Heliospheric energetic particle observations during the October–November 2003 events

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1. Introduction

After a quiescent period of two months without any significant major solar event, the series of intense solar flares and fast coronal mass ejections (CMEs) observed in late October and early November 2003 not only impressed the space physics community [Larson, 2004] but also strongly affected different regions of the heliosphere [López et al., 2004]. The associated solar energetic particle (SEP) events were some of the largest in solar cycle 23 as observed in the

ecliptic plane at the heliocentric distance of 1 AU [Cohen et al., 2005]. This series of events occurred 3.5 years after the peak month (April 2000) of the sunspot maximum of solar cycle 23, i.e., during the declining phase of the solar activity cycle [Drummond et al., 2004]. Although large SEP events are more frequent during the maximum of solar activity, major SEP events can occur at any time during the solar cycle, especially in its declining phase [Dwina and Smart, 2001]. That was the case of the well-studied SEP events in August 1972 and October–November 1992 [e.g., Lario and Cerruti, 2004] and it is again the case of the October–November 2003 events.

[1] From 19 October 2003 (day of year 292) to 5 November 2003 (day of year 309), 44 M-class and 11 X-class flares were observed [Woods et al., 2004] coinciding with the transit of the NOAA active regions AR 0484, 0486, and 0488 over the disk of the Sun. The intense level of solar activity continued after these active regions crossed the west limb of the Sun [de Koning et al., 2005]. The interplanetary consequences of these series of events extended over an even longer time interval. The system of transient interplanetary flows generated by this series of events expanded within the heliosphere arriving separately at the locations of the spacecraft distributed over the heliosphere [Richardson et al., 2005].

[2] The purpose of this paper is to document the physical consequences of these extreme events in terms of the energetic particle intensities measured by the current fleet of heliospheric spacecraft. We present energetic particle data measured by the spacecraft located in the inner heliosphere (<10 AU) from 20 October 2003 (day of year 293) to 2 December 2003 (day of year 336). These spacecraft include ACE, GOES-11, Ulysses, and Cassini. For those spacecraft located in the outer heliosphere (in this case we only include Voyager-2) we analyze energetic particle data from 30 March 2004 (day of year 90) to 23 June 2004 (day of year 175). Figure 1 shows the locations of the spacecraft at

Figure 1. Locations of Earth, Ulysses, Cassini, and Voyager-2 on 28 October 2003 (day 301).

the time of the X17 flare on 28 October 2000 (day of year 311). This flare was associated with the origin of the most intense SEP event observed at 1 AU during this time interval [Cohen et al., 2005]. The ACE spacecraft, in orbit around the L1 Sun–Earth libration point, and the GOES-11 spacecraft, in geosynchronous orbit, are too close to the Earth to be plotted separately in Figure 1. All the spacecraft considered in this study were at low heliolatitudes (∆ = 20°), with the exception of Voyager-2 that was at ∆ = 25°. The region of inertial heliolongitudes (∆) embraced by these spacecraft on day 301 was 104° east of the Earth and 122° west of the Earth, with the Earth (together with the ACE and GOES-11 spacecraft) moving westward at the rate of ~1° per day and the rest of spacecraft maintaining approximately the same inertial heliolongitude throughout the period considered in this paper.

[3] Multiprobes spacecraft observations of SEP events by widely separated observatories are difficult to interpret because of the variety of processes involved in the development of the SEP events. This is particularly true when the spacecraft are beyond 1 AU because (1) particle transport effects become the dominant factor in shaping the observed time-intensity profiles, (2) multiple particle injections at the Sun tend to occur in periods of intense solar activity when several CMEs occur sequentially in a short time interval, making the identification of the particle sources ambiguous, and (3) the particle intensities are modulated by traveling interplanetary structures on route between the particle sources and the observer. These transient structures are able to channel, confine, and reaccelerate energetic particles, modifying the characteristics of the SEP events measured beyond 1 AU. A description of these processes and their effects in the development of SEP events at distances beyond 1 AU can be found in the works of Lario et al. [2000a, 2004a].

In this paper, we first analyze the large-scale structure of the inner heliosphere (<10 AU) prior to the occurrence of the October–November 2003 events in order to establish the conditions under which these events occurred. In section 3 we present the energetic particle observations at 1 AU, Ulysses, Cassini, and Voyager-2 and discuss the changes in the different physical parameters of each spacecraft. In section 4, we discuss the longitudinal and radial dependence of both the time-intensity histories and the particle fluences integrated over the duration of the events. Finally, in section 5 we summarize the main results of this work.

2. Prevenient and Postevent Structure of the Heliosphere

[1] The inner heliosphere prior to 19 October 2003 (day of year 292) was characterized by solar wind parameters of high-speed solar wind character [Lackman et al., 2004]. Figure 2 shows solar wind and interplanetary magnetic field (IMF) data from ACE and Ulysses (Figures 2a and 2b) as well as ground-based data from the Cassini spacecraft (Figure 2c) from 18 August 2003 (day 230) to 5 January 2004 (day 370). Magnetic field observations were made by the Magnetic Fields Experiment (MAG) on ACE [Smith et al., 1998], the Vector Helium Magne- tometer (VHM) sensor on Cassini [Dougherty et al., 2004], and the VHM on Ulysses [Balogh et al., 1992]. The angular
Figure 2. (a) Hourly averages of the solar wind speed measured by the SWEPAM instrument on board ACE [McComas et al., 1998], magnetic field magnitude and orientation (in the RTN coordinate system) as measured by the MAG instrument on board ACE [Smith et al., 1998]. (b) Hourly averages of the solar wind speed measured by the SWOOPS instrument on board Ulysses [Bame et al., 1992], magnetic field magnitude and orientation (in the RTN spacecraft centered coordinate system) as measured by the VHM instrument on board Ulysses [Balogh et al., 1992]. (c) 10-min averages of the magnetic field magnitude and orientation (in the RTN spacecraft centered coordinate system) as measured by the VHM instrument on board Cassini [Dougherty et al., 2004]. The dashed vertical lines are spaced 27 days apart in Figure 2a and 26 days apart in Figures 2b and 2c. The symbols O and I identify in Figure 2a the high-speed solar wind streams with outward and inward magnetic polarities, respectively, whereas in Figures 2b and 2c they identify the associated CIRs.
Figure 3. Schematic representation of the ecliptic plane prior to the occurrence of the events in late October 2003. The solid lines represent nominal IMF lines connecting each spacecraft with the Sun, and the gray areas represent the outward polarity (O) and inward polarity (I) CIRs recurrently observed in the inner heliosphere prior to the events.

