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Source and consequences of a large shock near 79 AU

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[1] In March 2006, Voyager 2 (V2) observed a large interplanetary (IP) shock near 79 AU followed by a merged interaction region (MIR). This shock is comparable to the shock observed by V2 at 65 AU in October 2001; these two shocks are the largest observed by V2 since 1991 when V2 was at 35 AU. This shock provides the first opportunity to compare the plasma structure in an IP shock and MIR with the energetic particle fluxes in the termination shock (TS) foreshock region. The flux of >0.5 MeV particles observed by V2 decreased after the shock; the shock and MIR probably pushed the TS outward so that the foreshock region moved outside the distance of V2. The >70 MeV cosmic ray ions decreased in the MIR, probably due to the reduced inward transport caused by the enhanced magnetic field. We model two possible sources of this shock, fast streams from polar coronal holes and coronal mass ejections (CMEs); these sources, when combined, provide a reasonable match to the V2 data. **Citation:** Richardson, J. D., Y. Liu, C. Wang, D. J. McComas, E. C. Stone, A. C. Cummings, L. F. Burlaga, M. H. Acuna, and N. F. Ness (2006), Source and consequences of a large shock near 79 AU, *Geophys. Res. Lett.*, *33*, L23107, doi:10.1029/2006GL027983.

1. Introduction

[2] Voyager 2 moved past 80 AU from the Sun in 2006. As V2 traveled further from the Sun, the frequency and strength of shocks decreased [*Richardson and Wang*, 2005]. The shocks that are observed are useful for tracking parcels of solar wind from the inner to the outer heliosphere. The Bastille day CME in July 2000 produced a single large shock which formed in the inner solar system and then decayed monotonically until it reached Voyager 2 at 63 AU [*Wang et al.*, 2001]. The October 2001 (65 AU) and May 2004 (73 AU) shocks observed at Voyager 2 formed from the conglomeration of multiple interplanetary coronal mass ejections (ICMEs); the merger of the leading fast forward shocks from each ICME strengthened these shocks as they moved outward [*Wang and Richardson*, 2002; *Richardson et al.*, 2005a].

[3] The shocks listed above all preceded merged interaction regions (MIRs), regions of enhanced magnetic field magnitudes and fluctuations and often enhanced plasma density. MIRs dominated the solar wind dynamic pressure changes from 2001–2003 [*Richardson et al.*, 2003] and should affect the location of the termination shock (TS), where the solar wind slows down, is heated, and begins to move tailward due to the presence of the interplanetary medium. *Zank and Mueller* [2003] show that a large ICME can drive the TS out several AU. Beginning in 2002, Voyager 1 was in the TS foreshock region which is characterized by anisotropic beams of keV to MeV particles flowing along the magnetic field [*Stone et al.*, 2005; *Decker et al.*, 2005]. The anisotropies suggest the particles arrive on field lines connected to the blunt nose of the heliosphere [*Jokipii et al.*, 2004]. *Richardson et al.* [2005b] showed that many MIRs observed by V2, if propagated to the position of V1, coincided with a change in the energetic particle foreshock fluxes observed by V1. Since the V1 plasma instrument does not work, the V2 data provide the first opportunity to directly compare the effect of the plasma variation in shocks and MIRs on the energetic particles in the foreshock. We present data from a large shock observed by V2 at 79 AU in March 2006 and show the corresponding changes in the energetic particle fluxes. We investigate whether the shock and subsequent MIR were formed by fast streams expanding equatorward past the latitude of V2 or by a transient ICME.

2. Data

[4] Figure 1 shows 1-hour averages of the data observed by the V2 Plasma Science (PLS) experiment [*Bridge et al.*, 1977] in 2006. We presume that the jump in the speed, density, and temperature observed between days 59 and 60 are due to passage of a shock, although the actual shock crossing occurred in a data gap when V2 was not tracked by the Deep Space Network. The magnetic field magnitude did not increase across the data gap; the field does increase a day or two after the jump in the plasma parameters and stays high through most of the MIR. The lack of increase in the magnetic field on day 60 is not understood, although we can not rule out a short-lived magnetic field increase in the data gap. The speed jump, from 380–510 km/s, is comparable to that at the October 2001 shock even though V2 is now about 15 AU further from the Sun (and shocks decay with distance). The density rises in two steps, first by a factor of 2 at the shock and then by another factor of more than 2 a few days later, to a peak density of 0.0049 cm^{-3}. The temperature jumps by a factor of five at the shock and the dynamic pressure (not shown) increases by a factor of 4 at

