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OBSERVATIONS AND MODELLING OF THE INNER HELIOSPHERE

# Initial Fe/O Enhancements in Large, Gradual, Solar Energetic Particle Events: Observations from *Wind* and *Ulysses*

**Allan J. Tylka · Olga E. Malandraki · Gareth Dorrian · Yuan-Kuen Ko · Richard G. Marsden · Chee K. Ng · Cecil Tranquille**

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**Abstract** Shocks driven by fast coronal mass ejections (CMEs) are the dominant particle accelerators in large, "gradual" solar energetic particle (SEP) events. In these events, the event-integrated value of the iron-to-oxygen ratio (Fe/O) is typically $\sim 0.1$, at least at energies of a few MeV/nucleon. However, at the start of some gradual events, when intensities are low and growing, initially Fe/O is $\sim 1$. This value is also characteristic of small, "impulsive" SEP events, in which particle acceleration is due to magnetic reconnection. These observations suggested that SEPs in gradual events also include a direct contribution from the flare that accompanied the CME launch. If correct, this interpretation is of critical importance: it indicates a clear path to interplanetary space for particles from the reconnection region beneath the CME. A key issue for the flare origin is "magnetic connectedness", *i.e.*, proximity of the flare site to the solar footpoint of the observer's magnetic field line.

We present two large gradual events observed in 2001 by *Wind* at L1 and by *Ulysses*, when it was located at $> 60°$ heliolatitude and beyond 1.6 AU. In these events, *transient* Fe/O enhancements at 5 – 10 MeV/nucleon were seen at both spacecraft, even though one or both is not "well-connected" to the flare. These observations demonstrate that an initial Fe/O enhancement cannot be cited as evidence for a direct flare component. Instead, initial

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Guest Editors: Mario M. Bisi, Richard A. Harrison, and Noé Lugaz

A.J. Tylka (✉) · Y.-K. Ko
Code 7680, Space Science Division, Naval Research Laboratory, Washington, DC 20375, USA
e-mail: allan.tylka@nrl.navy.mil

O.E. Malandraki · G. Dorrian
Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, Lofos Nymfon, Thiseio, P.O. Box 20048, 11810 Athens, Greece

R.G. Marsden · C. Tranquille
European Space Agency (SRE-SM), ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands

C.K. Ng
College of Science, George Mason University, Fairfax, VA 22030, USA

Fe/O enhancements are better understood as a transport effect, driven by the different mass-to-charge ratios of Fe and O.

We further demonstrate that the time-constant of the roughly exponential decay of the Fe/O ratio scales as $R^2$, where $R$ is the observer's radial distance from the Sun. This behavior is consistent with radial diffusion. These observations thus also provide a potential constraint on models in which SEPs reach high heliolatitudes by cross-field diffusion.

**Keywords** Solar Energetic Particles (SEPs) · Solar flares · Coronal mass ejections · *Ulysses* · *Wind*

## 1. Introduction

Composition measurements are a powerful tool in investigating the acceleration processes that produce solar energetic particles (SEPs). In the case of small, so-called "impulsive" SEP events, large enhancements relative to nominal coronal composition (especially in $^3$He/$^4$He, Fe/O, and trans-Fe ions) indicate distinctive mechanisms at sites of magnetic reconnection (such as flares) in which some species are preferentially accelerated (Temerin and Roth, 1992; Miller and Vinas, 1993; Roth and Temerin, 1997; Litvinenko, 2001; Zhang, 2004; Liu, Petrosian, and Mason, 2006; Drake *et al.*, 2009; Knizhnik, Swisdak, and Drake, 2011). Composition measurements also facilitate studies of the interplanetary transport of SEPs. Ions at $\sim$MeV/nucleon energies in impulsive SEP events are essentially fully stripped of electrons (Luhn *et al.*, 1987; Popecki *et al.*, 2002; DiFabio *et al.*, 2008). On the other hand, in large, so-called "gradual" events, where shocks driven by fast coronal mass ejections (CMEs) are the primary accelerator, heavy ions below $\sim$10 MeV/nucleon are typically partially ionized (Luhn *et al.*, 1984; Oetliker *et al.*, 1997; Popecki *et al.*, 2002), with a range of mass-to-charge ratios characteristic of plasmas at a few million Kelvin. In these events, abundance ratios at a given MeV/nucleon energy thus compare ions with the same speed but different rigidities. These comparisons provide a way of untangling the rigidity- and velocity-dependent processes that govern SEP transport.