4. Energetic Particle Observations

4.1. AU Observations

[Figure 4] displays energetic particle data collected by the ACE and GOES-11 spacecraft from 20 October 2003 (day 293) to 2 December 2003 (day 336). Figures 4a and 4b show near-relativistic electron and low-energy ion intensities as measured by the EPAM instrument on board ACE. [Golub et al., 1998], whereas the figure 4c shows proton intensities observed by the Energetic Particle Sensor (EPS) on board GOES-11 [Sauer, 1993]. Figure 4d shows the IMF magnitude as measured by the MAG magnetometer on board ACE [Carsell et al., 1998]. The solid vertical bars indicate the passage of interplanetary shocks and gray vertical bars the passage of the ICMEs. Table 1 lists the arrival time of the shocks and the start and end times of the ICME passages. We have identified the passage of interplanetary shocks and ICMEs following the work of S克斯 [2004]. Malandrakis et al. [2005] also analyzed the energetic particle and magnetic field signatures associated with the passage of the ICMEs during this period. These signatures included bidirectional ~2 MeV ion flows (BiFs), bidirectional near-relativistic electron flows, low-variance magnetic field fluctuations, and smooth magnetic field rotations, and in some cases low-energy ion intensity depressions. All these signatures are typical of the passage of ICMEs in the ecliptic plane and at 1 AU from the Sun [Richardson, 1997; Nemechek and Goldstein, 1997]. In Table 1 we have indicated the start and end times of the ICMEs inferred from the analysis of these signatures that differ from the...
Figure 4. Hourly averages of the spin-averaged (a) electron, (b) ion, and (c) proton intensities measured by EPAM/EDE on board ACE [Gold et al., 1998], EPAM/LEMS120 on board ACE [Gold et al., 1998] and the LIPS on board GOES-11 [Sauer, 1993], respectively. Vertical arrows in Figure 4a indicate the solar events listed in Table 2. Dotted traces in the EPAM/LEMS120 ion time-intensity profiles indicate the time intervals with possible electron contamination. (d) Hourly averages of the magnetic field magnitude as measured by MAG on board ACE [Smith et al., 1998]. Solid vertical lines and gray vertical bars indicate the passage of interplanetary shocks and ICMEs listed in Table 1. The Earth's inertial heliographic longitude varied from $\Psi = 310.6^\circ$ on day 293 to $\Psi = 353.6^\circ$ on day 336.
Table 1. Interplanetary Shocks and ICMEs

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**Ulysses**

297/1711 - 298/2110  299/2023
301/0823 - -
303/0357* - -
310/1410* 311/0410 312/1090* 313/1931 - -
314/0075* - -
314/1015 315/0306 318/1050* -
317/1050 - -
319/0020 322/016* 324/090*
331/0315 - -
333/0125* - -

**Cassini**

314/1015 320/0580* - 325/0000 330/0000*

**Haystack**

119900Q2  Formation of a MIR

| Shock parameters and IMF identification at ACE can be found in the work of Skoug et al. [2004]. |
| IMF boundaries: Different from those identified by Skoug et al. [2004] and based on low-variability magnetic field minima, energetic particle signatures, and velocities. Only values of < 2 MeV MeV are observed from 295/1335 UT to 296/1424 UT, 302/1100 UT to 303/0855 UT, and 304/2500 UT to 305/1171 UT (see details in the work of Midikaduki et al. [2004]). |
| Low-energy ion intensity depressions extended to 301/1556 UT (Figure 2b). |
| Reverse shock. |
| Details of the ICMEs and shocks at Ulysses can be found in the work of de Korvin et al. [2005]. |
| Shock identification at Cassini based only on magnetic-field data. |
| See text for details on the IMF identification at Cassini. |
| Shock passage at Voyager-2 occurred at a 14-hour tracking gap. |
| Details of the MIR formation can be found in the work of Richardson et al. [2005]. |

analysis of Skoug et al. [2004]. Description of the energetic particle signatures observed within the ICMEs can be found in the work of Midikaduki et al. [2005]. |

15) Figures 4a and 4b show that near-relativistic electrons and < 1 MeV ion intensities remained above the pre-event level (i.e., the instrumental background level measured on day 293) for a period of more than ~40 days. The high-energy (~40 MeV) proton intensities, however, showed only enhancements in association with the occurrence at the Sun of the most intense well-connected solar flares and fastest CMEs. Table 2 lists the solar events associated with the near-relativistic electron events shown in Figure 4a as well as the halo and partial-halo CMEs observed by the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) during this period. (CME identification and parameters were obtained from the CME catalog compiled by S. Yohso and G. Michalek available at http://cdaw.gsfc.nasa.gov/). Association between solar flares and CMEs is based upon their temporal proximity, the site of the flare, and the direction of propagation of the CME (see also Table 1 in the work of Dryer et al. [2004]). The vertical arrows in Figure 4a indicate the occurrence of the events listed in Table 2. Solar events indicated in bold face in Table 2 indicate the events associated with >80 MeV proton enhancements as observed by GOES-11/EP (Figure 4c). Ion abundances and energy spectra measured during these five SEP events are analyzed in detail in the work of Cohen et al. [2007]. We refer the reader to this paper for further details. |

[14] The low-energy ion intensities shown in Figure 4b were measured by the low Energy Magnetic Spectrometer LEMS120 [Gold et al., 1998]. A very high fraction of the electrons that enter the LEMS120 collimator are diverted by a magnetic deflection system. However, when the >50 keV electron flux is sufficiently high, some electrons are counted in the LEMS120 ion telescope, even though the absolute efficiency for counting these electrons is quite small (~5%) [Kremeny, 1999]. We have indicated by dotted traces the time intervals when ion channels are probably contaminated by electrons at the beginning of the large SEP events when many electron events arrive promptly, well before the slower ions start reaching the spacecraft (Figure 4b). |

