Heliospheric energetic particle observations by the Cassini spacecraft: Correlation with 1 AU observations

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[1] We present energetic particle measurements from the Low-Energy Magnetospheric Measurement System (LEMMS) on board the Cassini spacecraft during its heliospheric cruise to Saturn. We cover 3 years (2000–2002) of data during the maximum of the solar cycle 23. Cassini’s heliocentric radial distance ranged from 2.5 to 8.0 AU. Energetic particle intensity enhancements were associated with either sporadic intense solar energetic particle events, the effects produced by recurrent corotating interaction regions, or the arrival of transient interplanetary shocks. High-energy (>25 MeV) ion intensity enhancements were exclusively associated with the prompt component of intense solar energetic particle events. The largest low-energy (<1 MeV) ion and near-relativistic (43–305 keV) electron intensities occurred at the passage of interplanetary shocks. We compare particle intensities measured during the major solar energetic particle events near Earth with those measured at Cassini. We find that in general, the most intense events were observed by both Cassini and near-Earth spacecraft. However, the arrival of energetic particles at Cassini’s larger heliocentric distance was modulated by the presence of magnetic field structures formed between the Sun and Cassini. We analyze the relative intensities of the particle events at Cassini in terms of the level of solar activity during the previous solar rotation. When a new injection of solar energetic particles occurs after a period of intense solar activity, it may produce a particle event at 1 AU but not at Cassini. Transient plasma flows generated by previous solar events can act as effective barriers to the propagation of energetic particles to Cassini. These structures cause delays in the expected arrival time of energetic particles at Cassini as well as an effective diminution of the prompt component of the solar energetic particle events at heliocentric distances from 2.5 to 8.0 AU. INDEX TERMS: 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 2134 Interplanetary Physics: Interplanetary magnetic fields; 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2139 Interplanetary Physics: Interplanetary shocks; KEYWORDS: energetic particles, heliosphere, interplanetary magnetic fields, interplanetary shocks, coronal mass ejections, corotating interaction regions


1. Introduction

[2] The Cassini spacecraft, launched on 15 October 1997, was specifically designed to study the Saturnian system. To ensure its arrival at Saturn in July 2004, Cassini used four gravity assist maneuvers at Venus (twice, in April 1998 and June 1999), Earth (in August 1999), and Jupiter (in December 2000). The interplanetary cruise of Cassini was initially planned to be a time of minimal spacecraft activity; however, several scientific instruments were already activated during its planetary flybys (especially after the Earth flyby) [Burton et al., 2001]. Some of these instruments were maintained active throughout most of the Cassini’s interplanetary cruise. Data from these instruments (although intermittently collected) provided valuable measurements of the interplanetary medium, especially during the maximum of the solar cycle 23. The range of heliocentric distances (2.5–8.0 AU) spanned by Cassini allows the characterization of the energetic particle transport conditions throughout different regions of the interplanetary medium in terms of both (1) the previous level of solar activity and (2) the existence of transient magnetic field compression regions traveling between the Sun and the observer.

that measures ions and electrons in the range of the few tens of keV to several MeV [Krinigis et al., 2004]. Interplanetary particle propagation in this range of energies can be strongly impeded by the presence of magnetic field structures [Sarris et al., 1975]. Regions of enhanced magnetic field strength and enhanced magnetic field turbulence have a clear influence in the modulation of the cosmic ray intensity [Burlaga et al., 1985, 1986]. These magnetic field regions have also been suggested to affect the transport of solar energetic particles (SEPs) along the interplanetary magnetic field (IMF) lines [Barouch and Bagnudeau, 1970; Barouch and Burlaga, 1976]. In particular, mirroring effects and scattering processes caused by irregularities in the IMF or by the presence of magnetic structures formed between the particle source and the observer have the ability to modify the time-intensity profiles of the SEP events [Barouch and Burlaga, 1976].

[4] During solar maximum the heliosphere is dominated by transient solar wind flows that propagate out from the Sun [McComas et al., 2000]. These transient flows include shock waves driven by coronal mass ejections (CMEs) or produced by the interaction between different solar wind streams, as well as other magnetic field structures such as interplanetary CMEs (ICMEs), magnetic holes, pressure balanced structures, regions of enhanced magnetic turbulence, etc. [Colburn and Sonett, 1966; Burlaga, 1984]. Isolated solar wind interaction regions may grow in size and amplitude with increasing distance from the Sun [Burlaga, 1995]. Eventually, neighboring interaction regions may also coalesce to form merged interaction regions [Burlaga et al., 1984]. The distance at which two interaction regions merge depends on their relative speeds. The net result of these two processes (i.e., growing and merging of the solar wind interaction regions) is that with increasing distance from the Sun, interaction regions become a dominant morphological and dynamical feature of the solar wind and IMF [Burlaga et al., 1985].

[5] Previous studies of low-energy particle observations in the ecliptic plane at distances between 2 and 8 AU include observations from the Pioneers 10 and 11 [Zwickl et al., 1975; Zwickl and Webber, 1977; Barnes and Simpson, 1976; McCarthy and O’Gallagher, 1976; McDonald et al., 1975, 1981a, 1981b; Hamilton, 1977; Hamilton et al., 1990], the Voyagers 1 and 2 [Decker et al., 1981], the Ulysses spacecraft when it was at ~2–3 AU in the ecliptic plane during the March and June 1991 events [Armstrong et al., 1993; Sanderson et al., 2000] or when it was at ~5 AU and close to the ecliptic plane in 1998 [Lanserotti and Sanderson, 2001; Lario et al., 2000]. Interplanetary low-energy particle enhancements observed at these distances were classified as (1) recurrent particle events associated with corotating interaction regions (CIRs), (2) solar energetic particles (SEPs) arriving directly from their injection close to the Sun, and (3) energetic particle enhancements associated with the passage of transient interplanetary shocks [McDonald et al., 1975, 1981a]. The predominant type of particle event depends on both the energy range of the observations and the period of time when the observations are performed. McDonald et al. [1981b] analyzed Pioneer 10 and 11 ~1 MeV proton data between 5 and 22 AU for the period 1978–1980 (around the maximum of the solar cycle 21) and concluded that whereas inside ~10 AU time-intensity histories are formed by a complex mixture of direct solar energetic particles and particles associated with interplanetary shocks, at larger distances (~14 AU) energetic particles associated with transient interplanetary shocks (Energetic Storm Particle (ESP) events) are the dominant type of solar particle event.

[6] The first analyses of the energetic particle observations from these distant spacecraft were focused on the characterization of the CIR and SEP events at large heliocentric distances (see references above). SEP events were analyzed in terms of diffusion-convection transport models assuming (1) an injection of particles close to the Sun, either impulsive (i.e., a delta-function in time) or of finite duration (i.e., an exponential function in time), and (2) a suitable expression for the radial diffusion coefficient of the energetic particles (see review by Hamilton [1981]). Whereas Zwickl and Webber [1977] assumed a dependence for the radial diffusion coefficient of the form \( \kappa_r = b \kappa_0 \alpha \), where \( b = 0.0 \pm 0.3 \) for 3.4–5.2 and 24–30 MeV protons, Hamilton [1977] gave a value of \( b = 0.4 \pm 0.2 \) for 11–20 MeV and 30–60 MeV protons. Some indications that the fit parameter \( \kappa_r \) may decrease beyond ~5 AU were suggested by Hamilton [1981]. None of these modeling efforts included either the effects of interplanetary acceleration by CME-driven shocks (whose acceleration efficiency changes in longitude and radial distance) or the effects that previous solar events may produce on the energetic particle transport conditions throughout the interplanetary medium. These works were focused on the study of the SEP events observed at large heliocentric distances but not on the conditions in the inner heliosphere that may lead to either the detection or nondetection of intense SEP events at large heliocentric distances. Energetic particles were assumed to be injected at the time of the solar flare and to redistribute to different longitudes via diffusion in the lower corona. Interplanetary transport conditions were parametrized only by the radial dependence of \( \kappa_r \) and did not account for magnetic inhomogeneities due to transient solar wind flows that affect the particle transport or for solar wind stream structures that play a role in determining the dynamics of the particle events [Hamilton, 1981].

