Dynamics of the Outer Heliosphere

Devrie S. Intriligator, Murray Dryer, Wei Sun, Craig D. (Ghee) Fry, Charles Deehr, and James Intriligator

Citation: AIP Conference Proceedings **719**, 117 (2004); doi: 10.1063/1.1809508
View online: http://dx.doi.org/10.1063/1.1809508
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/719?ver=pdfcov
Published by the AIP Publishing

Dynamics of the Outer Heliosphere

Devrie S. Intriligator [1], Murray Dryer [2,3], Wei Sun [4], Craig D. (Ghee) Fry [3], Charles Deehr [4], and James Intriligator [1,5]

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

Abstract. The asymmetric propagation through the solar wind of shocks from solar eruptions influences the dynamics of the outer heliosphere. In 2002, these effects – and not the crossing of the termination shock (TS) – may have been responsible for the differences in observations made by Voyager 1 (V1) at 85 AU, 34° North and Voyager 2 (V2) at ~67 AU, 24° South. We suggest these observations stemmed from two series of solar eruptions that propagated asymmetrically in longitude and primarily to the south. At V1 this led to unusually weak magnetic fields and increased access to particles from two sources: the TS and particles accelerated at the shocks created by the second series of solar eruptions as they propagated outward, passing V2. Because V1 was farther out, these particles showed anisotropies from an interior source. We used the HAFv2 model to study the propagation of the solar events. It predicted: 1) the 1 August 2002 shock observed on V2; 2) the trends in the V2 plasma and magnetic field data in August 2002; and implied 3) an extended period of increased particle transport near V1 in 2002. We estimate that on August 1, 2002 the termination shock was at ~ 121 AU.

INTRODUCTION

Krimigis et al. [1] concluded that V1 exited the solar wind and crossed the TS. McDonald et al. [2] concluded that V1 approached the TS and observed precursors. Burlaga et al. [3] examined V1 interplanetary magnetic field (IMF) data and concluded that V1 had not crossed the TS. We suggest that V1 and V2 observed different effects of the asymmetric propagation of solar events to the outer heliosphere. We used the 3D HAFv2 (Hakamada – Akasofu – Fry version 2) model [4,5] and validated its results through comparisons of its predictions with Voyager data and with the predictions of the 1D and 2D MHD models [6,7].

ASYMMETRIC PROPAGATION

Figure 1a (February 12, 2002) shows the results after 100 days of propagation of the 6-29 November 2001 events using the HAFv2 model [4]. This kinematic model projects solar wind flow from inhomogeneous sources on a surface at 2.5 solar radii out into space while adjusting the flow for stream-stream interactions as faster streams overtake slower ones. It uses a 3D approach to construct plane of sky maps of

CP719, *Physics of the Outer Heliosphere: Third International IGPP Conference,*
edited by V. Florinski, N. V. Pogorelov, and G. P. Zank

disturbances caused by solar events. In Fig. 1a the light (dark) circular lines show the IMF toward (away) sectors. The results show the distortions of the IMF lines from the spiral field configuration. In Fig. 1a the disturbance propagates in the downwind direction away from V1 and the solar apex direction.

Since the HAFv2 model is mainly used < 10 AU, it does not take into account the effects of pickup ions. These effects generally lead to a ~ 10% slowing of the solar wind [6]. For the ecliptic plots in our paper, this would imply the shock front and IMF distortions could be about 10% closer to the Sun than depicted. Fig. 1b (April 3) shows the events' increased extent in radial distance and in azimuthal width. The IMF between V2 and the Sun is deformed. In both downwind quadrants (right half of figure), the event propagated > 67 AU, allowing particles near the foreshock to propagate along field lines to V2, as discussed below. In Fig. 1c (May 23) the lower flank of the event is close to V2. Although V1 is magnetically connected to the shock front in both right quadrants, no flanks of the event reached V1.