[15] Low-energy ion intensities peaked at or near the arrival of at least six of the CME-driven shocks observed at 1 AU (Figure 4b). The ion intensity enhancement observed on days 319–321 is classified as a CIR event due to its distinct time-intensity profile, its soft spectra, inward anisotropies (not shown here), and its association with the outward polarity high-speed solar wind stream observed on day 319 (Figure 2a). The elevated ion intensities measured during this CIR event contrast with those measured in isolated solar minimum CIR events (i.e., without the occurrence of prior intense SEP events [see, e.g., Larou et al., 2001, Figure 2]). These high intensities are most likely due to reacceleration of SEPs by CIRs [Larou et al., 2001]. |

[16] To summarize, the successive injection of SEPs by intense solar events produced the multiple particle incidence that was observed at 1 AU during the time interval shown in Figure 4. The continuous acceleration of low-energy ions by CME-driven shocks and CIRs, led to the elevated low-energy ion intensities observed throughout a time period of more than 40 days (Figure 4b). |

3.2. Ulysses Observations

Figure 5 shows Ulysses observations in the same form as in Figure 4. Figure 5a presents high-energy relativistic electron and low-energy ion intensities measured by the HISCALE instrument [Lanzerotti et al., 1992], where as Figure 5c (with a different vertical scale) shows high-energy proton intensities measured by two different detectors of the COSPIN instrument [Simson et al., 1992]. The >50 MeV proton intensities were obtained from the particle analysis (PHA) data of the COSPIN/HEC telescope. Daily averages of the 11–94 MeV proton PHA channel are used in Figure 5c because of the limited number of PHA events.
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[*] The identification of interplanetary shocks (solid vertical lines) and ICMEs (gray vertical bars) in Figure 5 follows that given by de Koning et al. [2005] (see also Table 1). In Figure 5d we have identified the magnetic field enhancements associated with the passage of CIRs by the magnetic field polarity observed during the associated high-speed solar wind stream (I for inward and O for outward polarities; see Figure 2). The ICME observed by Ulysses between days 311 and 312 constitutes a specific case of an ICME interacting with a CIR [de Koning et al., 2005].

[**] The fast and wide ICME observed by Ulysses between days 320 and 324 was studied in detail in the work of de Koning et al. [2005]. These authors identify the solar origin of this ICME with a fast backside halo westernly directed CME observed by LASCO on day 311 (Table 2). Figure 5 shows that the passage of this ICME produced particle intensity depressions with respect to those measured at the time of the CME-driven shocks on days 317 and 319.

[***] Figure 5b shows that low-energy ion intensities were already elevated before the occurrence of the October–November 2003 events because of the effect of the recurrent CIR events observed in previous solar rotations (not shown here). Near-relativistic electron and 8–19 MeV proton intensities gradually started to increase already on day 297 (Figures 5a and 5e). We attribute these increases to the solar events occurring between days 295 and 299 on the eastern limb of the Sun (as seen from the Earth; Table 2) that slowly filled the heliosphere with energetic particles.

[****] Near-energy ion (<19 MeV) and near-relativistic electron intensities abruptly increased at 1710 UT on day 301 without any velocity dispersion effect. This increase occurred within the passage of the inward polarity CIR bounded by a forward and a reverse shock pair (Figure 5d). The X17 solar flare on day 301 (Table 2) was associated with the solar origin of the most intense SEP event observed at 1 AU [see Cohen et al., 2005, Figure 4]. However, the abrupt low-energy ion (<19 MeV) intensity increase at Ulysses occurred too early to be due to injection of SEPs at the time of this flare. Our interpretation is that Ulysses suddenly established magnetic connection with a tube flux
Figure 5. Spin-averaged (a) electron, (b) ion, and (c) proton intensities measured by HI-SCALE/DE [Lanza et al., 1992], HI-SCALE/LEMS120 [Lanza et al., 1992], and the COSPIN/LET and COSPIN/HET telescopes [Simpson et al., 1992]. Hourly averaged intensities are shown except for the 71–94 MeV pulse-height analysis (PHA) COSPIN/HET channel where 1-day averages are shown (see details of the PHA event processing in the work of Simpson et al. [1992]). Vertical arrows in Figure 5a indicate the solar events listed in Table 2. (d) Hourly averages of the magnetic field magnitude as measured by WMH on board Ulysses [Balogh et al., 1992]. Solid vertical lines and gray vertical bars indicate the passage of interplanetary shocks and ICMEs listed in Table 1. The heliocentric radial distance $R$, heliographic latitude $\Lambda$, and inertial heliographic longitude $\Psi$ of Ulysses varied from $R = 5.21$ AU, $\Lambda = 6.4^\circ$, $\Psi = 79.9^\circ$ on day 293 to $R = 5.27$ AU, $\Lambda = 4.1^\circ$, $\Psi = 80.3^\circ$ on day 336.
populated with low-energy particles that were injected into the interplanetary medium during the solar events prior to the occurrence of the X17 flare on day 301. McKibben et al. [2005] analyzed in detail the solar wind and magnetic field discontinuities observed within the CIR. These authors concluded that the abrupt ~19 MeV ion intensity enhance-
ment at 1710 UT on day 301 occurred in association with the passage of a stream interface formed within the CIR. According to McKibben et al. [2005], these energetic particles were injected from the Sun on day 299 but were not observed by Ulysses until the stream interface (that acted as a barrier for the energetic particles) reached the spacecraft. The rising intensities observed prior to the arrival of the stream interface were the result of particles that leaked through the stream interface onto field lines that intersected Ulysses (see details in the work of McKibben et al. [2005]).

[2] High-energy (>39 MeV) proton intensities increased at the end of day 301, about ~12 hours after the occurrence of the X17 flare on day 301. This increase was followed by a rapid enhancement at ~0545 UT on day 302. The time delay between the occurrence of the X17 flare on day 301 and these intensity increases is longer than what is expected from a zero-degree pitch-angle 70-MeV proton propagating scatter-free along a nominal Parker spiral connecting the Sun to Ulysses at 5.2 AU. Possible causes of these longer time delays include particle propagation effects over the ~13 AU field-aligned distances (assuming that the IMF topology was a undisturbed Parker spiral), delayed injection of particles onto IMF lines connecting the particle sources to Ulysses, longer path lengths than those assumed by nominal IMF topologies, and local effects by magnetic field structures crossing Ulysses that modulate the observed particle intensities (such as the inward polarity CIR observed during the onset of this event at Ulysses). The oscillations observed in the rising intensities at Ulysses were associated by McKibben et al. [2005] with oscillations of the magnetic field, indicating that different transport conditions existed in each flux tube.