[7] In this paper we use energetic particle observations to compare the most intense SEP events observed first by near-Earth spacecraft (i.e., ACE and GOES-8) with those observed later by Cassini. We describe the conditions that lead to the arrival of SEPs at heliocentric distances ~2.5 to 8.0 AU by comparing magnetic field with energetic particle data at locations near Earth and at Cassini. We cover 3 years of data around the maximum of the present solar cycle 23. In section 2 we describe the sources of the data used in this paper. In section 3 we give a global overview of the Cassini energetic particle data during this 3-year time interval and we compare 1 AU data with Cassini data, paying special attention to eight of the most intense SEP events observed at the Earth during this interval. Finally, in sections 4 and 5 we present the conclusions and summary of this study.

2. Instrumentation

[8] The data used in this paper are primarily from the Low-Energy Magnetospheric Measurement System (LEMMS)
on board Cassini. LEMMS is one of the three systems of the Magnetosphere Imaging Instrument (MIMI). Details on the MIMI/LEMMS detector can be found in the works of Krimigis et al. [2004] and Lagg et al. [2001]. LEMMS consists of two telescope systems to measure low-energy and high-energy particles (low-energy and high-energy heads). The opening angles of the two entrance apertures are 15° and 36° for the low-energy and high-energy head, respectively. The analysis of the particle type (ions or electrons) and of the incident energy is based on the energy loss of these particles in 11 semiconductor detectors at various positions inside the instrument. Electrons and ions entering the low-energy telescope are separated by an internal magnet. The high-energy head consists of a stack of solid state detectors where ions and electrons are distinguished by logic conditions among the energies deposited in each detector. In this paper we will use only selected rate channels of LEMMS. A complete list of these channels can be found in the works of Krimigis et al. [2004] and Lagg et al. [2001].

[8] The whole LEMMS assembly is mounted on top of a programmable turntable that can rotate around an axis of the spacecraft coordinate system. Unfortunately, during most part of the interplanetary cruise neither the Cassini spacecraft nor the LEMMS turntable rotated, preventing us from studying the particle incidence directions and flow anisotropies. Nevertheless, reorientations of the Cassini spacecraft and the LEMMS turntable were occasionally performed during the heliospheric cruise to Saturn. The effects that these reorientations produced on the particle intensities measured by the LEMMS telescopes will be indicated in each case.

[9] We also use data from the Cassini spacecraft magnetometer system [Southwood et al., 2001; Dougherty et al., 2004] that allows us to determine the effects that magnetic structures have on the energetic particle population. The use of magnetic field data alone to identify these magnetic structures prevents us from performing their complete characterization and classification as ICMEs, interplanetary shocks, pressure pulses, waves, or discontinuities. In particular, we will infer the passage of interplanetary shocks from the observation of low-energy (<1 MeV) ion intensity enhancements associated with an abrupt increase in the magnetic field magnitude. Further analyses using available plasma data from the Cassini spacecraft should be addressed to fully identify these structures as interplanetary shocks.

[10] The background in the LEMMS rate channels is mostly due to both (1) the Radioisotope Thermoelectric Generator (RTG) which supplies the electric power to Cassini and (2) the galactic cosmic ray background. Owing to the relatively high background rates of LEMMS, we restrict our investigation to the most intense solar energetic particle events. This limits somewhat the overall scope of the analysis performed in this paper and focuses our study on the few major SEP events observed out to 8 AU. The high background rates prevent us from accurately determining the onset of the SEP events at Cassini and identifying the periods of comparable intensities observed by different spacecraft in the late decay phase of the large SEP events, usually referred to as reservoirs [Roelof et al., 1992].

[11] The LEMMS experiment was looking to a fixed direction in the sky during most part of the time intervals analyzed in this paper. In the case of anisotropic particle distributions, distributions looking at different directions will observe different particle intensities. McCarthy and O’Gallagher [1976] and Zwickl and Webber [1977] showed that the anisotropy of solar energetic protons (>3 MeV) evaluated at the time of the maximum of the SEP events decreases gradually with the heliocentric radial distance. Whereas typical SEP events at 1 AU show anisotropy time profiles that exhibit a sharp increase at the onset of the event followed by a gradual decrease, SEP events at larger heliocentric distances show a more rapid decrease in the anisotropy profiles [McCarthy and O’Gallagher, 1976]. Therefore particle distributions during large SEP events at large heliocentric distances tend to be more isotropic than at 1 AU. Consequently, the fixed-looking direction of the LEMMS telescope introduces an uncertainty only during the onset of the events, when particle distributions are expected to be anisotropic. Later in the events, when isotropic distributions are usually observed, intensities measured by the fixed LEMMS telescopes are a good indication of the particle intensities that would be measured in any direction.

[12] In order to compare energetic particle observations at Cassini with those at 1 AU, we use data from the EPAM instrument on board the ACE spacecraft in a L1 Lagrangian Sun-Earth orbit [Gold et al., 1998] and from the EPS instrument on board the GOES-8 spacecraft in geosynchronous orbit [Sauer, 1993]. The EPS data have been corrected for background counts due to galactic cosmic rays and their secondaries, for the out-of-aperture responses, and for counts due to particles entering through secondary energy passbands (R. Zwickl, private communication, 2002). In order to characterize the interplanetary conditions observed at L1 prior to the onset of the major SEP events, we also use magnetic field and solar wind data from the Dual Technique Magnetometer (MAG) and Solar Wind Electron Proton Alpha Monitor (SWEPAM) instruments on board ACE [Smith et al., 1998; McComas et al., 1998]. Identification of the solar events associated with the origin of the major SEP events observed at both Cassini and at 1 AU is based on the Solar Geophysical Data reports (available at http://www.sec.nasa.gov/ftpmenu/), the Solar and Heliospheric Observatory (SOHO) Large-Angle Spectrometric Coronograph (LASCO) CME catalog compiled by S. Yashiro and G. Michalek (available at http://cdaw.gsfc.nasa.gov/), and on previously published analyses [e.g., Lawrence and Thompson, 2001; Smith et al., 2001; Nitta and Hudson, 2001; Cane et al., 2002; Sun et al., 2002; Lario et al., 2003a].

3. Observations

[14] Figure 1 shows 1-day averaged electron and ion intensities as measured by the rate channels of LEMMS. We cover 3 years of data (2000–2002) around the maximum of the solar cycle 23. The vertical yellow bar indicates the time interval around the Jupiter flyby between December 2000 and February 2001 [Krupp et al., 2002, 2004]. Vertical arrows in Figure 1 indicate low-energy (<800 keV) ion increases associated with the passage of interplanetary shocks (identified using only magnetic field data as a sudden increase in the field strength). This figure does not
constitute a comprehensive list of shocks observed by Cassini during this 3-year period. The largest low-energy (<800 keV) ion intensities throughout the time interval considered in Figure 1 were observed in association with the passage of interplanetary shocks (as per our identification), especially on day 342 of 2000 before the Jupiter flyby and on days 107 and 341 of 2001 (see details below). Near-relativistic (43–57 keV) electrons also exhibited very high intensities at the arrival of these shocks. The contribution of these shocks diminished at higher electron and ion energies. Indeed, the passages of these three shocks did not produce any intensity increase at ion energies above 25 MeV. A sequence of CIR events (black dots) observed during the first third of 2002 was associated by Lario et al. [2003b] with a sequence of CIRs observed at ACE. Analysis of these CIR events will not be addressed here; the reader is referred to Lario et al. [2003b] for their detailed analysis. Throughout this 3-year period, high-energy (25–60 MeV) ions show only a few increases which are associated with intense prompt SEP events. The analysis of these events is described in the next section.

Figure 2 compares ion and electron observations at 1 AU and at Cassini. We have identified the occurrence of the major SEP events observed during the 3-year interval. The largest and most intense events tend to be observed by both Cassini and near-Earth spacecraft regardless of the longitudinal separation between Cassini and Earth with two possible exceptions: Two large SEP events in November 2000 cannot be fully analyzed because of a data gap at Cassini, but two large SEP events in November 2001 are indeed exceptions. Whereas the first event in November 2001 is hardly observable in the Cassini time-intensity profiles, the second SEP event did not produce any particle intensity enhancement at this spacecraft. Apart from the intense SEP events, the highest 220–305 keV electron intensities (bottom panel of Figure 2) were reached during the Jupiter flyby [Krupp et al., 2002, 2004] and on day 341 of 2001 (described in detail below in section 3.2). The intensity increase on day 341 of 2001 stands out against the rest of the intensity increases because of its high level and its characteristic time-intensity profile (i.e., gradual increase and relatively sharp decrease). This type of profile is characteristic of the ESP events observed at large heliocentric distances [see McDonald et al., 1981b, Figure 1].