In large, gradual SEP events, the Fe/O ratio above a few MeV/nucleon sometimes shows a very strong transient enhancement at the beginning of the event, with Fe/O $\sim 1$, as typical of impulsive SEP events. These initial enhancements are observed when the particle intensity levels are low and rising. As intensities grow in these events, Fe/O typically decreases and approaches the nominal coronal value of $\sim 0.1$. Figure 1 shows an example of this behavior. Reames (1990) first reported these initial Fe/O enhancements and suggested that they indicate a contribution from the concomitant flare, since these enhancements were generally seen in events in which the flare was near the nominal footpoint of the Sun–Earth magnetic field line. (These "well-connected" events were also those with the largest intensities at onset.) A flare origin of the initial Fe/O enhancement in gradual events was subsequently discussed by other authors (Cane, Reames, and von Rosenvinge, 1991; Cliver, 1996; Cane *et al.*, 2003) as part of the evidence for "hybrid" events, in which both flare- and shock-acceleration contribute directly to the SEPs observed in interplanetary space.[1]

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[1] We distinguish "hybrid" events with a "direct" contribution from the concomitant flare from the other commonly-occurring process, in which remnants from flare activity are accelerated to their observed energies by interactions with CME-driven shocks (Mason, Mazur, and Dwyer, 1999; Tylka *et al.*, 2001, 2005; Desai *et al.*, 2006; Tylka and Lee, 2006).

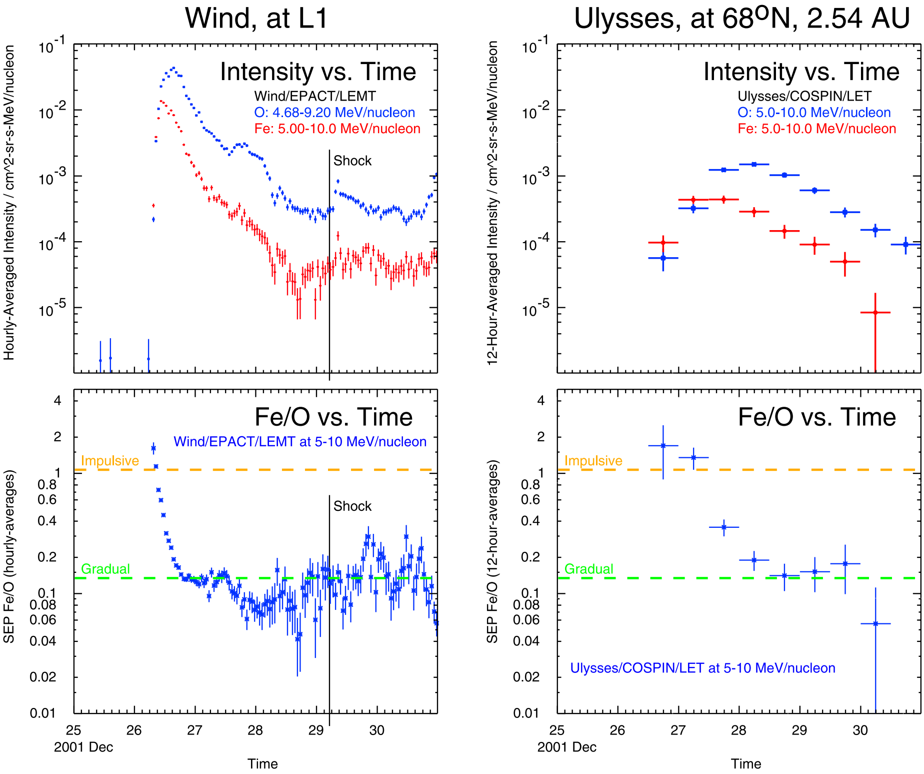

**Figure 1** Fe and O intensities (top panels) and Fe/O ratio (bottom panels) from *Wind* at L1 (left panels) and from *Ulysses* (right panels) for the SEP event of 26 December 2001. *Wind* data are hourly averages; the *Ulysses* data are 12-hour averages. Dashed horizontal lines in the bottom panels mark the average Fe/O ratios from impulsive and gradual SEP events at ~5 MeV/nucleon (Reames, 1995). Vertical lines in the left panels mark the arrival of a forward shock at L1, as given by the CFA *Wind* shock catalogue (http://www.cfa.harvard.edu/shocks/wi_data).

