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Propagation of the October/November 2003 CMEs through the heliosphere

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[1] The solar storms of late October, early November 2003 generated many ICMEs. The Wind, ACE, Ulysses, Cassini, Voyager 2, and Voyager 1 spacecraft are distributed throughout the heliosphere and observe the effects of these ICMEs. We investigate whether these ICMEs form a global merged interaction region. WIND, ACE, and IMP 8 data are combined to produce a plasma and magnetic field data set for these solar events at 1 AU. We use this data set as input to a 1-D MHD model, propagate the solar wind outward, and then compare our predictions with observations. The arrival times of ICMEs at Ulysses, Cassini, and Voyager 2 are consistent with the outward motion of a shell of ICME material; Voyager 1, however, sees no evidence of these ICMEs. These results are consistent with the creation of a large, but not complete, shell of outward-moving material and suggest true GMIRs are rare. **Citation:** Richardson, J. D., C. Wang, J. C. Kasper, and Y. Liu (2005), Propagation of the October/November 2003 CMEs through the heliosphere, *Geophys. Res. Lett.*, *32*, L03S03, doi:10.1029/2004GL020679.

1. Introduction

[2] Coronal mass ejections (CMEs) move outward from the Sun into the solar wind, where they are called interplanetary CMEs (ICMEs). Numerous models have been used to study ICME propagation in the inner heliosphere [i.e., *Riley et al.*, 2003; *Odstrcil et al.*, 2002]. For a few large ICMEs, the ejecta or preceding shocks have been traced from the inner (Earth and/or Ulysses) to outer heliosphere (Voyager 2) [*Paularena et al.*, 2001; *Wang et al.*, 2001a, 2001b; *Zank et al.*, 2001; *Wang and Richardson*, 2002; *Richardson et al.*, 2002].

[3] The solar events of October and November 2003 were extraordinary, with the largest solar flare ever recorded, solar wind speeds at Earth approaching 2000 km s^{-1}, damaged spacecraft, and power outages. Twelve X-class flares were observed from 19 October to 4 November from 90°E to 83°W on the solar surface; five subsequent halo CMEs and 1 subsequent limb CME probably were associated with the same active regions which were then behind the solar limb (see ftp://lasco6.nascom.nasa.gov/pub/lasco/status/LASCO_CME_List_2003). Solar latitudes of the flare locations were clustered at 8°N and 15°–20°S. This long period of sustained activity seems ideal for producing a global merged interaction region (GMIR), a shell of disturbed material with enhanced magnetic field strength hypothesized to be responsible for cosmic ray decreases [*Burlaga et al.*, 1985; *Burlaga*, 1995].

[4] If a GMIR is formed, the whole heliosphere would be affected by these events. We are fortunate to have a fleet of spacecraft distributed throughout the heliosphere at radial distances of 1 to 90 AU. Figure 1 shows the relative locations of these spacecraft in early November 2003. All the spacecraft were at low heliolatitudes except Voyagers 1 at 34°N and 2 at 25°S. This spacecraft fleet provides an opportunity to test how well the global effect of a string of CMEs can be predicted using observations at Earth and whether such a string of CMEs forms a GMIR. We use a model to predict the propagation of these ICMEs through the heliosphere and compare the model predictions to the observations at each spacecraft.

2. Model

[5] We use a 1-D, multi-fluid MHD model to propagate the October/November ICME events outward from 1 AU [*Wang and Richardson*, 2001]. This model has had success in predicting shock arrival times, shock jumps, and ICME structure in the outer heliosphere for other ICMEs, such as the September 1998 CME, the Bastille day CME, and the April/May 2001 CMEs [*Richardson et al.*, 2002; *Wang et al.*, 2001a, 2001b; *Wang and Richardson*, 2002]. Since we have input data at only 1 point in space, we use a 1-D model which includes the effects of pickup ions. The interstellar H density at the termination shock is set equal to 0.09 cm^{-3} [*Wang and Richardson*, 2003]. The model assumes the spacecraft are in the direction of the H in-flow; this approximation is good for Voyager 1 and 2 and the other spacecraft are too close to the Sun for the solar wind speed decrease to be significant. We use the observed solar wind parameters at 1 AU as input to the model and propagate the solar wind outward.