Large SEP events are usually associated with fast and wide CMEs at the Sun [Kahler, 2001, and references therein]. The almost simultaneous observation of these large SEP events by spacecraft widely separated in solar azimuth suggests that particle acceleration takes place over wide fronts of interplanetary shocks driven by these CMEs.
Figure 2. (top) One-day averaged high-energy ion intensities as measured by MIMI/LEMMS onboard Cassini (red trace) and EPS onboard GOES-8 (black thin trace). (bottom) One-day averaged electron intensities as measured by MIMI/LEMMS onboard Cassini (red trace) and EPAM onboard ACE (black thin trace). The yellow bar indicates the time interval of the Jupiter flyby.
[Cliver et al., 1995; Lario et al., 2000]. An alternative interpretation of these broad particle sources invokes cross-field diffusion of energetic particles in the interplanetary medium [McKibben, 1972]. The interplanetary propagation of SEPs between their source and the observer is modulated by the presence of magnetic field compressions in interplanetary space. Whereas the SEP events in August 2001 and September 2001 were clearly observed at Cassini, the two events in November 2001 were hardly detectable. On the other hand, these two latter events at 1 AU were more intense than the event in August 2001 and, as we will show below, the nominal footpoints of the magnetic field connections of both the Earth and Cassini to the Sun were very close throughout November 2001.

[17] In the following sections we describe the energetic particle observations at Cassini and at 1 AU for eight of the most intense SEP events observed at Earth during 2000–2002. We also include the period around the Jupiter flyby (November 2000) when two intense SEP events were observed at 1 AU. We discuss the conditions that led to the detection or nondetection of these SEP events at Cassini. By using solar wind and magnetic field observations at ACE together with continuous observations of the solar events (i.e., CMEs and solar flares), we will infer the interplanetary conditions under which energetic particles were able to propagate to Cassini. Instead of describing the SEP events in chronological order, we will start with those events having good data coverage and less physical complexity.

3.1. September 2001 Event

[18] Figure 3a shows electron (top panel) and ion intensities (second and third panels) as measured by LEMMS on board Cassini (gray traces) and by ACE/EPAM or GOES-8/EPS at 1 AU (black thin traces). The bottom panel of Figure 3a shows the magnetic field strength as measured by ACE (black thin trace) and Cassini (gray trace). Pre-event particle intensity levels have been subtracted from the ion intensities measured at Cassini but not from electron intensities where background levels are similar at Cassini/LEMMS and ACE/EPAM. It is evident from Figure 3a that time-intensity profiles at 1 AU present many more increases than at Cassini, where only a long-lasting gradual SEP event was observed. The most intense SEP event at Earth during this period was associated with a halo CME first observed by LASCO/C2 at 1031 UT on day 267 and temporally associated with an X2/2B flare at 0932 UT on the same day at S16E23 [Lario et al., 2003a]. This SEP event was followed by other less intense events at 1 AU. The vertical arrows in the first and third panels of Figure 3a indicate the onset of the solar events associated with new increases in the particle intensities measured by ACE and GOES. In the third panel of Figure 3a we also indicate the longitude (as seen from the Earth) of the optical (Hα) flare temporally associated with the solar events that generated the SEP events at 1 AU (question marks indicate those solar events without a reported optical association).

[19] The time-intensity profiles at Cassini did not reflect the occurrence of the subsequent solar events that occurred after day 267 but rather remained at the level due to the event on day 267 or decreased slightly. For similar energy channels and for a given time (i.e., the two top panels of Figure 3a), particle intensities at 1 AU were usually higher than at Cassini. The exception was the 4-day interval between days 288 and 292 when intensities at 1 AU decreased and the <13 MeV ion and the 43–57 keV electron intensities at Cassini were still high. From day 292 to day 298 an enhanced magnetic field region crossed Cassini. Low-energy (<13 MeV) ion intensities peaked on day 292 coincident with the increase of the magnetic field strength. Electron intensities that were approximately flat throughout day 291 suddenly decreased at the beginning of day 292. Electron intensities increased again late on day 297. This period of relatively low electron intensities coincided with a reorientation of both the Cassini spacecraft and the turntable where the LEMMS telescope is mounted. This reorientation resulted in a different looking direction of the LEMMS experiment with respect to the different components of the spacecraft; in particular, a change in the orientation of the LEMMS telescopes with respect to the RTG. The RTG contribution to the total measured particle intensity depends on the relative orientation of the LEMMS telescopes with respect to the RTG and is different for each energy channel. For example, the high-energy (25–60 MeV) ion intensities that had already decreased to background levels on day 283 were not affected by this reorientation. The LEMMS turntable returned to its original orientation at the end of day 297 and electron intensities suddenly increased. Estimation of the RTG contribution to the different energy channels as a function of the LEMMS telescope orientation has not been performed at this point.

[20] Figure 3b shows the temporal configuration of the Sun, Earth, and Cassini as seen from the north ecliptic pole at the time of the flare on day 267. Black and gray dots indicate the position of the Earth and Cassini, respectively, where φ indicates their longitude in the heliographic inertial coordinate system (φ is counted counterclockwise from the horizontal, i.e., φ = 0° points horizontally to the right). The longitudinal separation between both spacecraft, Δφ, is indicated in the header of the figure. Two nominal IMF lines connecting Earth and Cassini to the Sun have been plotted assuming a Parker spiral and a solar wind speed of 400 km s⁻¹. The angle φ, in the header of Figure 3b and listed on the top of Figure 3a indicates the longitude of the Cassini’s nominal magnetic connection angle with respect to the Sun-Earth line and following the plotted spiral magnetic field line. The distance z from the Sun to Cassini along this nominal IMF line is given in the header of Figure 3b (z = 22.3 AU). If we suppose that the first arriving particles at Cassini are aligned to the magnetic field, a 57 keV electron along this IMF line will take ~7 hours to arrive at Cassini, whereas a 60 MeV proton will take ~9 hours. Increases above the instrumental background level are observed ~1.5 days after the flare occurrence on day 267. We cannot determine the cause, or causes, of this delayed onset at Cassini. Possibilities include particle propagation effects over the 20–25 AU field-aligned distances, delayed injection of particles onto IMF lines connecting to Cassini, longer path lengths than those assumed in Figure 3b, local effects by magnetic field structures crossing Cassini that modulate the observed SEP intensities, and/or the looking direction of the LEMMS telescopes that does not allow us to detect the first arriving particles propagating along the magnetic field.
velocity dispersion at the onset of the SEP event at Cassini suggests that local effects affecting the particle transport have indeed a significant influence on determining the onset of the SEP event at ~6.4 AU.

[21] In order to determine the conditions that energetic particles injected at the time of the solar event on day 267 will experience during their travel from the Sun to Cassini, we analyze the history of solar events occurring prior to the main flare on day 267. The two top panels of Figure 3c show the solar activity prior to the occurrence of the main solar event on day 267. The first panel shows the number of X-ray flares per day that were classified as M-class or X-class. The second panel shows the total number of CMEs per day as observed by SOHO/LASCO (solid line),
the number of CMEs with angular sizes $\omega > 120^\circ$ and plane-of-sky speeds $v_{\text{CME}} > 600 \text{ km s}^{-1}$ (hatched rectangles), and the number of halo CMEs with plane-of-sky speeds $v_{\text{CME}} > 600 \text{ km s}^{-1}$ (black rectangles) as reported in the SOHO/LASCO/CME catalog compiled by S. Yashiro and G. Michalek (available at http://cdaw.gsfc.nasa.gov as of October 2003). We also indicate in the second panel of Figure 3c the longitude of the flares temporally associated with the wide CMEs (as seen from Earth at the moment of their injection). The last two panels of Figure 3c show the solar wind speed and magnetic field magnitude as measured by the ACE spacecraft. Solid vertical lines indicate the passage of interplanetary shocks by ACE.