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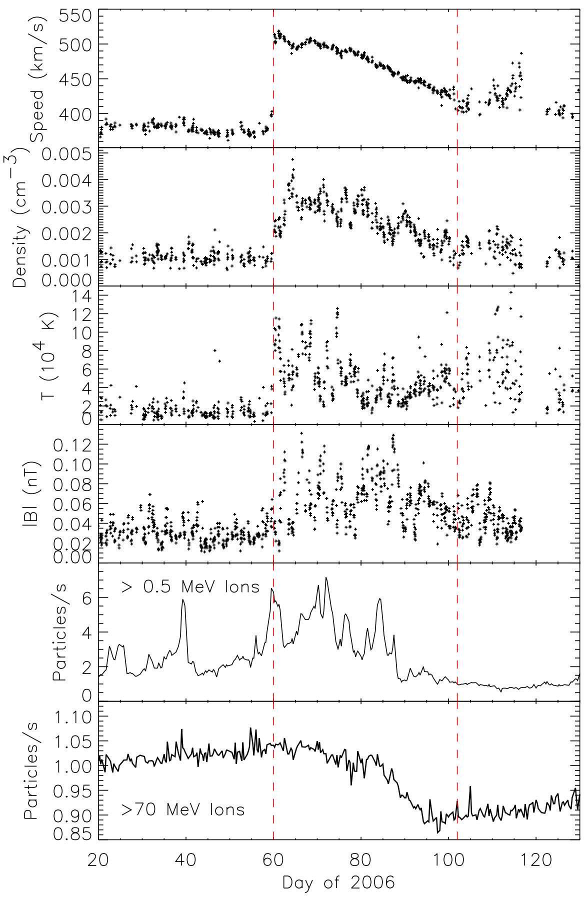

Figure 1. One-hour averages of the solar wind speed, density, temperature, and magnetic field magnitude and 6-hour averages of the >0.5 MeV ion and >70 MeV ion counting rates observed by V2 near the interplanetary shock of March 2006. The dashed vertical lines show the extent of the MIR which followed the shock.

the shock and by a factor of almost 8 at the peak pressure a few days after the shock. The magnetic field increases by a factor of about 2–4 a day or two after the shock.

[5] After the shock passage, the speed and density slowly decrease. The density stays above the pre-shock value for about forty days, which we identify as the width of the MIR as shown by the vertical lines in Figure 1. The magnetic field stays high in most of this region and begins to decrease at about day 95.

[6] Figure 1 also shows two V2 Cosmic Ray subsystem (CRS) [*Stone et al.*, 1977] ion populations, the >70 MeV cosmic rays and the >0.5 MeV ions. The >70 MeV particle counting rate begins to decrease on about day 72 and reaches a minimum near day 95. As shown by *Burlaga et al.* [1985, 2003], the flux of >70 MeV cosmic rays is closely related to the magnetic field magnitude. MIRs are regions of enhanced magnetic field magnitude and result in decreases in the >70 MeV cosmic ray flux since inward transport is decreased in the high field region.

[7] The >0.5 MeV counting rate has a peak at the shock, which implies that acceleration occurs at the shock. On day 87, the >0.5 MeV counting rate decreases to near the background level observed before V2 entered the foreshock region. The lower energy foreshock particles move along the magnetic field from the TS. The flux of these particles is most affected by changes in the connection of the TS to V2. The MIR is a large pressure pulse; it probably pushes the TS outward, weakening or severing the connection of V2 to the TS and decreasing the particle flux. The end of the first foreshock particle event observed by V1 was also attributed to the passage of a MIR [*Richardson et al.*, 2005b].

3. Shock Origin

[8] We next look for the driver of the IP shock. In mid-2005, Ulysses was at the same heliolatitude as V2, 26.5°S, with a longitudinal separation of about 120°. Thus we first look for the source of the shock observed at V2 in the Ulysses data. The Ulysses data from 2005 are shown in Figure 2; the density is normalized to 5 AU. Ulysses moves from 5.3 AU and 16°S heliolatitude at the beginning of 2005 to 4.5 AU and 37°S heliolatitude at the end of 2005. In mid-2005, the average solar wind speed increases; several high speed streams had speeds over 700 km/s [*McComas et al.*, 2006]. Not only do the high speed streams get faster, but the magnitude of the low speed wind in the troughs also increases. These speed increases compress the solar wind in front of them, as seen in the density plot. We hypothesize that these large speed flows, from polar coronal holes which expanded equatorward, drive the shock observed by V2. We test this hypothesis by using a model to propagate the Ulysses data to V2 and compare the model prediction to observations.

