

Voyager 2 observations related to the October–November 2003 solar events

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[1] A transient flow system observed at 1 AU from October 24–November 7, 2003 (consisting of several shocks, ejecta and possibly other flows) moved away from the Sun for ≈ 180 days to 73 AU, where Voyager 2 (V2) observed a large Merged Interaction Region (MIR) associated with a fast (560 km/s) stream that followed a forward shock and moved past V2 for ≈ 1.5 solar rotations. The MIR and stream were associated with a large decrease in the cosmic ray intensity and an exceptionally large enhancement in the flux of ≈ 2.5 MeV protons. The speed and the cosmic ray profiles observed by V2 were very simple, resembling the profiles of a shock/sheath/ejecta flow and a Forbush decrease, respectively, at 1 AU, but rescaled by a factor by a factor of ≈ 10 . The onset of the MIR-associated decrease in the cosmic ray intensity occurred 10 days after the shock, lasting several days, with a full recovery ≈ 70 days after the onset. **Citation:** Burlaga, L. F., N. F. Ness, E. C. Stone, F. B. McDonald, and J. D. Richardson (2005), Voyager 2 observations related to the October–November 2003 solar events, *Geophys. Res. Lett.*, 32, L03S05, doi:10.1029/2004GL021480.

1. Introduction

[2] A series of flows and 8 shocks moved past the ACE (Advanced Composition Explorer) spacecraft at 1 AU from October 24–November 7, 2003 (hereafter referred to as the “Halloween events” [Skoug *et al.*, 2004]. The Halloween events were associated with the largest flare ever recorded, solar wind speeds near Earth >1500 km/sec, energetic particles that affected spacecraft, and two ejecta (including a magnetic cloud) with intense magnetic fields that caused major geomagnetic storms. The set of events observed from October 24–November 7, 2003, is an example of a “transient flow system” at 1 AU, a series of flows including ejecta and shocks moving past a spacecraft over an interval of at least several days [Burlaga *et al.*, 1986a].

[3] The radial evolution of a transient flow system between 1 and of the order of 10 AU forms a “Merged Interaction Region” (MIR) characterized by high magnetic and thermal pressures over a broad region. For example, a transient flow system observed at 0.85 AU by Helios,

consisting of five streams and interaction regions, evolved to a single compound stream and two MIRs observed by Voyager at 6.2 AU [Burlaga *et al.*, 1986b]. The MIRs coalesced to form a single MIR that was observed by Pioneer 11 at 9.5 AU [Whang and Burlaga, 1986].

[4] The radial evolution of transient flow systems beyond ≈ 30 AU, in the distant heliosphere, is strongly affected by pickup protons [Axford, 1972; Holzer, 1972] where the interstellar pickup proton pressure dominates the internal pressure of the solar wind plasma [Burlaga *et al.*, 1996]. A number of papers discuss the effects of pickup protons on shocks and ejecta [Whang and Burlaga, 1986; Whang *et al.*, 1999; Zank, 1999; Rice and Zank, 2000; Richardson *et al.*, 2002; Wang and Richardson, 2001, 2002; Zank and Muller, 2003].

[5] Events very similar to those discussed in this paper were analyzed by McDonald *et al.* [1994, 2000]. A series of large solar flares in June 1991, during a recovery phase of the cosmic ray intensity, produced an MIR that was associated with fast flows, a decrease in the cosmic ray intensity and a broad enhancement of MeV particles observed by V2 at ≈ 36 AU and by Voyager 1 near 46 AU. Another exceptional set of events, the Bastille Day events, began as a transient flow system at 1 AU consisting of a very fast ($>1,100$ km/sec) stream containing a magnetic cloud, at least 4 ejecta (3 of which were magnetic clouds) and 5 shocks in a 10-day period [Smith *et al.*, 2001; Whang *et al.*, 2001]. The transient flow system produced a MIR at 5 AU [Whang *et al.*, 2001], and it evolved to a large stream and an MIR 6 months later at 63 AU, where it was detected by Voyager 2 (V2) [Burlaga *et al.*, 2001; Lepping *et al.*, 2001; Wang *et al.*, 2001a, 2001b].

[6] The Halloween events provide an opportunity to study the evolution of a transient flow system from 1 to 73 AU. We shall show that the Halloween events produced a MIR and a fast stream that were observed by V2. The MIR was associated with a decrease in the cosmic ray intensity and an unusually strong burst of energetic (≈ 2.5 MeV) protons.