[2] Observations at 1 AU (Figure 4) show that high-
energy (>40 MeV) proton increases occurred also in asso-
ciation with the solar events on days 302, 306, and 308 (boldfaced in Table 2). However, no clear flux increases were observed on the already elevated intensities at Ulysses. Lecacheux et al. [2000a] showed that separated SEP events at 1 AU may become merged at ~5 AU simply due to energetic particle propagation effects. Therefore it is not surprising that a peak at 1 AU is not seen in Figure 4c. Figure 4a shows a sequence of individual high-energy (>40 MeV) proton events (Figure 4c). Ulysses observations show only a single high-energy (>39 MeV) proton event from day 301 to 311 (Figure 5c). In addition, as observed from 1 AU, the SEP event on day 301 had a harder spectrum than the rest of SEP events shown in Figure 4c [Cohen et al., 2005]. Therefore the contribution of the event on day 301 to the high-energy component of the proton intensities was larger than the subsequent events seen from 1 AU. The solar events occurring after day 301 and until day 311 injected SEPs with a softer spectrum into an already elevated particle population, resulting in an extended SEP event at Ulysses without new high-energy proton intensity enhancements (Figure 5c).

[2] The following >39 MeV proton intensity enhance-
ment was observed by Ulysses on day 312. The most probable solar origin of this enhancement was related to the fast backside halo CMEs on days 319 and 311 (Table 2). The easterly directed backside halo CME on day 310 did not produce any effect on the already decaying intensities at 1 AU (Figure 4), whereas the event on day 311 produced only a small near-relativistic electron event at 1 AU (Figure 4a). The onset of this event at Ulysses was modu-
lated by the passage of an ICME and an outward polarity CIR on days 311–313 (Figure 5d). Details of the high-
energy component of this particle intensity enhancement can be found in the work of McKibben et al. [2005].

[2] An additional high-energy proton intensity increase was observed by Ulysses on day 323 near the passage of the trailing edge of the fast ICME. Analysis of the ion anisot-
ropy flows allows us to discern whether this new particle intensity enhancement was due to either a recovery of particle intensities after the passage of the ICME or a new injection of SEPs from the Sun. Figure 6 shows the evolution of the 1.87–4.80 MeV anisotropy coefficients measured in the solar wind frame from day 298 to 338 as observed by the Ulysses/HE-SIZE instrument [Lanzerotti et al., 1992]. These coefficients are deduced from the scattered data collected by the LEMS30 and LEMS120 telescopes, transformed into the solar wind frame by cor-
recting for the Compton-Getting effect, and fitting a reduced second-order spherical harmonic expansion [Sanderson et al. [1985] for details]. The first-order harmonic consists of three components with amplitudes A0, A1, and B0. The ratio A0/A1 (where A0 is the isotropic component; Figure 6a) represents, in the solar wind frame, the first-
order anisotropy resolved along the magnetic field direction (its sign is defined with respect to the IMF direction). A1 and B1 represent the flow transverse to the IMF and are pseudozero throughout the time interval covered in Figure 6, indicating that there was no net flow of particles across the IMF (Figures 6c and 6d). Eventually, the quantity A1/A0 (Figure 6c) represents the second-order harmonic distribution. A positive ratio A1/A0, when the first-order coefficients are close to zero, represents a bidirectional ion flow (BFI) along the IMF [Sanderson et al., 1985]. Details about the computation of the anisotropy coefficients can be found in the work of Lanzerotti et al. [1992].

[2] In Figure 6b we have identified the periods when the particle fluxes were directly outward along the IMF (indicated by minus symbol), and when BFI's were observed (indicated by B). The particle intensity enhancements on days 301, 311, and 324 showed outward flows along the field, whereas the shocks on days 310, 311, 319, and 336 produced changes in the particle flows indicating that these low-energy ions were flowing away from the shocks and hence most likely locally accelerated by the shocks. The passage of the fast ICME by Ulysses during days 320–324 was characterized by particle intensity depressions (Figure 5) and ~2 MeV BFI (Figure 6). Both signatures are typical of the passage of ICMEs at 1 AU [Richardson, 1997]. In this case, they were also observed at 5.2 AU. The outward particle flow observed after the passage of the ICME suggests that the new intensity
enhancement on day 324 was due to an injection of SEPs from the Sun possibly associated with the fast halo CMEs on day 322; Table 2) and not to a recovery of the fluxes observed prior to the ICME passage. Note also that the 8–19 and 39–70 MeV peak intensities at the end of day 324 were higher than what was expected following the decay trend established before the passage of the ICME (Figure 5c). The energy spectrum of this new particle injection was softer than the previous high-energy proton intensity enhancements seen by Ulysses. The arrival of these freshly injected particles was mediated by the passage of the ICME. Low-energy ions and near-relativistic electrons were only observed once the ICME was beyond Ulysses, whereas the >39 MeV protons were able to propagate across or within the ICMR as observed in the already increasing 39–70 MeV proton flux on day 323 (Figure 5c). The low count rates of the 71–94 MeV proton channel forced us to use 1-day averages in Figure 5c and we cannot discern whether the new injected >70 MeV propagated inside the ICME. The access of energetic particles into the ICME depends upon both the magnetic topology of the ICME and the energy, gyroradius, and source of the energetic particles [Lario et al., 2004b]. This discussion is beyond the scope of the present study. In any case, Figure 5 shows that the intensity increase was more pronounced after the trailing edge of the ICME passed past Ulysses, suggesting that the transport of particles to Ulysses was impeded by this intervening structure.

To summarize, Ulysses observations show that, as in the case of 1 AU observations (Figure 4), near-relativistic electron and >3 MeV ion intensities remained high (i.e., above the preevent level measured on day 298 for ions and on day 296 for electrons) for a long (~40 days) period of time. For example, the 340–640 keV ion intensity did not come back to the values measured on day 298 until day 345. These high intensities resulted from both the injection of SEPs from the Sun during the October–November 2003 events, and the effects that both CME-driven shocks and recurrent CIRs have in the interplanetary medium being able to reaccelerate low-energy particles.