[9] We use a 1-D, multi-fluid MHD model to propagate the Ulysses data outward from 5 AU [*Wang and Richardson*, 2001]. This model successfully predicted shock arrival times, shock jumps, and ICME structure in the outer heliosphere for the September 1998 CME, the Bastille day 2000 CME, the April/May 2001 CMEs, and the Halloween events in 2004 [*Richardson et al.*, 2002, 2005a; *Wang et al.*, 2001; *Wang and Richardson*, 2002]. The 1-D model includes the effects of pickup protons. The interstellar H

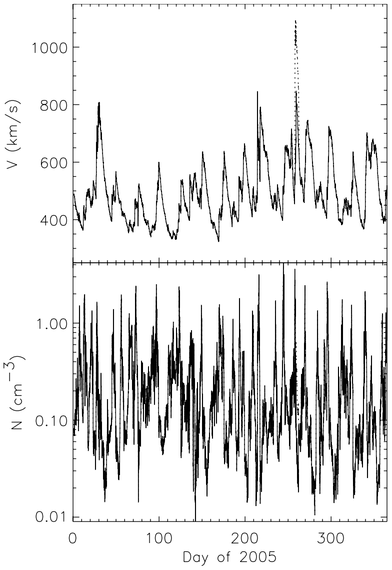

Figure 2. One-hour averages (solid lines) of the solar wind speed and density observed by Ulysses in 2005. The dotted lines show the simulated ICME data superposed on the Ulysses data from day 258–262.3.

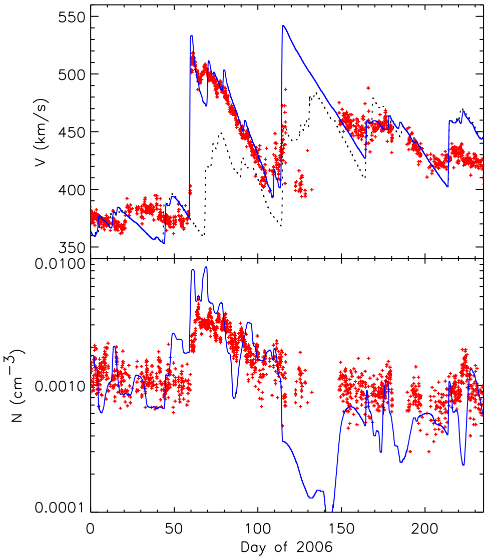

Figure 3. A comparison of the solar wind speed and density observed by V2 (data points), those predicted by a 1-D MHD model using Ulysses data as input (dotted line, only speed shown), and those predicted using Ulysses data with a superposed ICME as input (solid lines).

density at the termination shock is set equal to 0.09 cm^{-3}, which fits the observed speed slowdown in 2001 [*Wang and Richardson*, 2003]. The model assumes that the solar wind flow is in the direction of the local interstellar medium H inflow, a reasonable approximation for Voyager 2. We use the solar wind speeds, densities, temperatures, and magnetic field magnitudes observed at Ulysses as input to the model and propagate the solar wind outward.

[10] The top panel of Figure 3 compares the model speeds based on Ulysses data with V2 observations of the solar wind speed. The model predicts a speed increase at roughly the right time (about 10 days after it was observed), but the magnitude of the increase is smaller than observed, 90 km/s compared to 140 km/s. The feature that evolves into the model speed jump is the large speed spike on day 258 in Figure 2; thus it takes the shock about 167 days to reach V2 and the average shock speed is about 767 km/s. The density profile (not shown) also does not fit the data well. One reason for these discrepancies could be the slightly different latitudes of Ulysses and Voyager 2, if the latitudinal speed gradients were high. Another reason could be longitudinal differences; these differences would likely be related to transient events on the Sun rather than polar coronal hole expansion.