2. Trajectories and Travel Times

[7] Ideally, one would study the radial evolution of transient flow systems with spacecraft that are radially aligned with the Sun, but this is not possible when considering intervals of more than a few days and spacecraft that are widely separated in radial distance and latitude. During the interval from October 24–November 7, 2003, the inertial heliographic longitude of ACE, near Earth, changed from 315.6° to 329.5° , while V2 was at 215.3° . The latitude and longitude of V2 did not change significantly during the ≈ 180 days in which the flow system moved from 1 to 73 AU. Thus, the longitudinal and latitudinal separations

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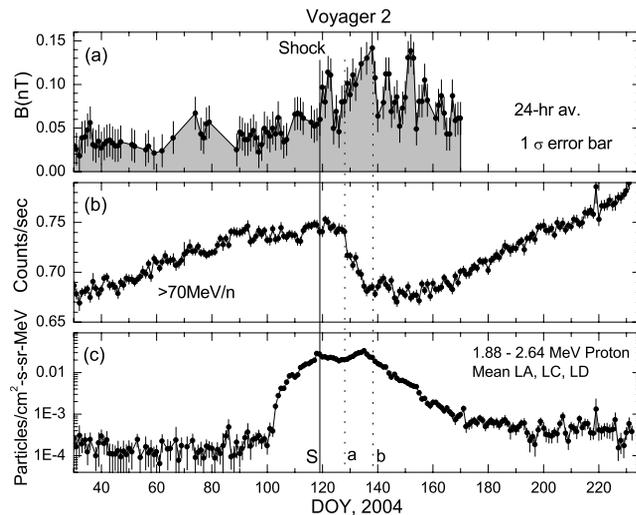


Figure 1. Daily averages of a) the magnetic field strength, b) the counting rate of >70 MeV/n cosmic rays, and c) the flux of 1.88–2.64 MeV protons observed by Voyager 2. Line a marks the onset of the MIR decrease in the cosmic ray intensity, and b marks the end of the rapid decrease.

between ACE and V2 were ≈ 100 – 114° and 29 – 30° , respectively.

[8] During the 14 days that the flow system moved past ACE, the source of the flows (the Sun) rotated $\approx 185^\circ$ relative to ACE. Thus, the flow system was spread out over a wide range of longitudes. It is very likely that the individual flows and shocks in the flow system had relatively large longitudinal and latitudinal extents. The average angular extent of CMEs near the Sun is $\approx 45^\circ$, and their extent can be as large as 120° [Hundhausen, 1996]. The angular extent of a shock driven by CME is often as large as 180° . Thus, it is reasonable to expect that V2 would observe some aspects of the flow system associated with the Halloween events (which were primarily in the southern hemisphere of the Sun) and possibly other related features as well, despite the longitudinal and latitudinal separations between ACE and V2.

[9] A shock associated with the Halloween events arrived at V2 on DOY 119, 2004 in a 14-hour tracking gap [Richardson *et al.*, 2005]. At this time, V2 was at 73 AU at the heliographic latitude $S 25^\circ$. The shock occurred at the end of a transition from relatively slow flows to fast flows over an interval of the order of a year [Burlaga *et al.*, 2005]. The shock formed by the merging of multiple shocks that were in the transient flow system at 1 AU.

3. Magnetic Field, Cosmic Rays and Energetic Particle Observations by Voyager 2

3.1. Magnetic Field Observations

[10] Daily averages of B observed by V2 from DOY 30–235, 2004, are shown by the points in Figure 1a. Observations are not plotted for days in which the uncertainties in B were relatively large. An abrupt increase of B by a factor of $\approx 1.6 \pm 0.6$ was observed on DOY 119, at the time the shock associated with the Halloween events arrived at V2. High-resolution observations show that the initial increase in B also occurred in a 14-hour data gap. A MIR, identified by its

relatively strong magnetic fields, moved past V2 during an ≈ 40 day interval (≈ 1.5 solar rotations) from DOY 128 to ≈ 167 , 2004. The average B in the MIR ($\langle B_2 \rangle \approx 0.088 \pm 0.0185$ nT) was 2.0 ± 0.9 times as large as the average B from DOY 30 through 118, 2004 ($\langle B_1 \rangle = 0.045 \pm 0.0185$ nT). The fluctuations in B relative to $\langle B_2 \rangle$ within the MIR were comparable to those observed ahead of the MIR from DOY 30–118. Within the MIR, $SD(B_2)/\langle B_2 \rangle = 0.029/0.088 = 0.34$, and ahead of the MIR $SD(B_1)/\langle B_1 \rangle = 0.017/0.045 = 0.38$, where SD is the standard deviation of daily averages of B .