3.3. Cassini Observations

Figure 7 shows energetic particle and magnetic field observations from the Cassini spacecraft. Energetic particle data were collected by the Low-Energy Magnetospheric Measurement System (LEMMS) of the Magnetospheric Imaging Instrument (MIMI) [Krimigis et al., 2004], whereas the magnetic field data comes from the VIM on board the Cassini spacecraft [Dougherty et al., 2004]. Unfortunately, the plasma instrument on Cassini was not oriented to observe the solar wind flow; therefore we use magnetic field data to determine the passage of shocks. The use of magnetic field data alone to identify plasma structures prevents us from performing their complete characterization and classification. In Figure 7d we have identified
Figure 7. Ten-minute averages of the (a) electron, (b) ion, and (c) proton intensities measured by MIMI/LEMMS on board Cassini [Krimigis et al., 2004]. Vertical arrows in Figure 7a indicate the solar events listed in Table 2. (d) Hourly averages of the magnetic field magnitude as measured by VHIM on board Cassini [Dougherty et al., 2004]. Solid vertical lines indicate the passage of possible interplanetary shocks listed in Table 1. The heliocentric radial distance \( R \), heliographic latitude \( \Lambda \) and inertial heliographic longitude \( \Phi \) of Cassini varied from \( R = 8.65 \) \( \text{AU} \), \( \Lambda = -3.5^\circ \), \( \Phi = -25.5^\circ \) on day 293 to \( R = 8.73 \) \( \text{AU} \), \( \Lambda = -3.6^\circ \), \( \Phi = 26.4^\circ \) on day 336.
two magnetic field discontinuities (solid vertical lines) that are presumably a forward and a reverse shock (their arrival times are listed in Table 1) bounding a structure with enhanced highly fluctuating magnetic field (see also Figure 2c).

The solar origin of this enhanced magnetic field structure is uncertain because of the intense level of solar activity occurring during this time interval (Table 2). Besides, this structure moved past Cassini when an outward polarity EIR structure was expected to be observed (Figure 2c). The interaction between solar wind streams results in regions of enhanced magnetic field magnitude [Barthol and Ogilvie, 1970]. We suggest that the interaction and coalescence of the numerous CMEs occurring at that time (mostly westerly directed, see Table 2), together with the outward polarity EIR, formed this enhanced magnetic field structure. Richardson et al. [2015] used a one-dimensional MHD model to propagate radially outward the plasma structures observed at 1 AU during this time interval (Figures 2a and 4d). At a distance of 8.7 AU, they obtained a forward shock in the middle of day 315 associated with the shock observed by ACE at 0555 UT on day 302. According to their model, the shock at 8.7 AU was followed by a low-density region from the middle of day 318 to late on day 323 when a forward shock, related to the shock seen by ACE at 1619 UT on day 303, arrived at 8.7 AU. Differences between the structures obtained by Richardson et al. [2015] at 8.7 AU and the Cassini observations could be due to the longitudinal separation between ACE and Cassini as well as the multiple CMEs expanding outward from various longitudes (Table 2).

The enhanced magnetic field structure observed by Cassini (Figure 7d) lasted ~15 days (from late on day 314 until day 330). The field direction varied considerably from day 316 to day 325 whereas day 325 to 330 a period with low-variability in both magnetic field magnitude and components was observed (Figure 2c). Detailed analysis of the individual features present within this large-scale structure and their identification with specific solar events are beyond the scope of this paper. The long duration of this event, the enhanced level of fluctuations in the magnetic field directions, together with the occurrence of multiple CMEs at the Sun, suggest that this field structure was part of a compound stream as defined by Birn [1975]. Similar examples of multiple compound streams are described elsewhere [e.g., Burlaga et al., 1986].

Particle intensities measured by the MIMI/LEMS were affected by high background intensities mostly due to the Radiosonde Thermoelectric Generator (RTG) and the galactic cosmic ray background [Lario et al., 2004a]. Figures 7a, 7b, and 7c show electron, ion, and proton intensities without any background subtraction. Enhanced low-energy ion intensities (Figure 7b) were only observed during the passage of the enhanced magnetic field structure, whereas the rest of the period plotted in Figure 7b only shows intensities at background level.

Electron intensities (Figure 7a) started to gradually increase above the background at the beginning of day 301. This increase was followed by a new gradual enhancement at the end of day 302 that continued until day 313 when intensities rose by more than one order of magnitude and peaked after the passage of the forward shock on day 314. High electron intensities were observed between the passage of the two shocks and abruptly decreased on day 322. The 25–60 MeV proton intensities (Figure 7c) started to gradually increase above the background at the end of day 302 reaching a first maximum on day 306 followed by a slow gradual decay of more than 8 days. The 25–60 MeV proton intensities peaked above the passage of shocks, remaining high between the two shocks and rapidly decreasing on day 322.

As in the case of Ulysses, we attribute the first electron intensity increase (at the beginning of day 301) to the solar events occurring prior to day 301, whereas the subsequent increase seen in both the 25–60 MeV proton and near-relativistic electron channels at the end of day 302 was mainly a result of the particle injection during the main solar event on day 301. The merging of SEP events at larger heliocentric distances [Lario et al., 2004a], the softer spectrum of the new solar events at 1 AU (Figure 4c), the deceleration of energetic particles propagating to Cassini, and the mitigating effect that intervening transient solar wind flows have on the prompt component of the SEP events [Lario et al., 2004a] are the possible reasons that no additional increases in the Cassini particle intensities were observed in association with the solar events occurring after day 302.

Lario et al. [2004a] showed that during the heliospheric cruise of Cassini to Saturn (at heliocentric radial distances ranging between 2.5 and 8.0 AU) the arrival of SEPs at Cassini was modulated by the presence of magnetic field structures formed between the Sun and Cassini. The structure of the inner heliosphere prior to the occurrence of the October–November 2003 events was dominated by the two recurrent high-speed streams (Figure 3). However, the series of solar events started with the appearance of the active regions AR04844 and AR04846 already on the eastern limb of the Sun (Table 2), producing a series of transient flows propagating toward these regions [Dwyer et al., 2004]. The presence of such a system of transient flows in the field lines connecting Cassini to the Sun may have had a mitigating effect on the prompt component of the SEP events [Lario et al., 2004a]. Comparison with other the SEP events observed during the Cassini heliospheric cruise (Figure 1 in the work of Lario et al. [2004a]) shows that the prompt component of the October–November 2003 SEP events at Cassini (i.e., the intensity enhancement observed from day 302 to day 312) was not intense. This result can be explained in terms of both the modulating effect of the intense outer stream propagating from the Sun and Cassini and the larger heliocentric radial distance of Cassini [Lario et al., 2004a].

