to Voyager 2 and finally to Voyager 1.

Figure 2 is a composite showing the results from three runs of the improved HAF with different input parameters. In the top – uppermost - panel, the Jan. 20 event is run alone as listed in Table 1. In the middle panel, the January 20 event is run alone, but it is tuned, i.e., the parameters listed for it in Table 1 are varied so that the shock arrival in the HAF simulation coincides with the shock arrival in the ACE data as shown in the middle panel in Figure 2. In the bottom panel, the Jan. 20 event is run along with all the events from Jan. 15 through Feb. 1, 2005 as listed in Table 1. In this case none of the data are tuned. They are all run as listed in Table 1. It is evident from Figure 2 that the simulation in the bottom panel where all the events from Jan. 15 through Feb. 1, 2005, were run not tuned yields the best fit to the spacecraft data.

The HAF ecliptic plane plot on the left in Figure 3 is associated with the middle panel in Figure 2. It shows the expected longitudinal distortion of the interplanetary magnetic field (IMF) and the propagation through the heliosphere – from the Sun to 100 AU - of the disturbances associated with the tuned Jan. 20 event only run in isolation, i.e., excluding the other solar events shown in Table 1.

Table 1. January 1 through February 1, 2005 solar events and HAF model inputs*

FF#	Date		Time	Lat	Lon	Vs(km/s)	Tau
0580	2005	0101	0030	N06	E33	1028	0200
0581	2005	0109	0854	S09	E70	847	0330
0582	2005	0114	1247	S07	E05	686	0020
0583	2005	0115	0554	N16	E04	1300	0300
0584	2005	0115	2234	N15	W05	1151	0200
0585	2005	0117	0944	N15	W25	1578	0500
0586	2005	0119	0814	N15	W51	1230	0300
0587	**2005**	**0120**	**0644**	**N14**	**W61**	**1006**	**0500**
0588	2005	0201	1032	N13	E158	3000	0200

*FF#: real-time "fearless forecast" events. Date & Time: start time of metric Type II. Vs (km/s): shock speed input at the Sun from real-time radio & halo/partial halo CME plane-of-sky speed estimates. Tau (hours & minutes): coronal shocks piston driving time above flare site.

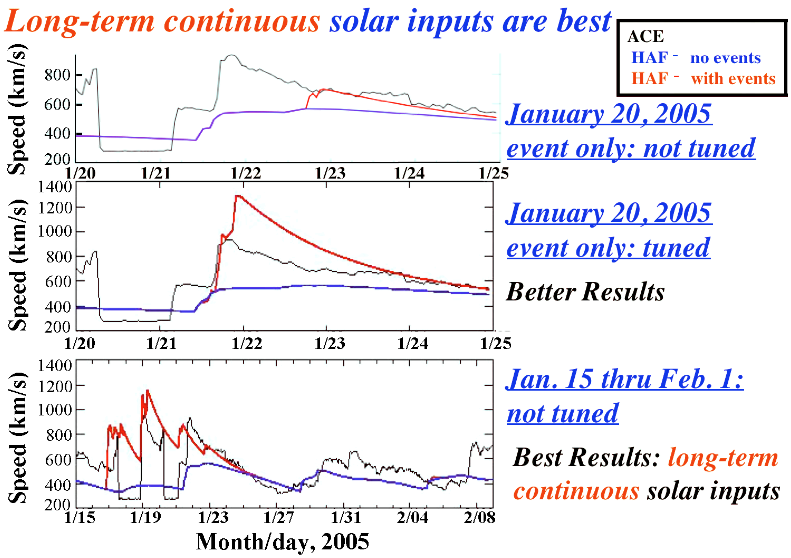

FIGURE 2. HAF results showing the necessity of continuous solar inputs and that long-term continuous solar inputs are best. The arrival of the shock(s) in the ACE speed data and the HAF simulation results for three different cases of solar input parameters: top panel input: Jan. 20 solar event only with parameters not tuned, i.e., as listed in Table 1; middle panel input: Jan. 20 solar event only with parameters tuned so that the arrival of the HAF shock coincides with the arrival of the shock in the ACE data; bottom panel inputs: solar parameters from Jan. 15 through Feb. 1 not tuned, i.e., as listed in Table 1. ACE data instrumental dropouts, due to temporary energetic particle impacts, should not be considered.