However, as subsequently discussed by Reames (2002), it is unclear that the magnetic topology associated with the launch of a fast CME permits particle access to interplanetary space from the reconnection region below the CME. Moreover, another explanation of initial Fe/O enhancements, which does not invoke two distinct acceleration mechanisms, is also possible. By combining high-precision observations with modeling of interplanetary transport, it was found that the temporal evolution of Fe/O, including the initial enhancement, can be generated by rigidity-dependent interplanetary transport, starting from a nominal Fe/O ~ 0.1 at the acceleration site (Ng, Reames, and Tylka, 1999, 2001, 2003; see also Mason *et al.*, 2006). The initial Fe/O enhancement observed far from the Sun occurs when

$$(M/Q)_{\mathrm{Fe}} > (M/Q)_{\mathrm{O}}, \tag{1}$$

$$\lambda_{\mathrm{mfp}} < L_{\mathrm{path}}, \tag{2}$$

where $M/Q$ is the ion's mass-to-charge ratio, $\lambda_{\mathrm{mfp}}$ is a scattering mean free path, and $L_{\mathrm{path}}$ is the physical pathlength of the magnetic field line from the acceleration site to the observer. At ~ MeV/nucleon energies, average charge states in gradual events typically correspond to $(M/Q)_{\mathrm{Fe}} \sim 4.0$ and $(M/Q)_{\mathrm{O}} \sim 2.3$ (Luhn *et al.*, 1984). Iron ions therefore have roughly twice the rigidity of oxygen ions at the same MeV/nucleon energy. Since $\lambda_{\mathrm{mfp}}$ generally increases with rigidity, the iron ions also have a longer mean free path. Furthermore, if mean free paths are small compared to $L_{\mathrm{path}}$, the transport process will be diffusive. As a result, the Fe intensity will rise more rapidly and reach its maximum before oxygen, corresponding to an initial enhancement in Fe/O that dies away as the event progresses. More generally, an initial Fe/O enhancement can arise whenever the pitch-angle scattering rate of Fe is significantly less than that of O.

If this transport explanation is correct, we expect to see – given sufficient instrumental collecting power – initial Fe/O enhancements even on widely separated spacecraft, at least one of which is unlikely to be magnetically connected to the flare site.

To investigate this possibility, we used observations from the *Low Energy Matrix Telescope* (LEMT) in the *Energetic Particle Composition and Transport* (EPACT) instrument suite on *Wind* (von Rosenvinge *et al.*, 1995) and the *Low Energy Telescope* (LET) in the *Cosmic and Solar Particle Investigation* (COSPIN) instrument package on *Ulysses* (Simpson *et al.*, 1992). Both instruments provided Fe and O intensities at $\sim$5 MeV/nucleon but with geometry factors of 51 and 0.58 $\mathrm{cm}^2\,\mathrm{sr}^{-1}$ for LEMT and LET, respectively. Sensitivity is thus limited by LET. We therefore surveyed LET observations for 1997 – 2006, looking for events with an initial Fe/O $> 0.8$ and sufficient ion statistics in 12-hour bins to follow the evolution in the ratio over at least 2 days. During this time period, *Wind* was generally at L1, while *Ulysses* was at $> 1.5$ AU and in an orbit that carried it high above the ecliptic plane. We identified two SEP events in this manner, associated with CMEs that erupted on 15 August 2001 and 26 December 2001. Both 2001 events[2] were cleanly observed by LEMT. Details of these events are given in Table 1. Comparative studies of proton and electron timings at *Ulysses* and at L1 in these two events have been reported previously (Dalla *et al.*, 2003a, 2003b). Event-integrated composition measurements from *Ulysses*/COSPIN/LET have also been previously reported for these events (Hofer *et al.*, 2003).