The time histories of the October–November 2003 events at Cassini were completely controlled by the passage of the enhanced magnetic field structure. The proton intensities above 2.2 MeV (Figure 7e) peaked on day 321 just after the shock passage on day 320 and coinciding with a depression of the magnetic field magnitude (Figure 7d). The abrupt decrease in particle intensities observed on day 322 and the increase in magnetic field magnitude suggests that Cassini entered into a new structure of this large-scale compound stream. Therefore particle intensities were modulated by the passage of local magnetic field structures. Unfortunately, the LEMMS experiment was looking to a
fixed direction in the sky during most part of the time interval considered in Figure 7. Consequently, we have not computed particle anisotropies for Cassini and the analysis of effect that these anisotropies had on the flow of energetic particles is not available.

3.4. Voyager-2 Observations

[1] Unlike the other spacecraft used in this analysis, Voyager-2 was located in the outer heliosphere (R = 71.6 AU) and south of the ecliptic plane (Δ = 24.8°) at the time of the October-November 2003 solar events (Figure 1). The system of transient flows generated during this series of events was predicted to arrive at Voyager-2 around day 119 of 2004, when Voyager-2 was at R = 73.18 AU, Δ = 25.2°, and 9 = 215.3° [Richardson et al., 2005]. Figure 8 shows energetic particle data from the Low Energy Charged Particle (LECP) experiment [Krüning et al., 1977] and solar wind speed from the Plasma Science (PLS) experiment [Bridge et al., 1977] on board Voyager-2. The solid vertical line in Figure 8 identifies the passage of a shock (Table 2) driven by the merged interaction region (MIR) formed as a result of the series of events in October–November 2003 [Richardson et al., 2005; Burlaga et al., 2005a]. The averaged transit speed of this MIR to travel from the Sun to Voyager-2 was about ~690 km s⁻¹. Voyager-2 solar wind observations prior to the occurrence of these events were described by Burlaga et al. [2005b]. The recurrent CIRs observed at ~1–9 AU prior to the October–November 2003 events (Figure 2) were not observed by Voyager-2 because they were overtaken by the faster CMEs ejected from the Sun. However, the period prior to the arrival of the MIR at Voyager-2 was characterized by a high wind speed due to the reappearance of coronal holes at the Sun [Burlaga et al., 2005a].

[2] Magnetic field data from Voyager-2 were analyzed in the work of Burlaga et al. [2005a]. Within the ~48 days time period with elevated solar wind speeds, i.e., from the shock passage on day 119 until day ~167 (Figure 8d), Burlaga et al. [2005a] identified the following magnetic structures: the shock (on day 119), a sheath-like region (from the shock up to day 128), and a relatively fast stream with smooth speed profile that decreased monotonically until at least day 167 (see Figure 2 in the work of Burlaga et al. [2005a]).

[3] Figures 8a, 8b, and 8c show the energetic particle intensities measured by Voyager-2 during this event. Intensities of the LECP energy channels were corrected for background by subtracting counts due to penetrating cosmic rays. The 3.0–17.3 MeV proton intensities began rising ~25 days prior to the passage of the shock, peaked ~1 day after the shock arrival and remained elevated for a period of ~70 days (Figure 8c). The 22–50 MeV proton channel (not shown here) showed an ~88% increase with respect to the intensities measured at the time of the shock passage. The 70 MeV proton intensity depression began on day 128 (9 days after the shock passage) in association with an increase in magnetic field magnitude [Burlaga et al., 2005a]. The minimum of the ~70 MeV proton intensity was reached on day 138 (19 days after the shock) coincident with the maximum of the magnetic field magnitude. The reader is referred to the work of Burlaga et al. [2005a] for further details on the evolution of the magnetic field during this event.

[4] Figure 8b shows that the low-energy (~200 keV) ion intensities began rising just a few (~10) days before the shock passage and peaked ~15 days after the shock. The intermediate-energy (~540–3500 keV) ion intensities showed peaks ~4 days and ~6 days after the shock, whereas the 3.0–17.3 MeV proton intensities (Figure 8c) peaked ~1 day after the shock. While the ~3 MeV proton time-intensity histories were dominated by the first peak close to the shock passage, the ~200 keV ion time-intensity histories were dominated by the second peak observed a few (10–15) days after the shock and contained in the region of enhanced magnetic field [Burlaga et al., 2005a]. The electron intensity profiles (Figure 8a) resemble those of the 3.0–17.3 MeV protons, rising ~15 days before the shock passage and peaking ~5 days after the shock. Electron intensity enhancements were also observed at the highest-energy electron channel of the LECP instrument (0.35–1.50 MeV).

[5] In contrast to the observations in the inner heliosphere, the particle event at Voyager-2 was only observed at energies below 17 MeV and in association with the passage of the MIR. The duration of the time interval with enhanced proton intensities increased with the proton energy. Since low-energy ion intensities did not peak at the time of the shock passage, we suggest that the shock did not locally accelerate particles. The fact that low-energy (~200 keV) ion intensities peaked ~15–20 days after the shock passage suggests that these particles were part of a particle population accelerated earlier in the event either during the solar events or by the traveling shocks when they were still close to the Sun and efficient enough to accelerate particles. These low-energy particles propagated along the highly twisted IMF in the outer heliosphere, undergoing adiabatic deceleration. The expanding MIR and associated shock partly overtook these particles that remained confined behind the shock by the magnetic structures formed in the MIR (similar examples have also been suggested by Deck and Krüning [2003]). Energetic particle observations before and during the shock arrival may consist of an ambient population that was magnetically reflected and swept ahead by the MIR bearing an enhanced magnetic field [Deck and Krüning, 2003].