**Figure 3b.** Nominal spatial configuration of the ecliptic plane on day 267 of 2001 as seen from the north ecliptic pole. Nominal IMF lines have been plotted assuming a solar wind speed $V_{\text{sw}} = 400 \text{ km s}^{-1}$. The solid straight line shows the longitude of the solar event associated with the origin of the main SEP event observed at 1 AU. The angles $\phi$ indicate the longitude of the Sun and Cassini in the heliographic inertial coordinate system. Angle $\phi_c$ indicates the Cassini's nominal magnetic connection angle on the Sun with respect to the Sun-Earth line and following the plotted magnetic field line. Here $z$ is the distance along the nominal field line from the Sun to Cassini.

**Figure 3c.** Solar and interplanetary activity prior to the onset of the main SEP event observed at 1 AU. From top to bottom: Number of X-ray flares per day classified as M- or X- class. Number of CMEs per day (solid line), number of CMEs per day with angular sizes $\omega > 120^\circ$ and plane-of-sky speeds $>600 \text{ km s}^{-1}$ (hatched rectangles), and number of halo CMEs per day with plane-of-sky speeds $>600 \text{ km s}^{-1}$ (black rectangles); the longitude of the flares temporally associated with these wide CMEs (as seen from Earth at the moment of their injection) is indicated. Solar wind speed and magnetic field magnitude as measured by ACE. Solid vertical lines indicate the passage of interplanetary shocks by ACE.

Although our observations are limited to only one point (the L1 Sun-Earth Lagrangian point where ACE and SOHO are located), the continuous observation of solar wind and magnetic field conditions at that point, together with the occurrence of CMEs all around the Sun can be used to infer the interplanetary structures that SEPs injected on day 267 will have to propagate through. The pre-event Sun prior to day 267 was characterized by a scarcity of wide and fast CMEs. The consideration of only fast and wide CMEs (as seen from L1) implicitly assumes that only these CMEs are able to produce plasma flow disturbances in the interplanetary medium that affect the particle transport. This is a simplification of our study since L1 is a single privileged point in the heliosphere and slow and narrow CMEs may also produce interplanetary disturbances that affect the energetic particle transport toward Cassini.

The interplanetary medium at L1 prior to day 267 did not show any large solar wind interaction regions or enhanced magnetic field regions. The relatively high-speed ($<600 \text{ km s}^{-1}$) solar wind streams observed during this period did not produce strong magnetic compressions observable at 1 AU. Note also that most of the wide and fast CMEs prior to the solar event on day 267 were directed toward the east (as seen from the Earth) and therefore did not directly impact the nominal magnetic field line connecting the Sun to Cassini (see Figure 3b). Therefore the conditions prior to the solar event on day 267 (compared with the other events described below) were, in principle, propitious for...
particle propagation out to ~6.4 AU, hence the observation of this relatively intense SEP event at Cassini (Figure 3a). However, the delayed onset of the SEP event at this spacecraft, together with the lack of velocity dispersion effects, suggest that particles were not able to freely stream away from their source to Cassini, but some local effect, probably due to the magnetic field enhancement observed between days 268 and 270 (bottom panel of Figure 3a), influenced the arrival of SEPs at Cassini.

3.2. November 2001 Events

Figure 4a shows the ion and electron intensities together with the magnetic field magnitude observed at Cassini (gray traces) and near the Earth (black thin traces) from day 307 to 351 of 2001. Three intense SEP events were clearly observed at 1 AU. The first SEP event was associated with a fast (1810 km s\(^{-1}\)) halo CME first seen at LASCO/C2 at 1635 UT on day 308 and temporally associated with an X1/3B flare at 1603 UT on the same day at N06W18 [Lario et al., 2003a]. The second SEP event was associated with a fast (1379 km s\(^{-1}\)) halo CME first seen at LASCO/C2 at 0530 UT on day 321 and temporally associated with an M2/1N flare at 0448 UT on the same day at S13E42 [Lario et al., 2003a]. This second event at 1 AU was hardly observable at ion energies above 39 MeV (third panel of Figure 4a). The third intense SEP event at 1 AU was associated with two halo CMEs at 2030 UT and 2330 UT on day 326, respectively, with the first temporally associated with an M3/2B flare at 2022 UT from S25W67 and the second with an M9 flare at 2232 UT [Lario et al.,...
The respective plane-of-sky speeds of both halo CMEs were 1443 km s\(^{-1}\) and 1437 km s\(^{-1}\), respectively. The site of the second flare has been located at S15W34 by Dalla et al. [2003]. The first and third SEP events were among the most intense SEP events observed at 1 AU throughout solar cycle 23 (see Figure 2).

A data gap in the LEMMS particle intensities from day 319 to day 325 does not allow us to see the effects of the second SEP event at Cassini. At the time of the first and third intense SEP events at 1 AU, Cassini’s energetic particle data did not show any signature of an intense SEP event. High-energy (>25 MeV) ion intensities showed only a small (less than one order of magnitude above the background) increase on day 310. Low-energy (<13 MeV) ions and near-relativistic (43–57 keV) electron intensities showed a gradual increase starting on day ~311. No rapid increase in the low-energy ion and electron intensities such as the one shown in Figure 3a was observed in the Cassini time-intensity profiles. Low-energy (<13 MeV) ions showed an additional small increase around day 316 associated with the arrival of a possible interplanetary shock as seen by the increase in the magnetic field magnitude (bottom panel of Figure 4a). The data gap from day 319 to day 325 prevents us from studying the complete evolution of the time-intensity profiles at Cassini during the first SEP event.

The third SEP event at 1 AU did not produce an intensity increase (observable above the background) at Cassini. Particle intensities in all energy channels remained very close to background levels for more than ~9 days after the onset of the SEP event at 1 AU. The only significant increase at Cassini was observed at low-energy (<13 MeV) ion and near-relativistic electron intensities beginning on day ~336 with a gradual increase and a peak coincident with the passage of an interplanetary shock on day 341. After the shock passage, low-energy ion intensities decreased with some oscillations due to magnetic field structures formed downstream of the shock. A clear decrease in the electron and low-energy ion intensities was observed on day 343 coincident with the arrival at Cassini of the ~1.5 nT peak in the magnetic field magnitude.

Figure 4b. The same as Figure 3b but on day 308 of 2001.

Figure 4c. Solar and interplanetary activity prior to the onset of the first major SEP event observed at 1 AU in November 2001. The format is the same as in Figure 3c.
disturbed than that sampled by the particles injected on day 267 (see Figure 3c). We propose that the presence of these transient flows and associated partial “shells” of enhanced IMF magnitude in the interplanetary medium impeded the particle transport from the Sun to Cassini, thereby reducing the particle intensity of the SEP event at Cassini. The way by which these structures affect the particle transport depends on the characteristics of the magnetic field structures and the way energetic particles propagate around and through these field regions. These magnetic field structures may be transparent to energetic particles with large gyroradii (i.e., high-energy ions), whereas particles with small gyroradii propagate tightly bound to the field lines and therefore are constrained to follow the small-scale structure of the field lines, undergoing mirroring and pitch-angle scattering processes (see discussion below).

[29] The lower panel of Figure 4a also shows that interplanetary magnetic field magnitude observed by ACE prior to the solar flare on day 326 contained several increases associated with jumps in flow speed (not shown here). In particular, the magnetic field enhancement on day 310 was large (B > 30 nT) and broad (~1 day wide) and was due to the passage of the CME ejected from the Sun on day 308 and associated with the origin of the first SEP event at 1 AU [Cane and Richardson, 2003]. Assuming an average transit speed of ~700 km s⁻¹ for this CME to travel from the Sun to Cassini, its expected arrival time at Cassini was on day 325, precisely when an enhanced magnetic field region crossed this spacecraft. Note that the longitude separation between the Earth and Cassini on day 310 was only Δφ = 38°. Therefore we suggest that the large-scale magnetic structure crossing Cassini between days 325–332 was the same ICME previously observed by ACE on days 310 and that it effectively prevented the arrival at Cassini of the SEPs injected late on day 326.