3. 1 AU Data

[6] The analysis of solar wind data at Earth from this time period was complicated by the effects of the energetic particles from the solar activity on the spacecraft and by the very high solar wind speeds which exceeded the energy ranges of many instruments. Figure 2 shows hourly average data observed near Earth constructed from a combination of ACE, Wind, and IMP 8 data for the period of enhanced activity (days 290–315, Oct. 18–Nov. 7). For each time, we selected data from the spacecraft which provided the most accurate parameters, for example, WIND in the high speed ICMEs, ACE in the regions when WIND was in the magnetotail or sheath, IMP 8 if both WIND and ACE data were not available. Magnetic field magnitudes are from ACE or WIND. For 11 hours on day 307 no plasma data are available, so we extrapolated the solar wind parameters. IMP

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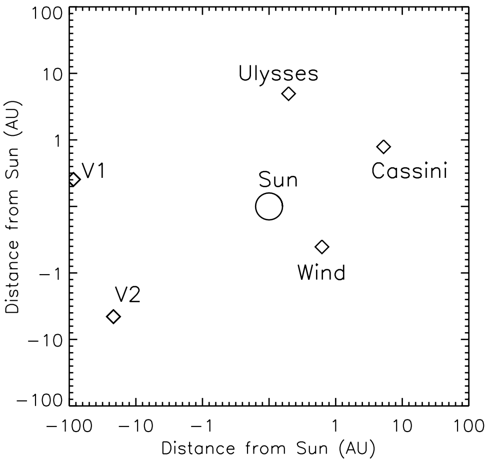

Figure 1. The locations of the heliospheric spacecraft fleet at the time of the October/November 2003 CMEs, with 0° heliolongitude directly right of the Sun. Note that the distances are logarithmic. See color version of this figure in the HTML.

8 densities were normalized to those of the other spacecraft by multiplying by 0.88. The peak speeds were about 1975 km s^{-1} on day 302 and the speed remained high for several days. The density in this event was relatively low, mitigating the effects of the fast speeds. We use data from days 200–350 of 2003 (see Figure 3) as input to the model.

4. Model-Data Comparison

[7] We have 1 AU solar wind data only at Earth's location; Earth is likely most affected by the halo CMEs on Oct 28 and 29, although small shocks are observed before and after the high speed region on days 302 and 303 which may result from other CMEs. Many of the CMEs have large widths and could affect major portions of the heliosphere [ftp://lasco6.nascom.nasa.gov/pub/lasco/status/LASCO_CME_List_2003]. Since we use a 1-D model, we tacitly make assumption of azimuthal symmetry, which is consistent with our hypothesis that the ICMEs merge into a large shell or GMIR.

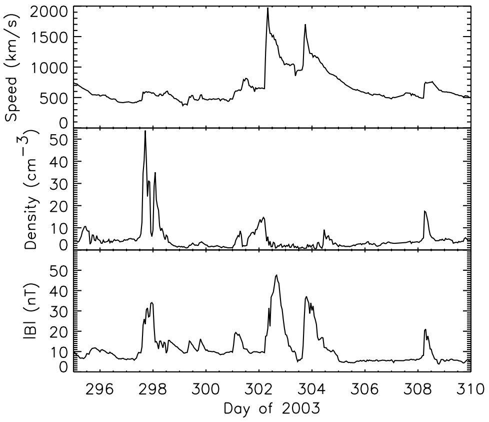

Figure 2. The solar wind speed, density, and magnetic field strength during the October/November 2003 ICMEs observed near Earth. This plot combines data from ACE, WIND, and IMP 8.