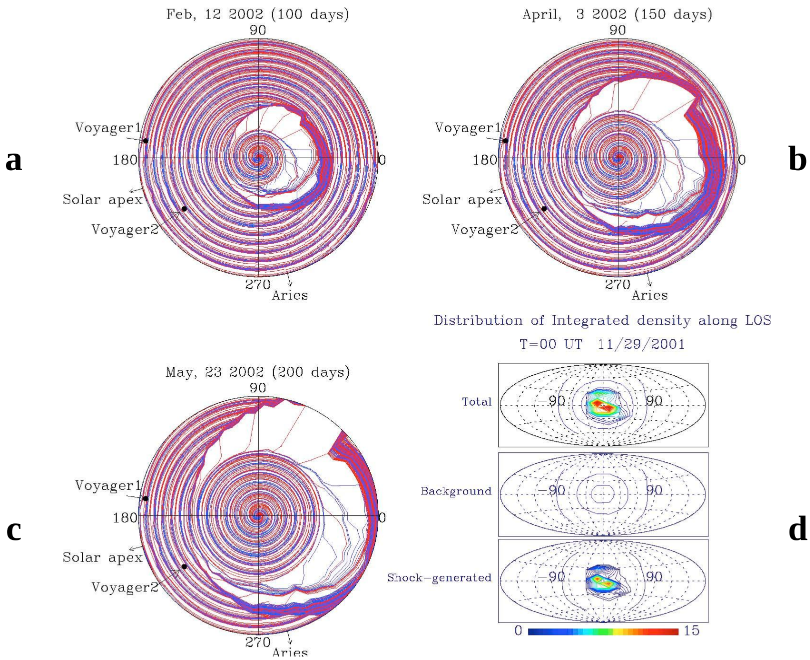

FIGURE 1. HAFv2 results show the asymmetric propagation of the November 2001 solar eruptions. **a.** Ecliptic plane projection of IMF lines in heliographic inertial coordinates showing the longitudinal distribution on Feb. 12, 2002 after 100 days since the initiation of the solar eruptions. The Sun is at the origin of the X axis. The radius extends to 90 AU. **b**. on April 12 after 150 days; **c**. on May 23 after 200 days. **d**. Latitudinal distribution. Line of sight (LOS) density obtained on the +X axis (0°) at 2 AU looking back at the Sun on November 29. The ecliptic plane coincides with the –90° to + 90° horizontal line.

Figure 1d shows the Hammer-Aitoff projection [5] of the plane of sky extent of the event seen by an observer on the +X (0°) axis at 2 AU looking back at the Sun. Since the main direction of propagation is along this axis, an observer is viewing the strongest part of the event. The lower panel shows the shock generated LOS density obtained by subtracting the background LOS density (middle panel) from the total LOS density (top panel). The event is mainly in the south; it will engulf V2 and extend to > 45° South. Probably it will not extend as far north as V1. Galactic cosmic rays (GCRs), anomalous cosmic rays (ACRs), and particles (e.g., ions, electrons) associated with the TS entering the outer heliosphere will have access to V1. Whereas, in the south, this event will overtake, sweep up, and accelerate the interplanetary particles; and also act as a barrier preventing the access to V2 of GCRs, ACRs, and TS particles.

HAFV2 MODEL VALIDATION AT VOYAGER 2

In Fig. 2 the jump in speed shows the shock arrival at V2 on 1 August (observations) and on 3 August (HAFv2 model). This shock arrival comparison validates a second HAFv2 model prediction associated with the solar eruptions between 1 March and 29 April 2002. The model's higher plasma speeds reflect the fact that effects of interstellar pickup ions are not included as well as other aspects of the model that are currently being adapted to analyze the outer heliosphere. For example, several brief speed dropouts, due to numerical noise not associated with physical processes, occurred prior to the modeled shock arrival.

Figure 3a (20 April) shows that these events propagated mainly along the -X axis (180°) toward V1 and V2. Fig. 3b (9 June) shows the leading shock approaching V1 and V2, followed by several more shocks and distortions in the IMF lines. The HAFv2 modeling in Fig. 3c (29 July) and Fig. 2 suggest that, between 27 July and 3 August, the leading shock engulfed V2.