## 2. The 26 December 2001 SEP Event

The left-hand panels of Figure 1 show the hourly averaged Fe and O intensities and Fe/O ratio observed by LEMT at 5 – 10 MeV/nucleon in the 26 December 2001 event. This event is an exceptionally clean example of the behavior we are investigating in this study. The Fe/O values are measured with high statistical precision. Over the first 12 hours of the event, the Fe/O ratio falls by more than an order of magnitude, from above the average "impulsive" value to near the nominal "gradual" value. The Fe and O intensities show a rapid rise from very low background levels prior to the event. The Fe intensity peaks $\sim$4 hours before the O intensity, whose continued rise then drives the fall of the Fe/O ratio.

This event is an ideal candidate for this study for other reasons as well. First, the associated flare was at W54 heliolongitude, close to the nominal footpoint of the Sun–Earth magnetic field line, making this a good opportunity for seeing a direct flare component. Second, this event was also a ground-level event (GLE), the kind of event in which some researchers have also posited a "hybrid" nature, with an initial flare component in $\sim$GeV

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[2] A third event that began at *Ulysses* late on 5 December 2006 also satisfied our survey criteria. However, the event was not well observed from L1, from which vantage point the event arose from a far-eastern source region, resulting in very low intensity levels with a very slow rise. The L1 observations also appear to have been complicated by multiple injections. The 5 December 2006 event was therefore omitted from further study. The December 2006 events are examined in more detail in Malandraki *et al.* (2009).

**Table 1** SEP events in this study.

| Active Region | CME[b] | | | Flare[c] | | | | | SEP Onset Times (UT)[d] | | | Radio Emissions Onset Times (UT)[d,e] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Estimated Launch Time (UT) | Speed ($\mathrm{km\,s^{-1}}$) | Angular Width | SXR Onset (UT) | SXR Peak (UT) | SXR End (UT) | Size | Location | at GOES (> 100 MeV protons) | at *Ulysses* (> 92 MeV protons) | Comment | Metric Type II | DH Type II |
| 9557[a] | 15 Aug. 2001 23:37 | 1575 | backside halo | not observed | | | | S21/W180-W195 | 00:40 – 00:45 | 04:00 – 04:10 | > 400 MeV protons observed by GOES | occulted | 00:10 |
| 9742 | 26 Dec. 2001 05:06 | 1446 | > 212° | 0432 | 0540 | 0647 | M7.1/1B | N08/W54 | 05:50 – 05:55 | 07:20 – 07:30 | Ground-Level Event | 05:02 | 05:20 |

[a] See Cliver *et al.* (2005) for details of the 15/16 August 2001 event.

[b] CME info from http://cdaw.gsfc.nasa.gov/CME_list/; estimated launch times and speed estimates from linear fits to height-time profiles.

[c] From Solar Geophysical Data.

[d] SEP and radio onsets for the August event are on 16 August.

[e] Radio times from Gopalswamy (2003).

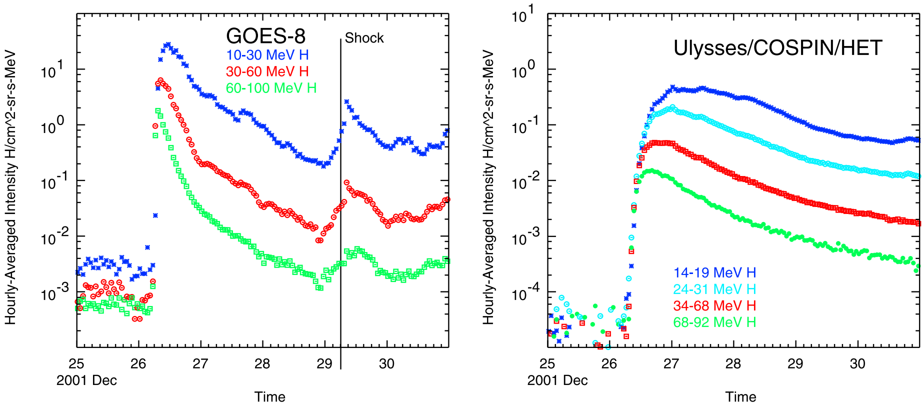

**Figure 2** Hourly averaged proton intensities from GOES-8 (left) and from *Ulysses* (right) for the 26 December 2001 SEP event. The vertical line in the left panel marks the arrival of a forward shock at Earth, as extrapolated from the shock arrival observed by *Wind* at L1.