In contrast, the HAF ecliptic plane plot on the right in Figure 3 displays the expected IMF distortion and the propagation of the not tuned Jan. 20 event run in the context of the Jan. 15 to Feb. 1, 2005 events as listed in Table 1. While the ecliptic plane plot on the left - for the Jan. 20 event (tuned) run in isolation - shows the shock propagating primarily in the direction of Voyager 1, the ecliptic plane plot on the right – for the Jan. 20 event (not tuned) run in the context of the events around it - shows the interplanetary disturbance actually propagates in a different direction: toward Voyager 2 and 270 deg longitude. Thus, it is evident that not only is it important, but it is a necessity, to run shock propagations, parameter time series, ecliptic plane propagations, and other analyses with continuous solar inputs and not in isolation, but in the context of the preceding and following solar events.

Since there has been a great deal of interest at this conference and generally on the December 2006 solar events, in Figure 4 we show a series of ecliptic plane plots [14] of the inner heliospheric longitudinal propagation of these events extending from the Sun at the origin to 2 AU. These plots show that for these events, even relatively close to the Sun in the inner heliosphere, there is the overtaking and merging of the associated interplanetary shocks and their asymmetric propagation through the solar wind.

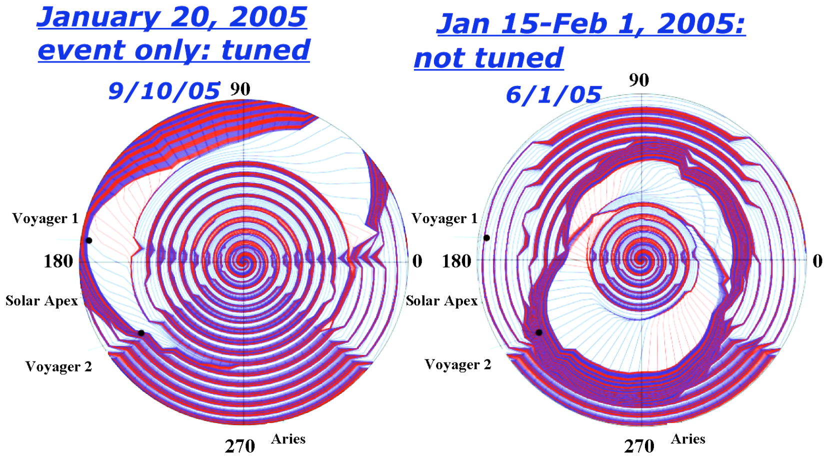

FIGURE 3. HAF ecliptic plane plots from the Sun (origin) to 100 AU with IMF lines showing the asymmetric longitudinal compressions and distortions from the spiral field configuration. The Sept. 10, 2005 plot on the left is due to the January 20, 2005 solar event alone tuned so that its shock arrival time at ACE coincides with the time of the shock observed in the ACE data. The June 1, 2005 plot on the right is due to the solar events between January 15 and February 1, 2005 run not tuned rather as shown in Table 1.