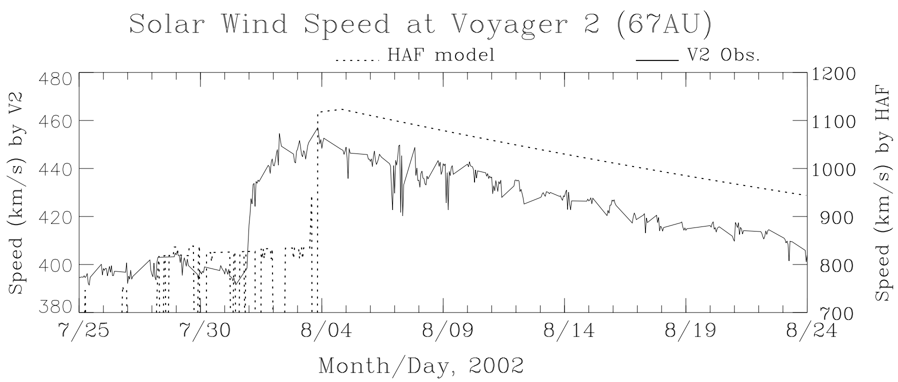

FIGURE 2. The arrival of the shock on 1 August 2002 at V2 in the solar wind speed data (hourly averages) and on 3 August in the HAFv2 results. The shock arrival validates the predictions of the HAFv2 model.

A further validation of the HAFv2 model is obtained by comparing its predictions with the V2 plasma and IMF data and with the Richardson et al. [7] model (Fig. 4). The speed and IMF increase between 2002.5 and the shock arrival at ~2002.6 as expected by the HAFv2 model (Fig. 3c). A strong shock propagates through the solar wind at a much higher speed than the solar wind speed. Thus, one would not expect the solar wind speed to be as high as the shock speed or the transit speed. After 2002.6, the IMF and the speed decrease again in agreement with the HAFv2 model (Fig. 3c) which shows a void after the arrival of the shock. In contrast, the Richardson et al. model (Figs. 4a,b) predicts a general decrease in speed before the arrival of the shock and a large increase in IMF strength afterwards. Thus, the IMF decrease after 2002.6 is more consistent with the HAFv2 model predicted IMF void than with the Richardson et al. [7] predicted increase. As noted above (Fig. 1b), the increase in 2-3 MeV H in March (2002.2) is also consistent with HAFv2 predictions.

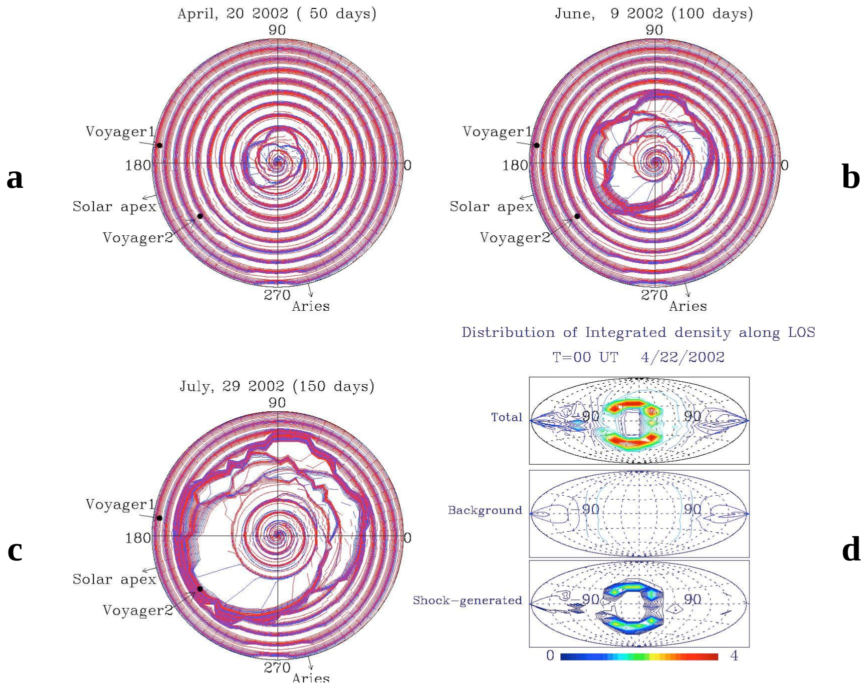

FIGURE 3. Same as Fig. 1 for the March/April 2002 solar events. **a**. 20 April (after 50 days). **b.** 9 June (after 100 days). **c.** 29 July (after 150 days). **d.** Latitudinal overview on 22 April seen by an observer at 1 AU on the radial vector extending from the Sun to V2 looking back towards the Sun.