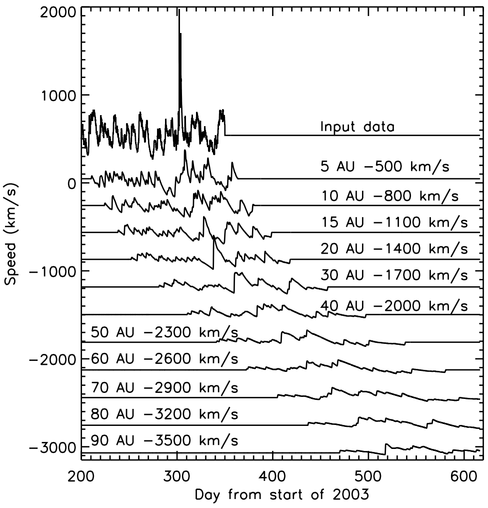

Figure 3. The evolution of solar wind speed with distance. The top trace shows the observed speeds at 1 AU. The remaining traces show the speeds predicted by the model at different heliospheric distances. The speeds in each model trace are shifted by the amount shown on the label.

[8] Figure 3 shows the observed speeds at 1 AU (days 200–350) and the model-predicted speeds at intervals of 5 AU out to 20 AU, then at intervals of 10 AU to 90 AU. The peak solar wind speeds rapidly decrease as the high-speed flow interacts with the preceding plasma. The high-time resolution results (not shown) show that the first shock (on day 302), which is faster than the second shock (late on day 303) at 1 AU, at first moves ahead of the second shock. By 3 AU the leading shock is slowed by the solar wind in front of it and the trailing shocks catch up, forming a single shock. Subsequent shock interactions strengthen the shock locally, but on average the shock jump decreases with distance. In the outer heliosphere the model predicts one main shock followed by a few weaker shocks.

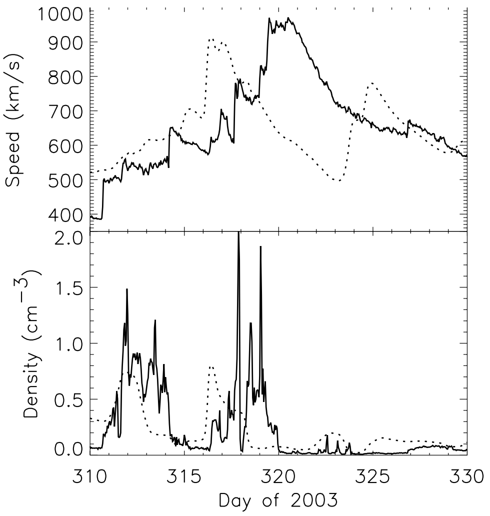

Figure 4. Comparison of model predictions (dashed lines) and data (solid lines) at Ulysses. The model times are shifted forward by 8 days. See color version of this figure in the HTML.

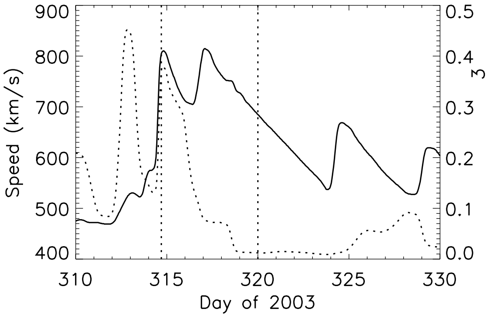

Figure 5. Model predictions for the plasma speed (solid line) and density (dashed line) at Cassini. The dotted vertical lines show the times when shocks were observed by Cassini. See color version of this figure in the HTML.