4. Discussion

[1] The series of solar events occurring in October–November 2003 produced SEP events with diverse time-intensity histories at the different spacecraft where they were observed. At 1 AU multiple intensity enhancements were observed in association with the intense solar events occurring at the Sun. Whereas low-energy ion intensities peaked at the time of the shocks, the high-energy particle enhancements were due to the fresh injection of SEPs from the Sun (Figure 4). At 5.2 AU, particle intensities were modulated by the passage of a fast ICME and the effects of the CIRs (Figure 5). Ulysses high-energy proton intensities showed only three gradual enhancements that contrasted with the multiple injections observed at 1 AU. At 8.7 AU
Figure 8. Five-day running averages of 1-day averages of the (a) electron, (b) ion, and (c) proton intensities measured by LEC on board Voyager-2 [Krimigis et al., 1977]. (d) Hourly averages of the solar wind speed as measured by PLS on board Voyager-2 [Bridge et al., 1977]. Solid vertical line indicates the passage of an interplanetary shock as listed in Table 1. The heliocentric radial distance R, heliographic latitude (Λ) and inertial heliographic longitude (Ψ) of Voyager-2 varied from R = 72.93 AU, Λ = −25.1°, Ψ = 215.3° on day 90 to R = 73.66 AU, Λ = −25.3°, Ψ = 215.4° on day 175.

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the time-history enhancements were observed in association with the passage of an enhanced magnetic field structure, whereas the prompt component of the SEP event associated with the X17 flare on day 301 was largely reduced (Figure 7). Finally, at 73.1 AU, only a ~20 MeV proton intensity enhancement was observed in association with the passage of a MIR (Figure 8).

The diversity of the time-intensity histories observed at the different spacecraft was due to both the multiple particle injections occurring at different times and longitudes (Table 2) and the passage over the spacecraft of magnetic structures controlling the particle intensities. The common feature of the events at all radial distances was the long time interval with elevated particle intensities. In the following, we study the evolution of the particle fluence integrated over the duration of the events at each spacecraft and the possible formation of energetic particle reservoirs in the inner heliosphere.

4.1. Energetic Particle Fluences

Figure 9 shows the energy spectra of the particle fluence evaluated over the time interval shown in Figures 4, 5, and 7 for 1 AU, Ulysses, and Cassini, and from day 100 to 170 of 2004 for Voyager-2. To compute the fluence F (in
units of particles cm$^{-7}$ s$^{-1}$ MeV$^{-1}$), we have first sub-
tacted the pre-existing intensity observed before the onset of the 
particle enhancement and then integrated the differential 
fluxes measured in each energy channel over the above 
defined time interval. The pre-event flux subtraction takes 
care of most of the RTG and galactic cosmic ray back-
ground contributions to the particle intensities measured by 
Cassini. Since presumably both sources were relatively 
constant during the time interval shown in Figure 7. We 
assume that the actual fluxes of the October–November 
2003 events at 8.7 AU were not higher than the fluxes 
deduced using Cassini measurements and shown in the 
lower left of Figure 9. 

We have fitted a power law $F = F_0 E^{-\beta}$ to the 
flux inferred from the electron channels and an exponential 
roll-off function $F = F_0 \exp(-E/E_0)$ to the combination of 
ion and proton channels (in the above equations, $E$ units are 
MeV and $F_0$ units are cm$^{-2}$ s$^{-1}$ MeV$^{-1}$). The values of 
the fitting parameters are given in each panel of Figure 9. 
Assuming a correct intercalibration between the different 
instruments on board each spacecraft, we obtain a radial 
dependence for $F_0$ as $R^{-1.6}$ for electrons and 
protons, respectively.

(c) It is of interest to compare the ion fluxes spectrum 
observed at Voyager-2 with that expected if the 
fluences spectrum at 1 AU were simply convoluted to the Voyager-2 
heliosphere. This is a good approximation since convection 
effects are expected to dominate the propagation of low-
energy ions in the outer heliosphere. Taking the midpoint 
times of the Voyager-2 and 1 AU averaging intervals as 
reference times and assuming spherical symmetric expen-
sion, the ion distribution observed at 1 AU on day 315 of 
2003 reached Voyager-2 at (73.3 AU) on day 135 of 
2004, implying a mean propagation speed of ~840 km s$^{-1}$ 
leaving the 185 day transit from 1 to 73.3 AU. We let assume that 
during this half-year interval, a "shell" of ions was isotropi-
cal, since presumably both sources were relatively 
cooling during its convection to Voyager-2. Then, 
the particle distribution function $f(r,\gamma)$ at radius $r$ and momentum 
$p = m_v v$ is constant along characteristics curves $\gamma = \gamma_0$ 
and constant in the $r - p$ plane, i.e., $f(r,\gamma) = f(\gamma_0, p_0)$ 
for $\gamma = \gamma_0$ and $p = p_0$. The differential intensity $f(r,\gamma)$ is 
related to the differential intensity $f(\gamma_0, p_0)$ measured at 1 AU by

$$
\int_0^\infty f(r,\gamma) d\gamma = \frac{m_v}{2\pi} \int_0^\infty f(\gamma_0, p_0) dp \gamma_0 (\frac{\gamma}{\gamma_0})^{\frac{\gamma}{\gamma_0} - 1} \left( 1 + \frac{\gamma}{\gamma_0} \right)^{\frac{\gamma}{\gamma_0} - 1}.
$$

(1)

This expression allows us to calculate $f(r,\gamma)$ at Voyager-2 
($r = 53.3$ AU) at the measured energy $\gamma$ given $f(\gamma_0, p_0)$ 
at 1 AU evaluated at $\gamma_0 = T_{\gamma_0}$. The lower right 
part of Figure 9 shows the ion fluxes predicted at 73.3 AU 
(thick solid line) using both equation (1) and the fluences 
measured at 1 AU (this dashed line). The larger fluences 
measured by Voyager-2 during the October–November 
2003 events suggests the processes not involved in this 
simple model such as particle reacceleration by propagat-
ning shocks (as observed at Ulysses) and additional 
particle sources contributed to the event observed at 
Voyager-2.

(c) Figure 9 also shows that whereas electron fluences 
are above the ion fluences at 1 and 5.2 AU, Cassini 
observed lower electron fluences. A possible interpretation 
is that at this distance, particle intensities were observed 
exclusively in association with the passage of two shocks 
and that ion shock acceleration in the interplanetary medium 
is more efficient than electron acceleration. On the other 
hand, the ~61 keV electron fluences at Voyager-2 were 
above those measured for the ions, suggesting the contri-
bution of an additional electron population associated with, 
for example, cosmic ray electrons swept by the MR and 
observed before the arrival of the shock (see discussion in 
the work of Decker and Krimigis (2003)).