VOYAGER 1 AND 2 ASYMMETRIES

The November 2001 and March/April 2002 eruptions caused effects near V1 that were very different from those near V2. These differences are reflected in the V1 and V2 data. Fig. 5a shows the V1 IMF magnitude. The 2001 values are adapted from [3]. The 2002-2003 values were provided by Ness and Burlaga. As noted above (Fig. 1b), the increase in 2 –3 MeV H ions seen on V2 near 2002.2 came from the acceleration of particles at the downwind foreshock of the November 2001 events. These particles found their way to V2 probably along IMF lines that threaded through both the foreshock region and the vicinity of V2. This particle increase endured for months as the shock propagated farther out in the heliosphere. It was ongoing on 1 August when the shock from the March/April eruptions arrived at V2. This arrival at V2 was seen as a modest but sharp increase in the 2-3 MeV H ions (Figs. 4, 5). In the >70 MeV/nuc ions (Figs. 4, 5), the shock arrival was observed first as an increase due to particle acceleration and then as a (Forbush) decrease due to the shielding effect of the shock. The modest increase at V2 on 1 August is consistent with our analysis for two reasons: the November 2001 shocks had earlier swept up and carried off particles in the south and, as these shocks propagated beyond V2, they continued to act as barriers to incoming particles from the TS. Thus, there were not many particles available for the March/April shocks to accelerate near V2.

At V1 the situation was different. The November event did not reach V1 in the north as shown in Fig. 1d and confirmed by the V2 IMF data in Fig. 5. From mid-March 2002 to early August, the IMF magnitude was unusually low, below the 0.041 nT 2002 yearly average value [3]. This is consistent with the HAFv2 predictions that

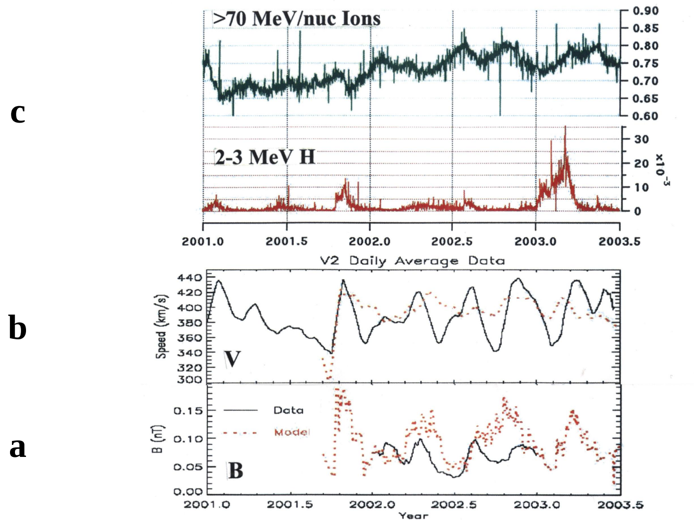

FIGURE 4. V2 data from 2001.0 to 2003.5. **a.** IMF magnitude. **b.** solar wind speed. **c.** CRS six-hour average counting rates of the 2-3 MeV hydrogen and the >70 MeV/nuc ions. Panels **a.** and **b.** (adapted from Richardson et al. [7]) show the daily averages of the parameters where the solid lines are the data and the dashed lines are from their model. 1 August 2002 corresponds to ~ 2002.6.

the November events did not reach V1, since the arrival of the shock would have been indicated by a sharp increase in the IMF data. There was a small increase in 2–3 MeV H ions near 2002.4 from the magnetic connection between V1 and the November event shock (Fig 1c).

INCREASED PARTICLE TRANSPORT NEAR VOYAGER 1

On 1 August the energetic particle intensities greatly increased following the interval of unusually low IMF strength. The low IMF strength implies reduced shear and compression in the solar wind, which in turn implies increased particle transport [8]. This increased particle transport led to enhanced fluxes of TS particles and GCRs entering the heliosphere near V1. Therefore, it is tempting to associate the preceding ~ 4.5 months of unusually low IMF values with this sudden particle increase and with the location of the TS. If we assume that the sudden increase in particles is because there is a magnetic "channel" of low values of IMF magnitude between V1 and the TS, we can estimate the distance to the TS. The average solar wind flows 100 AU/ year. For ~0.367 year there were unusually low IMF values. This implies that the termination shock is ~36.7 AU beyond V1 (100AU/yr x 0.367 yr) or at ~ 121 AU.