[9] Figure 4 compares the model predictions and the data at Ulysses, which is near the equatorial plane and 5.2 AU from the Sun. Ulysses was separated from Earth by about 120° heliolongitude; the CMEs on 2–4 Nov., which were near the west limb of the Sun, were more likely to affect Ulysses than the Oct. 28 and 29 CMEs observed at Earth. We had to time-shift the prediction forward by 8 days to match the model prediction, further evidence that Ulysses saw different ICMEs than those seen at Earth. Although the detailed ICME structure is different than predicted based on 1 AU data, the envelope of the speed change is similar. The density enhancements follow a similar pattern, but are larger in the data than prediction.

[10] Figure 5 shows that at Cassini at 8.8 AU, the model predicts a speed jump of about 300 km s^{-1} to 780 km/s at the end of day 314 of 2003 and a factor of two density jump, followed by a speed decrease to 670 km/s and then another shock at the end of day 316 with a speed jump to 800 km/s. The plasma instrument on Cassini was not oriented to observe the solar wind flow, but the MIMI instrument identified two shock passages and estimated the solar wind speed after the shocks [*Hamilton et al.*, 2004]. The first shock passed Cassini late on day 314 and the second on day 320; the solar wind speed after the shock, based on the pickup ion cutoff, was 750–800 km s^{-1}. The timing and speed jump at the first shock were close to the prediction, suggesting that Cassini, about 65° longitude west of Earth, observed the same ICME as Earth. The second shock reported by MIMI was a few days after the model prediction.

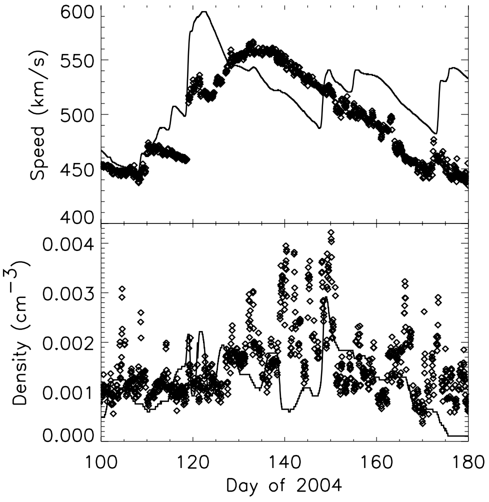

Figure 6. Comparison of model predictions (lines) and solar wind speeds and densities (diamonds) observed at Voyager 2. The model profiles are time-shifted back 14 days. See color version of this figure in the HTML.

[11] Figure 6 shows the model comparison with the Voyager 2 data, which is about 100° longitude east of Earth. The model results are time-shifted forward 14 days to match the arrival of the first shock (i.e., the observed shock arrives 14 days after the model predicts). The observed shock has a smaller speed increase and density jump than observed. This shock was the only large shock observed by Voyager 2 in the past 18 months, so we are confident it is associated with the October–November solar activity. Since Voyager 2 is far from the subsolar region of the ICME observed at Earth, if Voyager 2 observed the same ICME we would expect the shock to be both slower to arrive and weaker than a model based on data at Earth would predict. On day 127, an increase in speed and density is observed; these increases may signal the arrival of the MIR at Voyager 2 as it coincides with a decrease in the cosmic ray subsystem (CRS) >70 MeV/nuc count rate (see Figure 8). These decreases often occur when a MIR, often driven by an ICME and having an enhanced magnetic field strength, passes the spacecraft. Again, although the model and data are not perfect matches, the model does a reasonable job of reproducing the timing and some of the structure of the ICME at Voyager 2.

[12] The furthest heliospheric monitor is Voyager 1 at over 90 AU and at heliolongitudes between Voyager 2 and Ulysses. Figure 7 shows the model prediction for Voyager 1 at 92 AU; a shock arrival on June 12 with a speed jump of 100 km/s and a density jump at the shock of a factor of 2, followed two days later by a larger increase. The plasma instrument on Voyager 1 is not working, so the shock plasma parameters could not be directly measured, but a shock passage should have been clear from the energetic particle and magnetic field data. Figure 8 shows the >70MeV/nuc CRS data from 2004. The passage of the MIR by Voyager 2 produced a clear drop in counting rate centered on day 125. No similar clear indication of a shock or GMIR passage was observed by Voyager 1. This result suggests that the shock front was not a global feature.