[30] The magnetic field enhancement observed by Cassini between days 334 and 350 following the interplanetary shock on day 341 (bottom panel of Figure 4a) is most probably associated with the CME that left the Sun on day 326 and crossed ACE between days 328 and 330 [Cane and Richardson, 2003]. The longitude separation between Earth and Cassini on day 328 was Δφ = 21° and the assumed average transit speed of this structure to travel from ACE to Cassini is ~750 km s⁻¹. Whereas <13 MeV ion and <305 keV electron intensities peaked at the arrival of the shock on day 341, they decreased in intensity when this ICME crossed Cassini. Therefore energetic particles were clearly excluded from this region of high magnetic field.

[31] The effects that enhanced magnetic field regions, such as ICMEs or magnetic field compression regions formed in the interplanetary medium, have on energetic particles is diverse. In the following sections, we study other SEP events whose time-intensity profiles at Cassini were clearly affected by different magnetic field structures.

3.3. August 2001 Event

[32] Figure 5a shows energetic particle and magnetic field observations during the August 2001 event. The origin of the most intense SEP event at 1 AU during this period was associated with a non-Earth directed halo CME observed by SOHO/LASCO at 2354 UT on day 227 of 2001 [Lawrence and Thompson, 2001]. Following the history of the active regions on the visible part of the Sun (as seen from the Earth), Lawrence and Thompson [2001] localized the solar event generator of this halo CME as an active region at ~W165. Figure 5b shows the location and nominal magnetic connection of Earth and Cassini on day 228. The onset of the SEP event at Cassini was not observed until ~1 day after the CME with 25–60 MeV ion intensity increasing early on day 229 and 8–13 MeV ion and 43–57 keV electron intensities increasing in the middle of day 229. That is longer than the expected transit time for particles injected at the time of the flare to arrive at Cassini. The onset of this SEP event at Cassini occurred after the passage of a magnetic field structure crossing the spacecraft between days 227 and 229 (bottom panel of Figure 5a) that may have contributed to the delayed SEP onset observed at ~6.2 AU.

[33] Assuming that the longitude of the CME associated with this SEP event is correct, and considering that φ, for Cassini was around W120, Cassini was better connected to the active region than the Earth (Figure 5b). If the SEP event was observed by ACE and GOES-8, the more reason to expect this SEP event to be observed at Cassini. The preevent Sun (Figure 5c) was devoid of large solar events and produced at Earth no enhanced magnetic field regions with magnitudes >20 nT. The absence of significantly enhanced magnetic field regions throughout a complete solar rotation prior to the main solar event at the end of day 227 suggests good conditions for particle propagation in the interplanetary medium. Note that although a relatively slow (v_CME = 618 km s⁻¹) halo CME was observed late on day 226, its direction (toward the Earth), its speed, as well as the longitude of the temporally associated solar event (an erupting filament close to Central Meridian) were such that it could not interfere with the magnetic field line connecting to Cassini. Its ejection was too recent to embrace a wide extension of the heliosphere when the solar event occurred at the end of day 227. Therefore energetic particles injected at the end of day 227 were able to propagate along the IMF to Cassini and produce the SEP event shown in Figure 5a.

[34] The SEP event at Cassini extended for ~21 days. The rising phase of the SEP event was marked by the presence of an enhanced magnetic field structure (~2 nT) that crossed Cassini on days 232–233. Prior to this enhanced magnetic field structure, the magnetic field from days 228 to 231 was already disturbed with oscillations in both magnitude and direction (not shown here) which locally affected the arrival of SEPs at Cassini. The increase in magnetic field strength observed by Cassini on days 232 and 233 led to moderate decreases in the electron and low-energy (<13 MeV) ion intensities. Energetic electron intensities during this period of high magnetic field were low. Unlike the electron intensity decrease observed on days 292–298 of 2001 (section 3.1), no reorientation of the LEMMS turntable was performed at that time. Therefore we suggest that the electron and low-energy (<13 MeV) ion intensity decrease was due to either the effective exclusion of energetic particles from this region of enhanced magnetic field or the fact that Cassini established magnetic connection to a region less populated with energetic particles.

[35] Late in the event (days 242–249), electron intensities decayed with a similar rate at Cassini and ACE. These periods that display similar intensities and therefore evolve with similar decaying rates were previously observed by
McKibben [1972] and Roelof et al. [1992] and characterized as particle "reservoirs." During this period, however, low-energy (<13 MeV) ion intensities were larger at Cassini than at 1 AU. We note that the arrival of a weak interplanetary shock observed by Cassini at the beginning of day 246 may contribute to the low-energy ion intensity by locally accelerating ions (second panel in Figure 1).

3.4. April 2001 Event

[36] Figure 6a shows energetic particle and magnetic field observations at Cassini and at 1 AU from day 84 to 120 of 2001. A sequence of six intense high-energy (>39 MeV) ion events was observed at the Earth between days 88 and 113 of 2001. Energetic particle intensities at Cassini did not start to increase until day 95, after the passage of an enhanced magnetic field region. In fact, ion intensities increased gradually as the magnetic field magnitude decreased late on day 95.

[37] The most intense and long-lasting (>7 days) SEP event at Earth prior to the SEP intensity enhancement at Cassini was associated with a very fast ($v_{\text{CME}} = 2505 \text{ km s}^{-1}$) and wide ($\omega = 244^\circ$) CME observed by SOHO/LASCO at 2206 UT on day 92 and temporally associated with an X20 flare at 2132 UT from the National Oceanic and Atmospheric Administration (NOAA) Active Region 9393 located at N17W78 [Cane et al., 2002]. The onset of the SEP event at Cassini was not observed until 2 days later, suggesting that the magnetic field structure on day 95 efficiently delayed the arrival of energetic particles at Cassini. The onset of the SEP event on day 267 of 2001 (section 3.1), for example,
occurred just \(~1.5\) days after the parent solar event, even when Cassini was more distant from the Sun than in April 2001. We suggest that the bulk of the energetic particles injected into the interplanetary medium on day 92 at the time of the X20 flare was not observed by Cassini until the enhanced magnetic field magnitude crossed the spacecraft, i.e., when the magnetic field magnitude started to decrease on day 95.

Figure 6b shows the location and nominal connection of Earth and Cassini on day 92. Transient solar wind flows propagating from the eastern limb of the Sun (as seen from Earth) or directly toward the Earth will not impact directly the IMF line connecting the Sun to Cassini. Figure 6c shows the pre-event solar activity and pre-event solar wind and magnetic field as measured by the ACE spacecraft during a 25-day period of time equal to the transit time that a solar wind parcel at \(400\) km \(s^{-1}\) takes to travel from the Sun to the Cassini’s location (\(~5.5\) AU) on day 92. Solar activity remained at low levels throughout the first half of the period plotted in Figure 6c. On days 77 and 78 two relatively fast (\(v_{\text{CME}} = 752\) and \(879\) km \(s^{-1}\), respectively) and wide (halo and \(\omega = 148^\circ\), respectively) CMEs were observed by SOHO/LASCO, but they did not produce any SEP event or magnetic field disturbances at 1 AU. The magnetic structure observed between days 78 and 79 at L1 is a magnetic cloud associated with a slow (\(v_{\text{CME}} = 271\) km \(s^{-1}\)) CME observed by LASCO at 0350 UT on day 75 [Cane and Richardson, 2003].

Significant solar events prior to the X20 flare on day 92 started on days 83 and 84 when (1) a halo CME (\(v_{\text{CME}} = 906\) km \(s^{-1}\)) temporally associated with a M1/2N flare from the NOAA Active Region 9390 at N15E22, and (2) a halo CME (\(v_{\text{CME}} = 677\) km \(s^{-1}\)) temporally associated with a C9/1N flare from the NOAA Active Region 9402 at N16E25 were seen by LASCO/C2 at 2050 UT on day 83 and 1706 UT on day 84, respectively. The NOAA Active Region 9393 produced several M-class X-ray flares already on day 82 when it was at the eastern limb of the Sun. This active region was responsible for the first >39 MeV proton event at 1 AU shown in Figure 6a (on day 88). This SEP event was associated with a fast (\(v_{\text{CME}} = 942\) km \(s^{-1}\)) Earth-directed halo CME observed by LASCO at 1026 UT on day 88 [Cane et al., 2003] that later crossed the Earth on day 91 [Cane and Richardson, 2003]. The magnetic compression seen by ACE on day 90 also includes the passage of an ICME that left the Sun as a halo CME (\(v_{\text{CME}} = 519\) km \(s^{-1}\)) at 1250 UT on day 87 [Cane and Richardson, 2003]. Kinematic simulations of interplanetary shock wave propagation during this period show that, by the time of the X20 flare on day 92, the CME injected on day 88 propagated to an heliocentric distance of \(~2\) AU and did not intercept the nominal field line connecting the Sun to Cassini [Sun et al., 2002].