3.2. Cosmic Ray Observations

[11] Observations of daily averages of cosmic rays >70 MeV/n by the CRS (Cosmic Ray System) instrument on V2 from DOY 30–235 are shown in Figure 1b. A decrease in the cosmic ray intensity related to a MIR (which will be referred to as an “MIR-decrease”), characterized by a relatively rapid decrease in the counting rate followed by a long recovery, was observed by V2 from \approx DOY 128 to ≈ 200 , 2004. The complete recovery, to the counting rates observed just prior to the onset of the decrease, distinguishes this particular MIR-decrease from a “step-decrease” (which tends to maintain low counting rates long after the initial decrease phase) [McDonald *et al.*, 1994, 2000; Van Allen and Fillius, 1992; Webber and Lockwood, 1991]. Thus, the cosmic ray profile in Figure 1b suggests that the MIR was a “Local MIR” (LMIR) rather than a Global MIR (GMIR) [Burlaga *et al.*, 1993]. This MIR produced the biggest relative decrease of the >70 MeV/nuc cosmic rays observed by V2 during solar cycle 23.

[12] Prior to the MIR-decrease in Figure 1b, the counting rate increases from DOY 30–90 (when B is relatively low), as part of a recovery of the cosmic ray intensity, and it tends to level out from DOY 90–119 (when $B \approx 0.04$ nT). The counting rate decreases from DOY 128 (the line a in Figure 1) to DOY 138, while B increases to a maximum on DOY 138 in the MIR (the line b in Figure 1). The counting rate goes through a minimum while the MIR moves past V2, and then the counting rate recovers to the level observed before the MIR-decrease. The qualitative relationship between B and changes in the counting rate from DOY 30–170 is the same as that given by the “CR-B relation” [Burlaga *et al.*, 1985, 2005].

[13] The cosmic ray intensity profile in the MIR-decrease at V2 is similar to that of a Forbush decrease observed at 1 AU [Lockwood, 1971], except for the much larger time scale of the former. A Forbush decrease at 1 AU lasts a few days, whereas the MIR-decrease near 73 AU was observed by V2 for at least 70 days. A Forbush decrease at 1 AU typically immediately follows a single shock driven by a single flow between the Sun and 1 AU, whereas the MIR-decrease observed by V2 follows ≈ 10 days after a shock that resulted from the coalescence of several shocks that were in the transient flow system at 1 AU. A Forbush decrease at 1 AU is usually related to a single ejection passing the spacecraft in ≈ 1 day, whereas the stream and MIR observed by V2 were associated with the coalescence of several ejecta containing strong magnetic fields in the transient flow system at 1 AU.

3.3. Energetic Particle Observations

[14] The flux of 1.88–2.64 MeV protons (hereafter, “the 2.5 MeV protons”) observed by the CRS instrument of V2

from DOY 30–235 is shown in Figure 1c. The dominant feature is a large, long-lasting enhancement in the flux with a maximum near the shock. The energetic particle event at V2 is the biggest of the solar cycle 23 events for the 2.5 MeV protons.

[15] The energetic particle enhancement shown in Figure 1c begins at least 17 days before the arrival of the shock. A narrow local maximum in the flux (which appears much larger on a linear scale) is very near the shock, and it possibly represents ongoing acceleration of particles by a shock (implying that a shock really was present in the data gap, as we have been assuming). A second local maximum in the flux occurs within the MIR (on DOY 135) near the time that B reaches its maximum value 0.14 nT, on DOY 138. The flux of energetic particles is relatively high throughout most of the MIR, but it decreases following DOY 135.

[16] It is possible that the energetic particle enhancement is produced, at least in part, by several shocks observed in the transient flow system at 1 AU and the interactions among the shocks beyond 1 AU. Models of the acceleration of the particles that include the complexity of the evolution of transient flow systems are needed before one can draw more definite conclusions about the cause of the profile of 2.5 MeV protons in Figure 1c.

4. Magnetic Field and Plasma Observations by Voyager 2

[17] The daily averages of B versus time are repeated in Figure 2a for reference, and the hourly averages of speed V , the solar wind proton temperature T , and density N are plotted versus time from DOY 90–170 in Figures 2b, 2c, and 2d, respectively. The temperature T does not include the electrons or pickup protons. The relation between B and the solar wind plasma parameters can be seen in Figure 2. The shock S on DOY 119 is associated with a large abrupt increase in V , smaller increases in T and N , and the increase in B discussed in Section 2.1.

[18] A large relatively fast stream is shown in Figure 2b. Note that the speed profile following DOY 128 (marked by the vertical line a) is relatively smooth. The speed rises to a broad maximum and then decreases monotonically until at least DOY 167. The maximum speed, ≈ 560 km/sec, is unusual at such a large distance from the Sun (73 AU). The fast flow following the line a moves past V2 for ≈ 40 days, ≈ 1.5 solar rotations. At 1 AU a magnetic cloud and other ejecta typically move past a spacecraft in ≤ 1 day, and the largest type of flow (a corotating stream) moves past a spacecraft in ≤ 10 days. The large extent of the stream observed by V2 is the result of the evolution of the transient flow system observed at 1 AU in the Halloween events. The strong and variable magnetic fields observed within the stream (Figure 2a) as well as the variable T and N within the stream (Figures 2c and 2d) are consistent with the view that the stream and MIR formed by the interaction and coalescence of several shocks, ejecta and possibly other flows. However, the simplicity and smoothness of the speed profile requires an explanation.