5. Discussion and Summary

[13] The October/November flares and CME effects were among the largest and most widespread ever observed. In

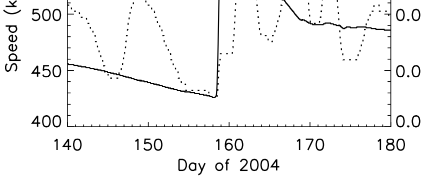

Figure 7. Model predictions for speed and density at Voyager 1. See color version of this figure in the HTML.

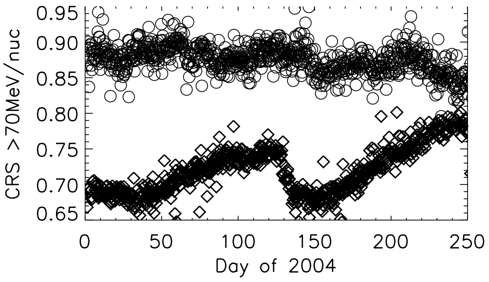

Figure 8. CRS >70 MeV/nuc counting rates from Voyagers 1 (circles) and 2 (diamonds). See color version of this figure in the HTML.

addition to the large geomagnetic storms at Earth, the effects of these storms extends to Ulysses, Cassini, and Voyager 2, spacecraft separated by 270° in heliolongitude. This series of large storms seemed ideal for forming a GMIR, a shell of material moving outward encircling the heliosphere. GMIRs are hypothesized to have a major role in decreasing cosmic ray intensities in the inner heliosphere. The fleet of spacecraft now assembled in the heliosphere combined with the propagation model to give the timing the shock passage allows a test of whether a GMIR is formed by the October/November solar activity.

[14] The shocks arriving at Wind, Cassini, and Voyager 2 are consistent with one large, almost 180° in longitude, ICME expanding outward. But these shocks could also lead different, but similar, ICMEs from different longitudes. Ulysses, on the opposite side of the heliosphere, observed an ICME which, based on the structure and timing, is clearly a separate event. ICMEs expand as they move outward, so these ICMEs should merge. The lack of a shock signature at Voyager 1 indicates a true GMIR did not form, either because of a gap in heliolongitude in the Voyager 1 direction or because the ICMEs didn't reach the 33°N heliolatitude of Voyager 1. Given the number and size of the CMEs observed near the Sun, this result suggests that true GMIRs may be rare structures.

[15] Although these events may not create a true GMIR, these events are large and the shock and following ICME will continue outward and encounter the termination shock and heliopause. The termination shock will be initially be driven outward; this motion could show up as a decrease in the MeV range particle intensities observed by Voyager 1. Shocks and GMIRs are possible triggers for the heliospheric radio emissions observed after solar maximum the last three solar cycles [*McNutt*, 1988; *Gurnett et al.*, 1993, 2003]. The Bastille day CME, which arrived at Voyager 2 in January 2001, did not trigger radio emission but the October 2001 shock at Voyager 2 was a possible trigger of the most recent heliospheric radio emission [*Gurnett et al.*, 2003]. We would expect the Oct/Nov 2003 shock to arrive at the heliopause in March 2005; however, the shock is not seen by Voyager 1, the spacecraft closest to the nose of the heliosphere, and the strength is similar to that of the Bastille day shock, so this event may not be of sufficient extent and/or strength at the heliopause to trigger radio emission.

[16] **Acknowledgments.** The Ulysses SWOOPS data (D. McComas, P.I.) was obtained from NSSDC and the Voyager CRS data (E. Stone, P.I.) from the GSFC web site. The work at MIT was supported under NASA contract 959203 from JPL to MIT, NASA grant NAG5-11623, and by NSF grants ATM-0203723 and ATM-0207775. C. Wang was supported in part by NNSFC 40204009 and 40325010 from China.