On 1 August, V1 was magnetically connected to the TS, and observing enhanced particle fluxes, beaming, and anisotropies. If, on 1 August, V1 also detected GCRs, ACRs, and other TS particles that had been deflected toward the outer heliosphere by the 1 August shock near V2, then these particles may have been streaming from radial distances closer to the Sun than V1 and from more southerly latitudes. This could provide an explanation for the observations at V1 – the beaming, anisotropies, electrons, and the particle abundances, including the low carbon abundance.

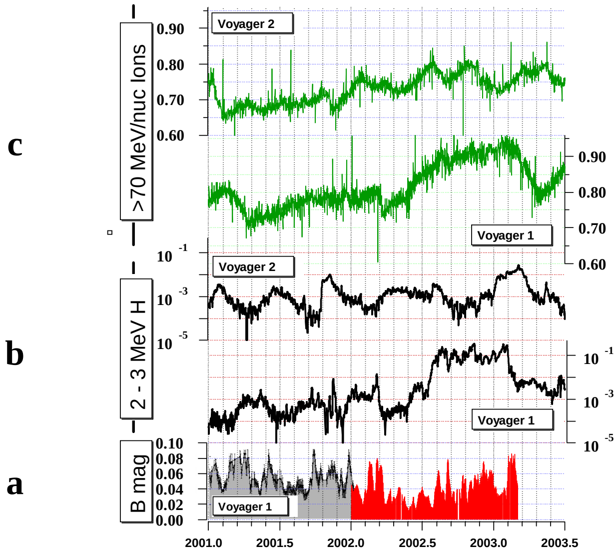

FIGURE 5. V1 and V2 data from 2001 to 2003. **a.** V1 IMF magnitudes (5-day running averages). **b.** CRS 2-3 MeV hydrogen data. **c**. CRS > 70 MeV/nuc ions (CRS counting rates are six-hourly averages).

ACKNOWLEDGMENTS

We are grateful to the Voyager experimenters for making their data available to us: E.C. Stone and F.B. McDonald for the CRS data, N. F. Ness and L. F. Burlaga for the 2002 Voyager 1 IMF data, and J. D. Richardson for the plasma data. We acknowledge the NSSDC. We benefited from useful discussions with J. R. Jokipii, E. C. Stone, R. Mewaldt, A. C. Cummings, L. F. Fisk, S. M. Krimigis, R. B. Decker, and L. F. Burlaga. The work by DSI and JI was supported by Carmel Research Center. The work by MD, CDF, WS, and CSD was supported by the DoD project, University Partnering for Operational Support (UPOS), and by NASA's Living With a Star (LWS) Targeted Research and Development Program.

REFERENCES

1. S. M. Krimigis, R. B. Decker, M. E. Hill, T. P. Armstrong, G. Gloeckler, D.C. Hamilton, L. J. Lanzerotti, and E. O. Roelof, *Nature* **426**, 45 – 48 (2003).
2. F. B. McDonald, E. C. Stone, A. C. Cummings, B. Heikkila, N. Lal, and W. B. Webber, *Nature* **426**, 48 – 51 (2003).
3. L. F. Burlaga, N. F. Ness, E. C. Stone, F. B. McDonald, M. H. Acuna, R. P. Lepping, and J.E.P. Connerney, *Geophys. Res. Lett*. **30**, doi: 10.1029/2003CL018291 (2003).
4. C. D. Fry, M. Dryer, Z. Smith, W. Sun, C. S. Deehr, and S.-I. Akasofu, *J. Geophys. Res*. **108**, 1070, doi:10.1029/2002JA009474 (2003).
5. W. Sun, C. S. Deehr, C. D. Fry, M. Dryer, Z. Smith, and S.-I. Akasofu, *Geophys. Res. Lett*. **30**, doi:10.1029/2003GL017574 (2003).
6. C. Wang, J. D. Richardson, and J. T. Gosling, *J. Geophys. Res*. **105**, 2337-2344 (2000).
7. J. D. Richardson, C. Wang, and L. F. Burlaga, *Geophys. Res. Lett*. **30**, (23), 2207 doi: 10.1029/2003GL018253 (2003).
8. D. S. Intriligator, J. R. Jokipii, T. S. Horbury, J. M. Intriligator, R. J. Forsyth, H. Kunow, G. Wibberenz, and J. T. Gosling, *J. Geophys. Res*. **106**, 10,625 – 10, 634 (2001).