Last year at this conference we presented the first results on planar magnetic structures (PMS) [1,12,13,15,16] in the solar wind in association with the Halloween 2003 events. Our motivation was that in Intriligator, Jokipii, Horbury, et al. [13] we showed that the reduction of cross-field particle transport in corotating interaction regions (CIRs) was consistent with it being due to compression. The energetic particle profiles in CIRs [17-19] show an intensity minimum at the stream interface that was tempting to

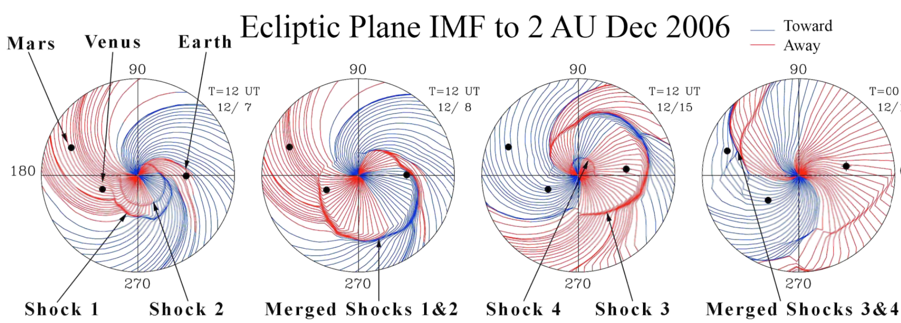

FIGURE 4. HAF ecliptic plane plots with IMF lines showing the asymmetric longitudinal compressions and distortions from the spiral field configurations due to the Dec. 2006 solar events. The four shocks from the events are shown. Note their evolution and merging.

associate with the increased IMF cross-field magnitude and its increased low frequency turbulence due to compression at the stream interface. Last year [1,12] we showed that planar magnetic structures were associated with the Halloween 2003 events at each spacecraft we examined: ACE, Ulysses, Cassini, Voyager 2, and Voyager 1.

Figure 5 shows the changing cone angle of the PMS normal with respect to the radial direction. Generally the cone angle of the PMS normal with respect to the radial direction decreases as the PMS propagate farther out in the heliosphere. The Voyager 2 cone angles in Figure 5 do not appear to follow this trend. Our analyses also indicate that generally, with the exception of Voyager 2, the planes forming the PMS become better defined as they propagate farther out in the heliosphere. At Voyager 1 the small cone angle of the PMS normal and the well-defined planes forming the PMS imply that there is substantial compression associated with the PMS near V1. It is tempting to associate this compression with the apparent simultaneous strong modulation of the galactic cosmic rays [1,12]. This is consistent with the reduced particle transport we reported earlier in association with the increased compression near the stream interface of corotating interaction regions [13]. We plan to investigate the role of compression and particle transport in association with planar magnetic structures and with the termination shock and the heliopause.

The reason for the Voyager 2 PMS not following the trends with respect to the smaller cone angle and better defined PMS planes with distance is not known. It is tempting to speculate that it is due to noise in the Voyager 2 IMF data or to the physical properties of the blunt asymmetric heliosphere with its smaller radial extent in the south near Voyager 2. To investigate this more we estimated the local shock speed at Voyager 2 using the Rankine-Hugoniot relations [20]. When we redo the estimate of the local shock speed without the plasma density and replace it with the IMF magnitude we obtain a similar shock speed. This supports the value of the Voyager 2 magnetic field magnitude. Thus, this may imply that the properties we obtained for the PMS at V2 are, in fact, a reflection of the physical properties of the outer heliosphere in the south near Voyager 2 where the heliosphere is of smaller extent. Clearly this issue warrants additional investigation, including the study of planar magnetic structures in the outer heliosphere associated with other solar events.

Figure 6 shows the "average transit speed" – denoted by the X - if the PMS at each spacecraft had propagated radially outward from one spacecraft to the next. Since, for example, there is a wide longitudinal separation (~90 deg) between ACE and Ulysses [1,12] it is unlikely that this is the case. Ulysses is not observing the same solar wind that was observed at ACE. Ulysses is observing different solar wind with its entrained IMF that propagated radially out from the Sun to Ulysses. Thus, in Figure 6 the average transit speed from ACE to Ulysses is not included. Figure 6 shows the average transit speed from Ulysses to Cassini. Even though there are large longitudinal and latitudinal separations between Cassini and Voyager 2 and then between Voyager 2 and Voyager 1, these respective average transit speeds are included since, during the propagation of disturbances to the outer heliosphere, merged interaction regions or even global merged interaction regions may be formed that are of wide longitudinal and latitudinal extent.