References

Burlaga, L. F. (1995), *Interplanetary Magnetohydrodynamics*, Oxford Univ. Press, New York.

Burlaga, L. F., F. B. McDonald, M. L. Goldstein, and A. J. Lazarus (1985), Cosmic ray modulation and turbulent interaction regions near 11 AU, *J. Geophys. Res.*, *90*, 12,027–12,039.

Gurnett, D. A., W. S. Kurth, S. C. Allendorf, and R. L. Poynter (1993), Radio emission from the heliopause triggered by an interplanetary shock, *Science*, *262*, 199–203.

Gurnett, D. A., W. S. Kurth, and E. C. Stone (2003), The return of the heliospheric 2–3 kHz radio emission during solar cycle 23, *Geophys. Res. Lett.*, *30*(23), 2209, doi:10.1029/2003GL018514.

Hamilton, D. C., N. Krupp, D. G. Mitchell, and S. M. Krimigis (2004), Shock events at Cassini associated with the October–November 2003 solar flares, *Eos Trans. AGU*, *85*(17), Jt. Assem. Suppl., Abstract SH32A-05.

McNutt, R. L., Jr. (1988), A solar-wind 'trigger' for the outer heliosphere radio emissions and the distance to the terminal shock, *Geophys. Res. Lett.*, *15*, 1307–1310.

Odstrcil, D., et al. (2002), Merging of coronal and heliospheric numerical two-dimensional MHD models, *J. Geophys. Res.*, *107*(A12), 1493, doi:10.1029/2002JA009334.

Paularena, K. I., C. Wang, R. von Steiger, and B. Heber (2001), An ICME observed by Voyager 2 at 58 AU and by Ulysses at 5 AU, *Geophys. Res. Lett.*, *28*, 2755–2758.

Richardson, J. D., K. I. Paularena, C. Wang, and L. F. Burlaga (2002), The life of a CME and the development of a MIR: From the Sun to 58 AU, *J. Geophys. Res.*, *107*(A4), 1041, doi:10.1029/2001JA000175.

Riley, P., J. A. Linker, Z. Mikić, D. Odstrcil, T. H. Zurbuchen, D. Lario, and R. P. Lepping (2003), Using an MHD simulation to interpret the global context of a coronal mass ejection observed by two spacecraft, *J. Geophys. Res.*, *108*(A7), 1272, doi:10.1029/2002JA009760.

Wang, C., and J. D. Richardson (2001), Energy partition between solar wind protons and pickup ions in the distant heliosphere: A three-fluid approach, *J. Geophys. Res.*, *106*, 29,401–29,408.

Wang, C., and J. D. Richardson (2002), Development of a strong shock in the outer heliosphere, *Geophys. Res. Lett.*, *29*(8), 1181, doi:10.1029/2001GL014472.

Wang, C., and J. D. Richardson (2003), Determination of the solar wind slowdown near solar maximum, *J. Geophys. Res.*, *108*(A2), 1058, doi:10.1029/2002JA009322.

Wang, C., J. D. Richardson, and K. I. Paularena (2001a), Predicted Voyager observations of the Bastille Day 2000 coronal mass ejection, *J. Geophys. Res.*, *106*, 13,007–13,013.

Wang, C., J. D. Richardson, and L. F. Burlaga (2001b), Propagation of the Bastille Day 2000 CME shock in the outer heliosphere, *Solar Phys.*, *204*, 413–423.

Zank, G. P., W. K. M. Rice, I. H. Cairns, J. W. Bieber, R. M. Skoug, and C. W. Smith (2001), Predicted timing for the turn-on of radiation in the outer heliosphere due to the Bastille day shock, *J. Geophys. Res.*, *106*, 29,363–29,372.

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