protons followed by a second component from the CME-driven shock (Vashenyuk, Balabin, and Gvozdevsky, 2009; McCracken, Moraal, and Stoker, 2008; In another study, however, Moraal and McCracken (2011) found no evidence for two components in this particular GLE.) Finally, the event was also clearly observed at *Ulysses*. At the time of this event, *Ulysses* had just completed its passage over the north pole of the Sun and was located at 68°N heliographic latitude and at 2.54 AU radial distance from the Sun.

Figure 2 compares the proton intensities at $\sim 10-100$ MeV observed by the *Geostationary Operational Environment Satellite-8* (GOES-8, in geosynchronous orbit about Earth) and from the COSPIN/*High Energy Telescope* (HET) on *Ulysses* for this event. The well-behaved time profiles indicate that both GOES-8 and *Ulysses* intensities were dominated by a single event, at least until 29 December 2001.[3] Figure 3 compares simultaneous observations of $>92$ MeV protons from *Ulysses* and $>100$ MeV protons from GOES-8, with 10- and 5-minute averages, respectively. These timelines show that event onset at these energies occurred at *Ulysses* $\sim 90$ minutes after onset at GOES-8.

The right-hand panels of Figure 1 show the *Ulysses*/LET time profiles of Fe and O intensities and the Fe/O ratio at $5.0-10.0$ MeV/nucleon, the same energy range as provided by *Wind*/LEMT. Twelve-hour averages were used for the *Ulysses* data, both for statistical reasons and because temporal evolution occurs more slowly at farther distance from the Sun, as discussed below in Section 4. The *Ulysses* intensity profiles show the same qualitative behavior as at *Wind*, with the Fe and O intensities rising smoothly from immeasurably low background levels. Fe reaches its maximum intensity before the O intensity, just as observed at L1. Although the *Ulysses* measurements have much less statistical precision, evolution in the Fe/O ratio, like that at L1, is clearly evident.

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[3] Gopalswamy (2003) suggested that the increase on 29 December 2001 was another SEP event, associated with the eruption of a $\sim 2000\ \mathrm{km\,s^{-1}}$ CME behind the east limb. However, this increase may also have been due to the approach of the interplanetary shock noted in Figures 1 and 2. According to the *Wind* shock catalogue (http://www.cfa.harvard.edu/shocks/wi_data), this shock was oblique, with a shock-normal angle $\theta_{\mathrm{Bn}} \sim 50 \pm 5^{\circ}$. As a result, the *Wind* spacecraft could have been connected to the strongest part of the shock *after* it had passed L1, thus explaining why the peak intensity was observed after shock passage.

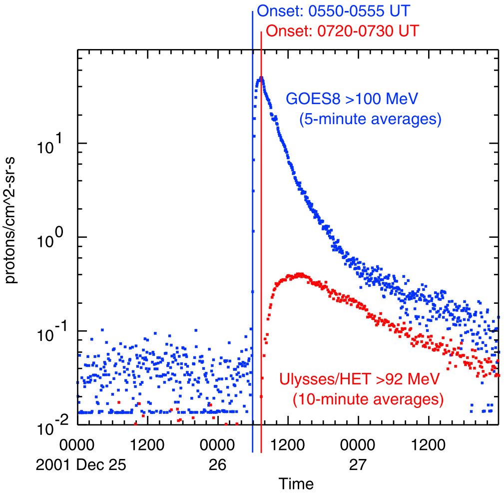


**Figure 3** Onset of the 26 December 2001 SEP event, as seen by > 100 MeV protons from GOES-8 and from >92 MeV protons from *Ulysses*. The GOES-8 and *Ulysses* intensity measurements are 5-minute and 10-minute averages, respectively. Vertical lines mark the onset times. Pre-event background levels have been subtracted both from GOES-8 and from *Ulysses*, with pre-event values in this figure showing the residuals.