With the exceptions of the two halo CMEs on days 83 and 84 and the fast halo CME (\(v_{\text{CME}} = 1475\) km \(s^{-1}\)) form the East limb of the Sun (E90) on day 91, all the other significant events during this period were associated with NOAA Active Region 9393, including a partial halo CME propagating toward the west (as seen from the Earth) and observed by SOHO/LASCO at 1126 UT on day 92 [Sun et al., 2002]. Kinematic simulations show that the much faster CME temporally associated with the X20 flare on day 92 was able to overtake and interact with the previous CME injected early on day 92 [Sun et al., 2002]. Therefore the transient flows prior to the X20 flare on day 92 were either (1) directed toward the east or toward the Earth and hence unable to directly disrupt the spiral patterns associated with the streams connecting to Cassini, (2) too recent to extend over a large region of the heliosphere, or (3) slower than the CME ejected on late day 92 that easily overtook them. Consequently, the transport to Cassini of the energetic...
particles accelerated in the interplanetary medium by the shock driven by the fast CME on day 92 was not directly affected by the transient flows originated from the prior solar events. We suggest that the delayed arrival of SEPs at Cassini was due to both the magnetic field enhancement crossing the spacecraft on day 95 and the time spent by the shock driven by the CME on day 92 to overtake the preceding CMEs and inject the shock-accelerated particles into the IMF lines connecting to Cassini.

The rest of SEP events observed at 1 AU from day 100 onward (Figure 6a) were associated with the NOAA Active Region 9415 [Sun et al., 2002] that rotated into the visible solar disk just as NOAA Active Region 9393 was departing the disk on day 93. The occurrence of two fast (1199 km s\(^{-1}\) and 2465 km s\(^{-1}\)) and wide (\(\omega = 167^\circ\) and complete halo) CMEs from the NOAA Active Region 9415 already at western solar longitudes on days 105 and 108 produced two relative intense SEP events at 1 AU. Near-relativistic (43–57 keV) electron and <13 MeV ion intensities at Cassini were still high. Low-energy (<1 MeV) ion intensities showed an additional increase related to the arrival of an interplanetary shock at Cassini on day 107 (see Figure 1). This increase was not due to the prompt component of the SEP events observed at 1 AU. In fact, the prompt component of the first event on day 105 was not observed at the 25–60 MeV ion intensities even when the SEP event at 1 AU and at these high energies was more intense than the event on day 92. The SEP event on day 108
occurred when Cassini was immersed in an enhanced magnetic field region, and only a very small increase in the 25–60 MeV ion intensities was observed on day 110 when the magnetic field magnitude observed by Cassini started to decrease (Figure 6a). Solar activity prior to the occurrence of these two SEP events at 1 AU was intense, with most CMEs from NOAA Active Region 9415 directed toward the west and therefore intervening in the nominal connection between the Sun and Cassini (Figure 6b). Therefore we suggest that the disturbances propagating in the interplanetary medium on days 105 and 108 prevented the direct propagation of the SEPs injected on these days to Cassini.

3.5. November 2000 Events Prior to the Jupiter Flyby

The first major SEP event observed at L1 in November 2000 (Figure 2) was associated with a fast ($v_{CME} = 1738$ km s$^{-1}$) partial-halo ($\omega = 170^\circ$) CME temporally associated with an M7 flare at 2300 UT on day 313 from N10W77 [Lario et al., 2003a]. This event was one of the most intense SEP events observed at L1 throughout solar cycle 23 (Figure 2). Unfortunately, a data gap in Cassini LEMMS observations prevents us from studying the consequences of this event at ~5 AU. Two less intense SEP events with onsets on days 329 and 330 were observed at 1 AU. Figure 7a shows energetic particle and magnetic field observations from Cassini at ~5 AU and near Earth from day 328 of 2000 to day 65 of 2001. The data gap at Cassini lasted until day 335 and therefore we cannot determine whether the prompt component of these two latter events was detected at Cassini. However, the rate channels of the LEMMS instrument were near background levels on day 335, suggesting that either (1) the prompt component of these SEP events was not observed at ~5 AU, (2) it lasted less than 5 days, or (3) it did not produce any significant intensity increase above the background level.
from the NOAA Active Region 9236 near the Central Meridian, and an additional halo CME from the NOAA Active Region 9240 (at N07E49) [Nitta and Hudson, 2001]. These authors associated the origin of the second SEP event near Earth with the fast halo CME ($v_{\text{CME}} = 2519 \text{ km s}^{-1}$) first seen by SOHO/LASCO at 0131 UT on day 330 and temporally associated with an M8 flare from N07E49 at 0102 UT on the same day. Note that the site of this flare was very close to the Cassini’s nominal connection; however, we do not have any evidence that the prompt component of this event was directly observed by Cassini.

Figure 7c shows the solar activity and magnetic field structures observed at 1 AU prior to the fast halo CME early on day 330 (i.e., flare at N07E49). The time interval considered in this figure covers the $\sim 21$-day transit time that a 400 km s$^{-1}$ solar wind parcel takes to travel from the Sun to Cassini’s radial position ($\sim 4.8$ AU) on day 330. The interplanetary medium was quite disturbed from day 309 to day 316. By the time of the solar event on day 330, the high-speed solar wind stream observed by ACE on days 317–319 was beyond the Cassini’s radial position (assuming an averaged transit speed of $\sim 700$ km s$^{-1}$). The origin of this high-speed stream was a recurrent equatorial coronal hole present in the solar disk for a number of solar rotations; for example, the high-speed stream was observed again at L1 on days 342–345. The presence of this recurrent high-
speed stream produced a corotating interaction region in the interplanetary medium that has not been included in the magnetic field topology illustrated in Figure 7b.

Solar activity remained at low levels until day 328 when several wide and fast CMEs occurred, not only directed toward the Earth but also directed toward the eastern limb (as seen from the Earth). The sequence of CMEs on day 329 generated an interplanetary structure that at the time of the E49 flare early on day 331 was traveling between the Sun and 1 AU. This structure was later observed at 1 AU as an ICME between days 332 and 333 [Cane and Richardson, 2003]. The presence of these traveling structures did not impede the arrival of SEPs at 1 AU. Particle intensities during this SEP event at 1 AU were dominated by the component associated with the passage of a strong shock at 1124 UT on day 331 [Cane et al., 2003]. Considering the good radial alignment between Sun, Earth, and Cassini (Δφ = 3° on day 331), it is reasonable to assume that this shock at L1 was related to the shock observed by Cassini at 2312 UT on day 342 (average transit speed 735 km s⁻¹). Therefore we suggest that the particle enhancement observed by Cassini at the end of day 196 in coincidence with the passage of a magnetic field increase and enhanced magnetic field region. Figure 8b shows the spatial configuration of the ecliptic plane on day 196 and the nominal IMF connection of Earth and Cassini to the Sun. The transit time for 57 keV electrons along the nominal IMF line connecting the Sun to Cassini (z = 9.4 AU) is ~3.0 hours while for a 60 MeV proton is ~3.8 hours. The onset of the SEP event at Cassini occurred ~12 hours after the flare. The SEP event at

The rest of the time interval considered in Figure 7a covers the Jupiter flyby described by Krupp et al. [2002, 2004]. Owing to the high variability of the Jovian magnetosphere, multiple bow shock crossings were measured on board Cassini, the first one registered on day 363 [Kurth et al., 2002]. Each one of these bow shock crossings produced changes in the intensities of low-energy electrons. From day 16 to 32, Cassini observed a whole series of sporadic low-energy electron intensity increases that has been interpreted by Krupp et al. [2002] as leakage of energetic particles from Jupiter’s dusk magnetosphere. The nonoccurrence of intense SEP events during this period at 1 AU assures us that low-energy ion and electron intensity enhancements are indeed associated with the Jupiter’s magnetosphere. Note that some of the electron intensity enhancements shown in Figure 7a may be caused by changes in the spacecraft and the LEMMS turntable orientation. Details of Cassini’s data during this period can be found in the work of Krupp et al. [2004].