[11] We looked for large transient events which could be responsible for the V2 shock. The most reasonable possibility is the series of flares and CMEs from September 4–17, 2005 associated with solar active region 10808 [http://www.ngdc.noaa.gov]. The largest event in this series was the X-17 flare observed on September 7, 2005 at 12°S solar latitude and 88°E solar longitude. LASCO had a 24-hour data gap starting at 1100 on September 7, so if this flare were associated with a CME the CME would not have been observed. Six other CMEs with speeds over 1500 km/s were observed by the SOHO LASCO instrument between Sept. 3 and 13, 2006 [see http://cdaw.gsfc.nasa.gov/CME_list/]. The X-17 flare occurred as the active region rotated around the limb of the Sun, so Earth was about 90° from the center of the CME. Ulysses was nearly opposed to Earth, thus also 90° from the CME center. V2 was roughly 60° from Earth and 30° in longitude from the CME location. This active region solar latitude of 12°S was relatively close to the heliolatitude of V2 at 26°S. Thus an ICME associated with this large flare should have a much larger effect at V2 than at Ulysses. The large shock which reached V2 in Oct. 2001 was produced by ICMEs associated with a series of flares in April/May 2001 which were weaker than the flares in September 2005. The solar wind speed and density within the Sept. 2005 ICMEs were not measured but, given the strength of the flare activity and its alignment with V2, we hypothesize that the ICMEs associated with this flare activity contributed to the observed shock.

[12] We test this hypothesis by superposing a speed and density increase on 4.3 days of the Ulysses data to simulate an ICME and then using the model to propagate the modified data to V2. We vary the speed and density of the ICME until we get a reasonable match to the V2 observations. The time of the added ICME corresponds to the time of the X-17 flare, which occurred on day 250, plus an 8 day propagation time to Ulysses, corresponding to an average shock speed of 1150 km/s. The superposed ICME is shown by the dotted line in Figure 2; the speed peaks at about 1100 km/s, 300 km/s above the ambient fast solar wind. The density is increased only slightly. The speed is high but does not seem unreasonable for a very large ICME; V2 saw an IP shock in 1979 at 5.6 AU, further out than Ulysses, with a speed jump of 530 km/s and a downstream speed of 1030 km/s [see data at http://web.mit.edu/space/www/voyager.html].

[13] The top panel of Figure 3 shows that the new model speed profile fits the data near the shock much better than the model profile without the ICME. The timing and speed jump match quite well as does the decrease in speed after the shock. Before the shock the two model profiles are essentially identical since the solar wind has no knowledge of the IP shock. The broad envelope of the density profile predicted by the model is similar to that observed, but the match is not as good as for the speed. The density is higher than observed before the shock and thus the density jump at the shock results in too high a density after the shock as well. The small scale density structure is larger than observed, with density increases of a factor of 2 lasting a few days. These density structures are likely the consequence of using a 1-D model; when the plasma is compressed in the 3-D heliosphere it can expand perpendicular to the flow; in a 1-D model the density peaks cannot dissipate. The model magnetic field magnitude profile (not shown) looks very similar to that of the density and is higher than the observed field values after the shock. Again, this result is likely the consequence of using the 1-D model.

[14] The model predicts a strong reverse shock near day 113 with a speed jump to 540 km/s and a density decrease to below 0.0003 cm^{-3}. The data show an increase in speed and decrease in density at roughly the same time. For the periods from day 114–120 and 130–150 the densities at V2 are below the PLS instrument threshold, which is of order 0.0005–0.0007 cm^{-3} (and depends on the speed and temperature of the plasma). This period coincides well with the low density period predicted by the model. The excep-

tion is the data observed from days 122–128 which had densities of 0.0006–0.001 cm^{-3} and speeds near 400 km/s. After day 135 the effect of the shock passage is less and the two model profiles track reasonably well. The speed is 450 km/s from days 150–180, well above the speed before the shock, and this increased speed results from the higher speed streams observed at Ulysses.

4. Summary

[15] The interplanetary shock which passed V2 in March 2006 rivals that of Oct 2001 as the largest shock seen by V2 since 1991. The speed jump was 130 km/s and the density rose by a factor of 2 at the shock and another factor of 2 behind the shock. The shock preceded a MIR in which the average magnetic field strength was increased by a factor of 2–4 and which took approximately 40 days to pass V2.

[16] This event drove the first MIR observed while V2 was in the TS foreshock region. The MIR caused a decrease in the flux of >70 MeV cosmic ray particles consistent with the increased magnetic field strength reducing inward particle transport. The lower energy foreshock particles have a peak at the shock, perhaps due to local shock acceleration, have more peaks at the start of the MIR passage, and then fall to low intensities 28 days after the shock passage and remain at low intensities after the MIR. Similar to the end of the first foreshock particle event observed by V1, we think that the interplanetary shock and MIR drive the TS outward, so the magnetic field lines at V2 were no longer well-connected to the TS.