4.2. Energetic Particle Reservoirs

[87] Multiperpendicular observations of energetic particle 
intensities have shown that particle fluxes measured during 
the decay phase of large SEP events often present equal 
intensities that evolve similarly with time [McKibben, 
1972]. These periods of small longitudinal, latitudinal, 
and radial particle intensity gradients, named reservoirs by 
Rostel et al. [1992], have been observed during isolated 
major SEP events [McKibben et al., 2003; Lario et al., 
2003] and during periods of intense solar activity when a 
sequence of events occurred at the Sun [Rostel et al.; 
Macdowall et al., 2001]. Possible mechanisms for the 
formation of particle reservoirs are described in the work 
of Lario et al. [2003]. The October–November 2003 series 
of events with elevated intensities for long time intervals 
seems appropriate for the formation of a particle reservoir.

[88] Figure 10 shows ~48 keV electron intensities mea-
sured by ACE, Ulysses, and Cassini from day 294 to 336.

The exception of a ~2 day interval from day 322 to 
324, when Ulysses and Cassini observed simultaneously 
similar electron intensities, no other period with equal 
electron intensity was simultaneously observed. During this 
2-day interval (322–325), Ulysses was within the fast 
ICME (Figure 5) and Cassini was still immersed in the 
compared stream that moved past this spacecraft 
(Figure 7). Electron intensities during this period, however, 
were already depressed due to the passage of these plasma 
structures over the two spacecraft.

[89] Figure 10 shows multiple electron intensity enhance-
ments at ACE from day 294 to 311 that contrast with the 
gradual enhancement observed by Ulysses from day 297 to 
311. Figure 9 of Lario et al. [2006a] shows that multiple 
signatures separated by a short time interval may be 
observed at 1 AU as distinct SEP events but at a single 
smooth profile at 5 AU simply due to propagation effects.

[90] The highest electron intensities at Ulysses were observed 
between days 314 and 316, just after the passage of the 
CIR structure on day 313 and before the arrival of the 
forward shock on day 316 (Table 1). During this time 
interval, ~2 MeV ion anisotropy coefficients were remark-
ably close to zero (Figure 9), consistent with a particle 
population stagnated between these two structures and 
connected with the solar wind speed. Similar periods of 
isotropic enhanced particle intensities at Ulysses confined 
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between two enhanced magnetic field structures have been previously observed by Ulysses (e.g., when it was at 5.2 AU in November 1998; see Figure 8b of Lario et al. [2000a]). [54] The highest electron intensities at Cassini were observed during a period of ~8 days (314–321) also in association with the passage of the enhanced transient magnetic field structure (Figure 7). Kallenrode and Cliver [2001] suggested that the presence of two converging shocks is an appropriate situation to generate long-lasting periods of high ion intensities. The proposed mechanisms leading to these high ion intensities are the formation of strong magnetic field enhancements that act as both ion reaccelerators and as efficient barriers for particle mirroring [Kallenrode and Cliver, 2001]. Reflection of near-relativistic electrons by enhanced magnetic field structures and electron acceleration by traveling interplanetary shocks at distances beyond 1 AU have also been previously suggested [e.g., Sarris and Malandraki, 2003; Lupate, 1989; Sarris and Kremeges, 1985]. Therefore we suggest that traveling enhanced magnetic field regions were responsible for shaping the time-intensity profiles of both ions and electrons at Cassini and thus producing this period with elevated particle intensities. [55] The electron intensities at 1 AU from day 314 to 318 were also elevated and decaying more slowly than during the decay phase of the rest of SEP events observed during this period (Figure 4a). This period with slow decaying electron intensities occurred when the ensemble of transient solar wind flows previously observed at 1 AU were already beyond 1 AU. We suggest that both the enhanced magnetic field structures formed beyond 1 AU capable of mirroring energetic particles back to 1 AU, together with the particle injection from the backside solar events occurring from day 313 to 317 (Table 2) contributed to these elevated and slow-decaying electron intensities at 1 AU.

[56] The time-intensity profiles observed in the inner heliosphere during the October–November 2003 events were determined by both new particle injections occurring at the Sun and the formation of transient plasma structures traveling in the interplanetary medium. The highest electron intensities at Ulysses and Cassini occurred in association with the passage of enhanced magnetic field structures. The confinement and reacceleration of energetic particles within these structures made possible the observation of these events in the outer heliosphere. The highest electron intensities at 1 AU were observed during the prompt component of the SEP events and exceptionally in association with the passage of the CME-driven shock on day 302 (Table 1). The discrete nature of SEP injections, occurring at separated times and longitudes, together with the marked differences in both the characteristics of the transient structures propagating separately toward different longitudes and the various effects that these structures have on the particle populations resulted in different time-intensity profiles at each spacecraft. Therefore no periods with equal particle intensities were observed by this fleet of spacecraft.

5. Summary

[57] The main points presented in this paper are summarized as follows:

[58] 1. The series of events in October–November 2003 produced SEP events with different signatures at the heliocentric distances where they were measured. The sequence of events generated from the NOAA Active Regions 0484, 0485, and 0486 during their transit across the solar disk and that continued once in the backside of the Sun; Table 2) produced a system of transient flows with different speeds and characteristics toward the different longitudes. The ICMEs observed at 1 AU, Ulysses, and Cassini were
associated with different solar events occurring at different times and different longitudes.

[2] The system of transient flows disrupted the sequence of recurrent CIRs observed in the inner heliosphere, but it reemerged in the subsequent solar rotations.

[3] The time-intensity histories of the SEP events were dominated by the passage of transient interplanetary structures. The prompt component of the SEP event associated with the fast halo CME and X17 flare on day 301 (Figure 5b) occurred in the inner regime with a radial distance. Whereas separated high-energy proton events where observed at 1 AU, they became merged at 5 AU. At 5 AU, the highest particle intensity was observed around the passage of an enhanced magnetic field structure. At Voyager 2, the particle event was associated with the passage of a MIR.

[4] The control that local interplanetary structures establish on the time-intensity profiles led to the nonobservation by two different spacecraft of a period with equal intensities.

[5] Particle fluxes measured throughout the duration of the event decrease with heliocentric distance slower than what is expected from adiabatic cooling in a symmetric propagating shell.

[6] Particle intensities measured at Voyager 2 involved a particle population swept by the MIR, presumably formed by galactic and anomalous cosmic rays, and a population of previously shock-accelerated particles that remained confined behind the MIR-driven shock.

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References