Figure 8a shows energetic particle and magnetic field observations at Cassini and at 1 AU from day 191 to 209 of 2000. Unlike the rest of the events analyzed in this paper, Cassini was relatively close to the Sun (~4 AU). The main solar event at the Earth was associated with a fast (v_CME = 1674 km s⁻¹) halo CME observed by SOHO/LASCO at 1054 UT on day 196 and temporally associated with an X5/3B flare at 1021 UT on the same day at N22W07 from the NOAA Active Region 9077 [Smith et al., 2001]. The first particles associated with this event were observed by Cassini at the end of day 196 in coincidence with the passage of a magnetic field increase and enhanced magnetic field region. Figure 8b shows the spatial configuration of the ecliptic plane on day 196 and the nominal IMF connection of Earth and Cassini to the Sun. The transit time for 57 keV electrons along the nominal IMF line connecting the Sun to Cassini (z = 9.4 AU) is ~3.0 hours while for a 60 MeV proton is ~3.8 hours. The onset of the SEP event at Cassini occurred ~12 hours after the flare. The SEP event at
Cassini extended for ~9 days before intensities returned to background levels.

[49] Figure 8c shows the pre-event solar activity and magnetic field structures observed at L1 during the ~30-day time interval that includes the ~17 days that a solar wind parcel at 400 km s\(^{-1}\) takes to travel from the Sun to Cassini’s radial position (~4 AU) on day 196. Solar and interplanetary activity prior to day 191 was low. Signs of intense solar and interplanetary activity started on day 191, i.e., a few days before the Bastille Day. With the exception of a fast (\(v_{\text{CME}} = 839\) km s\(^{-1}\)) but narrow (\(\omega = 62^\circ\)) CME from N17W65 at 2013 UT on day 194, all the other significant solar events that occurred after day 191 were generated by the NOAA Active Region 9077 and propagated out from the eastern limb of the Sun [Dryer et al., 2001]. This direction is where Cassini’s nominal magnetic field connection to the Sun was established. The weak flanks of the shocks driven by these CMEs produced the small magnetic field increases observed by ACE between days 192 and 196 [Smith et al., 2001]. Kinematic simulations of the interplanetary shock wave propagation during this period show that the central part of the CMEs prior to the Bastille Day event were directed toward the east as seen from the Earth [Dryer et al., 2001]. Therefore transient flows prior to the Bastille Day were localized in azimuth toward the regions where Cassini was nominally connected, and in principle they would have prevented the direct transport of particles from their source to Cassini. However, an intense SEP event with similar time-intensity profiles as 

Figure 8a. The same as Figure 3a but for the Bastille Day 2000 event.
the SEP event on day 267 of 2001 (section 3.1) was observed by Cassini.

Kinematic simulations of interplanetary shock propagation show that at the time of the flare on the Bastille Day (day 196) a corotating interaction region (CIR) arrived at Cassini. The transient flows caused by CMEs occupied only a portion of the ecliptic plane, i.e., they did not encircle the Sun [Dryer et al., 2001]. Direct particle propagation from their source to the Cassini’s heliocentric radial distance (\(r = 4 \text{ AU}\)) was possible through either those portions of the ecliptic plane devoid of enhanced magnetic field regions or through the CIR and the subsequent high-speed stream that generated this CIR at Cassini. Based on the results of these simulations, we suggest that the energetic particles injected during the Bastille Day 2000 event were able to enter into the CIR structure as well as the following high-speed stream. In fact, low-energy (<1 MeV) ions showed a local maximum peak intensity at the time of the possible reverse shock observed on day 200 (Figure 1), suggesting that reacceleration of particles occurred within the CIR. Limitations of Cassini solar wind data at this time do not allow us to confirm or reject this scenario. However, in contrast to the other events analyzed here, the intensity increase occurred at the same time that an enhanced magnetic field region was crossing Cassini.

3.7. Summary of the SEP Event Observations at Cassini

Table 1 summarizes the Cassini observations during the eight intense SEP events at 1 AU described above. The prompt component of the SEP events was observed in both electron and ion intensities for all the events with the exception of the events on day 330 of 2000 and day 321 of 2001 (because of data gaps), it was absent during the event on day 326 of 2001, and it was diminished in intensity and only observed in the 25–60 MeV intensities during the event on day 308 of 2001. The onsets of all the SEP events were delayed with respect to the expected arrival time of particles propagating along the nominal IMF field lines connecting the Sun to Cassini. None of the onset of the SEP events at Cassini showed the velocity dispersion effects expected from direct particle propagation along magnetic field lines. For five out of the eight events, the onset was influenced by the presence of local magnetic structures at Cassini. The only event without a magnetic field structure at its onset was the event on day 308 of 2001; however, in this case, the interplanetary conditions between the Sun and Cassini were disturbed and affected the particle transport from their source to Cassini. The onsets of the prompt components of the SEP events occurred after the crossing of magnetic field enhancement structures, with the exception of the event on day 196 of 2000 when particle intensities increased during the passage of an IMF structure, and the event on day 326 of 2001 when the prompt component was not observed.

4. Discussion

We discuss the heliospheric energetic particle observations from the Cassini spacecraft in terms of the previous analyses of data from distant spacecraft. McDonald et al. [1975, 1981a] showed that during solar maximum, low-energy (<1 MeV) ion intensity increases inside ~5 AU are a mixture of prompt components of SEP events and ESP events associated with the passage of transient interplane-
Table 1. Characteristics of the SEP Events at Cassini

<table>
<thead>
<tr>
<th>Event</th>
<th>Prompt Component</th>
<th>Cassini Heliocentric Radial Distance</th>
<th>25–60 MeV Ion Peak Intensity&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Prevent Interplanetary Conditions</th>
<th>Onset Affected by a Local IMF Structure</th>
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<td>yes</td>
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<tr>
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<td>0.01</td>
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</tr>
<tr>
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<td>-</td>
<td>disturbed</td>
<td>yes&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
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<td>no</td>
<td>6.6</td>
<td>-</td>
<td>disturbed</td>
<td>yes&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
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</tr>
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</tr>
<tr>
<td>330/2000</td>
<td>?&lt;sup&gt;l&lt;/sup&gt;</td>
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<td>yes&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
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<td>4.0</td>
<td>0.15</td>
<td>disturbed</td>
<td>yes</td>
</tr>
</tbody>
</table>

<sup>a</sup>Units are in AU.
<sup>b</sup>Only observed at 25–60 MeV ion intensities.
<sup>c</sup>Not possible to discern because of a data gap in Cassini/LEMMS observations.
<sup>d</sup>The crossing of this IMF structure probably impeded the arrival of SEPs at Cassini.

Figure 1 shows this transition from a mixture of prompt components of SEP events and ESP events in early 2000 (radial distances from 2.5 to 4.5 AU), to a period when the largest 1 MeV ion intensities were associated with ESP events (middle of 2001 and afterward).

High-energy (25–60 MeV) ion intensities throughout the 3-year interval studied here (2000–2002) show only increases associated with the prompt component of SEP events. The prompt component of the SEP events is due to direct particle propagation from their source near the Sun out to the observer. Because shocks generally weaken as they move outward from the Sun, they are less efficient at injecting and accelerating particles; therefore at large heliocentric distances, such shocks are, in general, not able to accelerate particles to these high energies.

In section 3 we have shown several examples of intervening regions of enhanced magnetic field that affect the transport of energetic particles from their source to Cassini. The inability of the particles to cross or penetrate through these magnetic field structures controls the time-intensity profiles of the SEP events at large heliocentric distances. In particular, compressed magnetic field regions between the Sun and the spacecraft can either attenuate the intensity of the SEP events observed by Cassini and/or delay the arrival of SEPs at this spacecraft [Barouch and Burlaga, 1970; Barouch and Burlaga, 1976]. The effects that these enhanced magnetic field regions have on the particle transport depends on the characteristics of these structures; i.e., the increase in the magnetic field magnitude that allows the mirroring of energetic particles and the existence of enhanced magnetic field turbulences that contribute to hindering the particle transport through these field regions [Burlaga et al., 1986].