[19] Between the shock S and the stream, whose leading edge we subjectively chose as line a in Figure 2 (based on the time of an increase in B corresponding to a large, abrupt decrease in the cosmic ray intensity), is a “sheath-like”

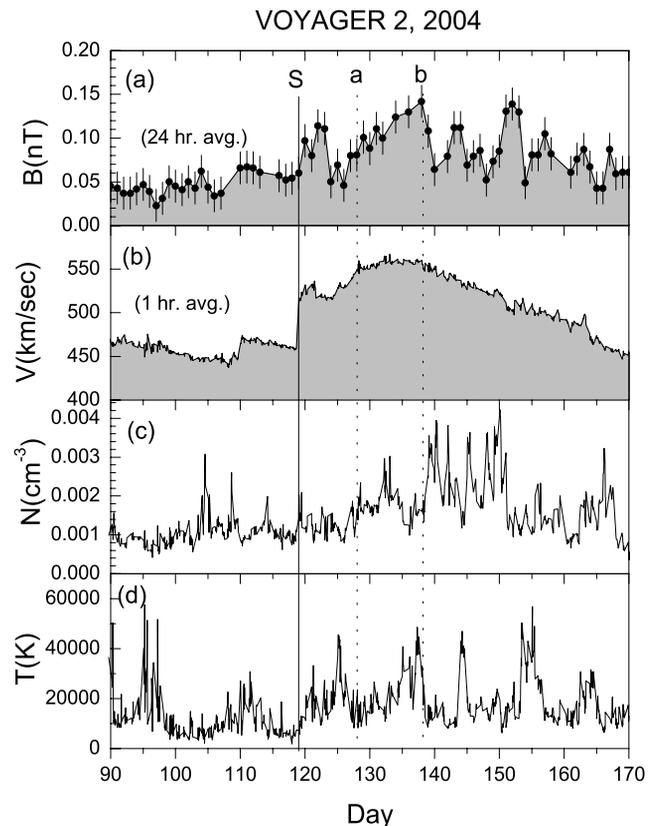


Figure 2. a) Daily averages of the magnetic field strength observed by Voyager 2. b–d) hour averages of the solar wind speed V , density N , and the solar wind proton temperature T . The temperature T does not include the electrons or pickup protons. Line a indicates the onset of the rapid decrease in the cosmic ray intensity, and b the end of that rapid decrease.

region that moved past V2 in ≈ 9 days. The region is “sheath-like” insofar as it is a region containing enhanced values of B , T , and N between a shock and a fast stream, as one often observes the sheath between a shock and ejecta at 1 AU. The size of this region is an order of magnitude greater than that of a sheath at 1 AU. The shock S probably formed from the coalescence of several shocks, unlike most shocks observed at 1 AU. Yet, B , N and T are higher in the sheath-like region than ahead of the shock, as is observed in sheaths at 1 AU. The sheath-like region is just part of a MIR, which is defined as a region of enhanced magnetic and thermal pressure resulting from the coalescence of two or more interaction regions. One can ask whether the sheath-like region in Figure 2 is a coincidental feature of the evolution of the particular October–November transient flow system or whether it is an asymptotic state of the evolution of a class of transient flow systems at 1 AU. Perhaps this question can be answered by further observations and models of the evolution of systems of transient flows.

5. Summary and Discussion

[20] We have observed the MIR related to the transient flow system at 1 AU from October 24–November 7, 2003 (consisting of several shocks, ejecta and possibly other

flows), propagated out to 73 AU in the course of ≈ 180 days. It was observed at Voyager 2 as a very large MIR (≈ 40 days = 1.5 solar rotations) associated with a relatively simple, large (≈ 40 days), fast (560 km/s) stream following a forward shock. The MIR and stream were associated with a large decrease in the cosmic ray intensity. An exceptionally large enhancement in the flux of 1.88–2.64 MeV protons was also observed, beginning at least 17 days before the shock arrived at V2, reaching a local maximum near the shock and a second local maximum near the time of maximum speed in the stream and maximum magnetic field strength in the MIR.

[21] A transient flow system can persist for a long time (>180 days), propagate over very large distances (>72 AU), and have a long-lasting effect on the heliosphere. The speed and the cosmic ray profiles observed by V2 were very simple. It is of interest to determine, observationally and theoretically, whether these simple profiles are coincidental and unique to the Halloween events or whether they might represent an asymptotic state of a class of transient flow systems containing an exceptionally fast stream at 1 AU.

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