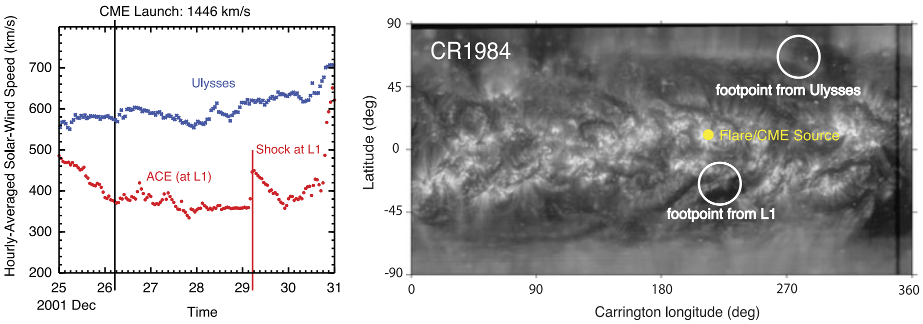


**Figure 4** (Left): Solar-wind speed as observed at *Ulysses* (blue) and by ACE at L1 (red) during the 26 December 2001 event. Vertical lines mark the estimated CME launch time and the arrival of a forward shock at L1. (Right): Synoptic map of the Sun from SOHO/EIT observations for the Carrington rotation containing the 26 December 2001 event. The yellow dot marks the source region of the associated flare. The white circles mark the footpoints of the magnetic field lines that connected the Sun to L1 and to *Ulysses* at the start of the SEP event. These footpoint locations were calculated using the observed solar-wind speeds and the Potential Field Source Surface (PFSS) model. See text for details.

We next consider the locations of the L1 and *Ulysses* magnetic footpoints relative to the flare site. The left panel of Figure 4 shows the solar-wind speeds observed by the *Advanced Composition Explorer* (ACE) at L1 and by *Ulysses* during this event. *Ulysses* resides in a high-speed stream; L1 does not. This difference in solar-wind speeds is *prima-facie* evidence that the L1 and *Ulysses* had different magnetic footpoints at the Sun. The right panel of Figure 5 shows a synoptic map of the Sun from observations by the *Extreme ultraviolet Imaging Telescope* (EIT) on the *Solar and Heliospheric Observatory* (SOHO) for the Carrington rotation containing the 26 December 2001 event. The yellow point marks the source region of the associated flare. The white circles mark the footpoints of the magnetic field lines that connected the Sun to L1 and to *Ulysses* at the start of the SEP event. These footpoint locations were calculated using the observed solar-wind speeds and the Potential Field Source Surface (PFSS) model (Schatten, Wilcox, and Ness, 1969; Wang and Sheeley, 2006). The white cir-