Assuming the PMS, observed at Voyager 1 from July 31 to August 7, 2004, continues to propagate farther out in the heliosphere, we can estimate when it might reach the heliopause. Even if at this time the termination shock were located just beyond Voyager 1 near 93 AU, it would imply that the heliopause was located near ~ 124 AU. Thus, even if the PMS transit speed shown at Voyager 1 in Figure 6 did not decrease beyond the termination shock, it is unlikely that the plasma wave signal [21] observed in the fall of 2004 was associated with the interplanetary shock from the Halloween 2003 solar event reaching the heliopause. This appears to imply that, if the plasma wave signal observed in the fall of 2004 was caused by a solar initiated event, then that solar event occurred before the Halloween 2003 solar events.

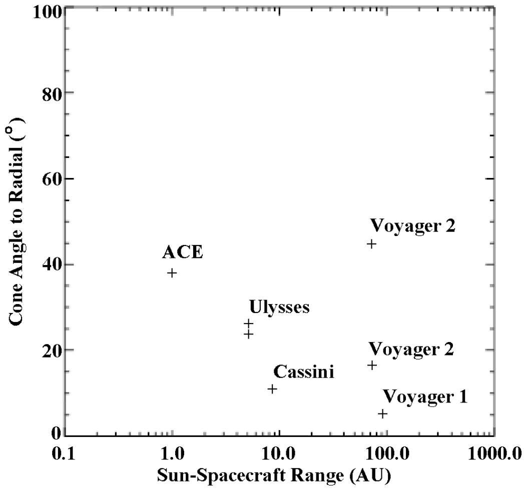

FIGURE 5. Changing cone angle of planar magnetic structure normal with heliospheric distance. The two values at Ulysses and Voyager 2 are for the two planar magnetic structures at each spacecraft.

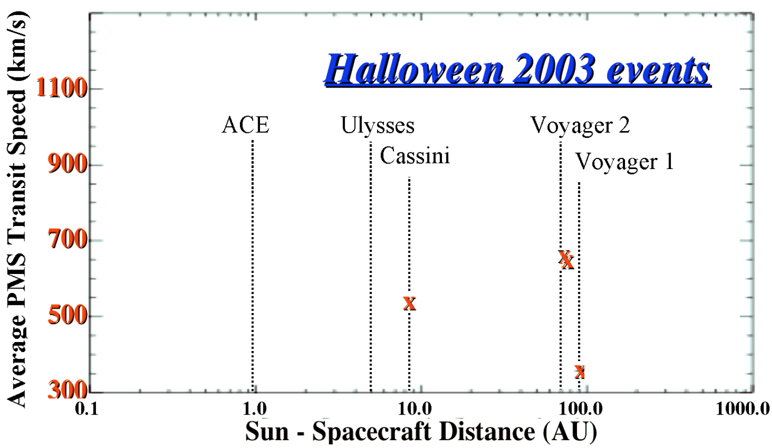

FIGURE 6. Average PMS transit speed (km/s) – denoted by X - with heliocentric distance (see text). The light vertical dotted lines indicate spacecraft positions.

SUMMARY

Our 3D models with *continuous* solar inputs are essential for the interpretation of in-situ data at diverse heliospheric and heliosheath locations. 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. We showed for the January 2005 solar events that even using our 3D simulation in isolation without including the preceding and following events can lead to erroneous longitudinal asymmetries extending out to the distances of Voyager 2 and Voyager 1. Our continuing studies of the planar magnetic structures associated with the Halloween 2003 solar events implies that at Voyager 1 the simultaneous strong modulation of galactic cosmic rays may be due to the compression associated with the planar magnetic structure.

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