We suggest that enhanced magnetic field regions propagating between the Sun and the spacecraft may act as effective reflecting barriers for the solar energetic particles. These magnetic barriers impede the free streaming of SEPs toward the outer heliosphere resulting in the storage of energetic particles between the Sun and the enhanced magnetic field regions. The observation of the energetic particles confined between the Sun and these propagating enhanced magnetic field regions is only possible after the field regions pass by the Cassini position. Energetic particles confined between the Sun and the propagating magnetic structures undergo the processes of convection, drifts, diffusion, and adiabatic deceleration, resulting in fluxes that diminish and eventually (in the outer heliosphere) fall below detectable levels. The result is that at large heliocentric distances, high-energy ion intensity increases will be rare. The low-energy ion increases will be associated locally with the passage of interplanetary shocks or interplanetary magnetic field structures able to confine them.

Morrison [1956] was the first to suggest that enhanced magnetic field regions may affect the transport of energetic particles in interplanetary space. In particular, he envisioned that “changes in time and energy of the incoming cosmic ray beams were due to the random diffusion of particles through turbulent clouds of magnetized plasma emitted from the Sun.” He suggested that these turbulent clouds were most probably formed by the “continual emission of smaller clouds from various parts of the Sun.” Barouch and Burlaga [1975] showed that cosmic ray intensity decreases were correlated with regions of enhanced magnetic field strengths. Burlaga et al. [1984] suggested that the formation of these regions of enhanced magnetic field magnitude and turbulence were a key factor in determining the partial exclusion of cosmic rays from the heliosphere. A small isolated transient flow may produce a single Forbush decrease at the Earth, but it does not produce a long-term modulation effect. Consequently, Burlaga et al. [1986] suggested that shells formed by a sequence of transient events were responsible for the long-term variations of cosmic ray intensity. The requirement for the formation of these shells was that the system of transient flows extended over a broad range of latitudes, i.e., the transient flows were ejected from the Sun over a solar rotation or more [Burlaga et al., 1986].

An intriguing suggestion at the end of the Morrison [1956] paper states: “The Sun emits cosmic-ray particles at times of flares; study of their arrival or non-arrival as a function of the kind of magnetic regime around the earth expected from this picture, for the epoch of flare, should allow a more or less direct test as soon as flares become frequent enough.” Just as galactic cosmic rays entering the heliosphere encounter an outward flowing solar wind carrying a turbulent magnetic field, solar energetic particles
may find this turbulent magnetic field in front of them as they propagate outward from the Sun. Just as the interaction between galactic cosmic rays and the interplanetary magnetic field reduces the cosmic ray intensity observed at the Earth, the interaction between SEPs and the turbulent magnetic field may delay the arrival of energetic particles at Cassini. Whereas Morrison [1956] and Burlaga et al. [1986] regarded the formation of this shell as the cause for sweeping away the cosmic rays, we regard it as the cause for delaying (or even impeding) the arrival of SEPs at Cassini. The formation of a system of transient flows between the Sun and the observer acts as an effective barrier not only for the galactic cosmic rays coming from the outer heliosphere and propagating inward but also for SEPs propagating outward from the Sun. [58] The formation of a system of transient flows able to envelop the Sun at small (≤5 AU) heliocentric distances requires a rapid sequence of CMEs propagating in different directions. If CMEs are localized in a narrow range of longitudes, it is likely that no “shell” of disturbances completely encircles the Sun. The separation and number of CMEs has to be adequate in order to be distributed over a broad range of longitudes. The transit time of the transient flows driven by the CMEs to travel from the Sun to 1 AU compared with the occurrence rate of CMEs at different longitudes is not long enough to create a shell between the Sun and the Earth. Therefore the effects of these shells on SEPs can only be detected at larger heliocentric distances where Cassini is. [59] The nondetection of the prompt component of the first SEP event in November 2001 (day 308) in the low-energy ion and near-relativistic electron intensities, together with the small 25–60 MeV ion intensity enhancement during this event at Cassini, are consistent with the existence of a turbulent shell of shock-associated transient flows. Since each shock may extend over ∼100° in longitude [Cane, 1985] and since several fast CMEs were seen to propagate outward from the Sun in several directions, the turbulent regions formed behind the shocks driven by these CMEs will most probably envelop the Sun and therefore impede the arrival of SEPs at Cassini. SEPs can only arrive at Cassini if they are able to diffuse through at least one of the possible turbulent patches existing in the shell. When the system of transients is localized in one hemisphere of the Sun or the separation and characteristics of the different transient flows are not adequate to form strong magnetic barriers, Cassini is not effectively shielded from new injections of SEPs, and energetic particles can reach the heliocentric radial distance where Cassini is. [60] The characteristics of the transient flows (i.e., level of magnetic turbulence, structure of the magnetic field increase) determine their effects on the SEP transport. Burlaga et al. [1984] showed that the magnetic fields in this shell are not only enhanced but they may include large-scale compressive fluctuations (magnetosonic mode MHD waves), as well as small-scale Alfvén fluctuations, so that mirroring, diffusion, and gradient drifts may be important mechanisms for the effective confinement of energetic particles, and possibly for additional acceleration. Therefore individual magnetic field structures traveling between the Sun and Cassini may also delay the arrival of SEPs at Cassini as well as attenuate the intensity of the SEP events at large heliocentric distances. [61] The arrival of energetic particles at Cassini is also modulated by the passage of local magnetic field structures through the spacecraft. Enhanced magnetic field regions, such as the ICME passing over Cassini on days 343–349 of 2001, produced decreases in the energetic particle intensities. The injection of energetic particles from the Sun while Cassini is inside an enhanced magnetic field region may cause the nondetection of the SEP event by Cassini, depending on the magnetic topology of this region. For example, the passage of the ICME over Cassini from day 325 to day 328 of 2001 prevented the arrival of the SEPs injected from the Sun on day 326 (section 3.2). On the other hand, the enhanced magnetic field region associated with a CIR observed by Cassini from day 196 to 200 of 2000 did not impede the arrival of energetic particles injected during the Bastille Day 2000 event (section 3.6). Apart from the events shown in section 3, similar examples of delayed onset of SEP events by magnetic structures formed between the Sun and the observer can be found in the literature, see for example Sanderson et al. [2000] or Lario et al. [2003a]. In these two cases, the arrival of energetic particles at the spacecraft was modulated by the presence of magnetic field structures propagating between the particle source and the spacecraft.

5. Summary

[62] We have presented energetic particle observations from the Cassini spacecraft throughout its inner heliospheric cruise to Saturn. Although our analysis is restricted to the more intense events because of the high background levels at Cassini, we have separated the energetic particle enhancements as (1) due to direct arrival of SEPs injected close to the Sun, (2) associated with recurrent CIRs (as described by Lario et al. [2003b]), or (3) associated with the passage of transient interplanetary shocks. Inspection of the time-intensity profiles during these 3 years of data shows that (1) high-energy (>25 MeV) ion intensity enhancements are exclusively associated with the prompt component of intense SEP events, (2) near-relativistic electron and low-energy (<13 MeV) ion intensities are a mixture of the prompt component of SEP events and ESP events, and (3) the highest low-energy (<1 MeV) ion intensities and near-relativistic electrons are observed in close association with the passage of transient interplanetary shocks.

[63] By comparing Cassini with observations at 1 AU, we observe that (1) when intervening conditions between the Sun and Cassini are favorable for particle propagation, the most intense SEP events are generally observed at both locations (Earth and Cassini) regardless of their longitudinal separation. (2) The magnetic field structures formed between the Sun and Cassini prevent the free streaming of energetic particles throughout the interplanetary medium. The inability of the particles to cross these magnetic field structures or penetrate through their elevated field magnitudes causes the storage of energetic particles behind these structures. (3) An isolated disturbance between the Sun and Cassini is not enough to prevent the arrival of SEPs at the heliocentric radial
distances where Cassini is. Such a disturbance can thus be viewed as a localized region extending over a wide (but finite) range of longitudes but not encircling the Sun. (4) The conditions required to shield Cassini from new SEP injections are either the formation of a system of transient flows distributed over a broad range of longitudes and able to confine energetic particles or the crossing of an enhanced magnetic field region over Cassini when the new injection of SEPs occurs.

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