[17] Two possible drivers of this shock were considered. The first was equatorward movement of high speed coronal hole streams to the latitude of V2, which compressed the ambient solar wind plasma and formed a shock. Ulysses, at nearly the same latitude as V2, saw an increase in the average solar wind speed and faster coronal hole flow. Propagation of the Ulysses data to V2 produced an IP shock but did not provide a good match to the observed IP shock.

[18] In September 2005, a series of flares and CMEs occurred near the longitude (within 30°) and latitude (within 15°) of V2. The solar wind in these ICMEs was not measured in the inner heliosphere, but these flares were more intense than those which drove the October 2001 shock and are a plausible source for the March 2006 shock. We added data simulating an ICME to the Ulysses data which enabled us to match the observations at V2 reasonably well. Both drivers suggested above thus had an effect on the shock and MIR observed by V2. After the shock passage the speed remained high, probably due to the equatorward excursion of the high-speed streams observed by Ulysses.

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References

Bridge, H. S., J. W. Belcher, R. J. Butler, A. J. Lazarus, A. M. Mavretic, J. D. Sullivan, G. L. Siscoe, and V. M. Vasyliunas (1977), The plasma experiment on the 1977 Voyager mission, *Space Sci. Rev.*, *21*, 259–287.

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.

Burlaga, L. F., N. F. Ness, F. B. McDonald, J. D. Richardson, and C. Wang (2003), Voyager 1 and 2 observations of magnetic fields and associated cosmic-ray variations from 2000 through 2001: 60–87 AU, *Astrophys. J.*, *582*, 540–549.

Decker, R. B., S. M. Krimigis, E. C. Roelof, M. E. Hill, T. P. Armstrong, G. Gloeckler, D. C. Hamilton, and L. J. Lanzerotti (2005), Voyager 1 in the foreshock, termination shock, and heliosheath, *Science*, *309*, 2020–2024, doi:10.1126/science.1117569.

Jokipii, J. R., J. Giacalone, and J. Kota (2004), Transverse streaming anisotropies of charged particles accelerated at the solar wind termination shock, *Astrophys. J.*, *611*(2), L141–L144, doi:10.1086/423993.

McComas, D. J., H. A. Elliott, J. T. Gosling, and R. M. Skoug (2006), Ulysses observations of very different heliospheric structure during the declining phase of solar activity cycle 23, *Geophys. Res. Lett.*, *33*, L09102, doi:10.1029/2006GL025915.

Richardson, J. D., and C. Wang (2005), Voyager observations of interplanetary shocks, in *Proceedings of the Physics of Collisionless Shocks, Fourth Annual IGPP International Astrophysics Conference*, *AIP 781*, pp. 278–282, Am. Inst. of Phys., Palm Springs, Calif.

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.

Richardson, J. D., C. Wang, and L. F. Burlaga (2003), Correlated solar wind speed, density, and magnetic field changes at Voyager 2, *Geophys. Res. Lett.*, *30*(23), 2207, doi:10.1029/2003GL018253.

Richardson, J. D., C. Wang, and J. C. Kasper (2005a), Propagation of the October/November 2003 CMEs through the heliosphere, *Geophys. Res. Lett.*, *32*, L03S03, doi:10.1029/2004GL020679.

Richardson, J. D., F. B. McDonald, E. C. Stone, C. Wang, and J. Ashmall (2005b), Relation between the solar wind dynamic pressure at Voyager 2 and the energetic particle events at Voyager 1, *J. Geophys. Res.*, *110*, A09106, doi:10.1029/2005JA011156.

Stone, E. C., R. E. Vogt, F. B. McDonald, B. J. Teegarden, J. H. Trainor, J. R. Jokipii, and W. R. Webber (1977), Cosmic ray investigation for the Voyager missions: Energetic particle studies in the outer heliosphere—and beyond, *Space Sci. Rev.*, *21*, 355–376.

Stone, E. C., A. C. Cummings, F. B. McDonald, B. Heikkila, N. Lal, and W. R. Webber (2005), Voyager 1 explores the termination shock region and the heliosheath beyond, *Science*, *309*, 2017–2020, doi:10.1126/science.1117684.

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 L. F. Burlaga (2001), Propagation of the Bastille Day 2000 CME shock in the outer heliosphere, *Sol. Phys.*, *204*, 413–423.

Zank, G. P., and H.-R. Mueller (2003), The dynamical heliosphere, *J. Geophys. Res.*, *108*(A6), 1240, doi:10.1029/2002JA009689.

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