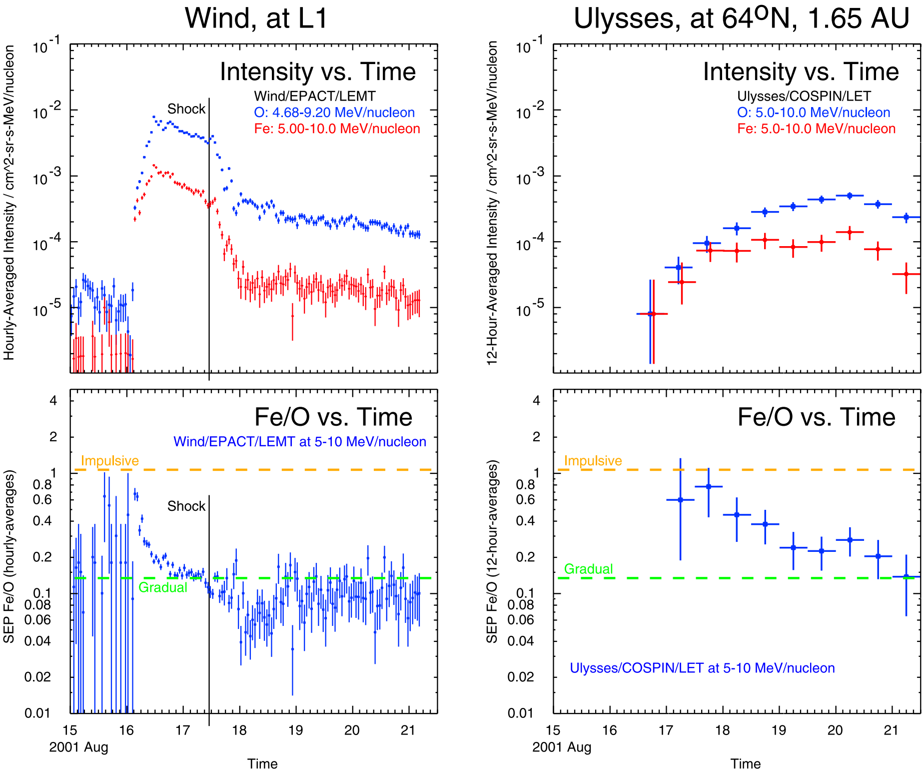


**Figure 5** Like Figure 1, but for the 16 August 2001 event. One-sigma Poisson error bars (Gehrels, 1986) have been used for the *Ulysses* Fe and O intensity measurements at the start of the event. In the first time interval, each of these *Ulysses* intensities is based on a single ion. The corresponding Fe/O measurement ($\sim 1$) has been omitted from the plot because of its large statistical uncertainty.

cles mark the footpoint locations, with the size of the circle reflecting the uncertainty in the field-line trace back due to intrinsic assumptions of the method (such as constant speed) and limitations of coronal field models and input magnetograms (*e.g.* Neugebauer *et al.*, 1998; Riley *et al.*, 2006; Wang, Pick, and Mason, 2006; MacNeice, Elliott, and Acebal, 2011). The error estimates for the footpoint locations also vary from case to case, depending on other factors, such as the size of the coronal hole. For the events in this study, we estimate the uncertainty as ± 15°.

The solar locations of the flare and the satellite footpoints are summarized in Table 2. The angular separation between the flare location and the L1 footpoint is 35° (12° in longitude). The angular separation between the flare and the *Ulysses* footpoint is 74° (68° in longitude). As we will discuss further in Section 5, it is reasonable to classify L1 as "well-connected" to the flare. That assignment, however, is probably not tenable for *Ulysses*. In addition, the angular separation of the L1 and *Ulysses* footpoints is 101° (56° in longitude). If both initial Fe/O enhancements were ascribed to a direct flare contribution, this is the minimum angular range over which the flare particles must have been distributed.

**Table 2** Flare and magnetic footpoint locations: Carrington coordinates (degrees).

| SEP Event Date | Carrington Rotation | Flare Location | | L1 Footpoint | | Flare/L1 Angular Separation | | *Ulysses* Footpoint | | Flare/*Ulysses* Angular Separation | | L1/*Ulysses* Angular Separation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Longitude | Latitude | Longitude | Latitude | Longitude Only | Spherical Angle | Longitude | Latitude | Longitude Only | Spherical Angle | Longitude Only | Spherical Angle |
| 16 Aug. 2001 | 1979 | 281 | −21 | 157 | 13 | 124 | 126 | 184 | 64 | 97 | 112 | −27 | 54 |
| 26 Dec. 2001 | 1984 | 211 | 8 | 223 | −25 | −12 | 35 | 279 | 68 | −68 | 74 | −56 | 101 |

## 3. The 16 August 2001 SEP Event

Figure 5 presents another event in which transient Fe/O enhancements are seen both at L1 and at *Ulysses*. This event is the well-known 16 August 2001 ‘backside’ event which has been associated with a source region at W180-195 (Cliver *et al.*, 2005). Peak particle intensities are smaller than in the December event at both locations and in ions (Figure 5) as well as protons (Figure 6).

Figures 5 and 6 also mark the arrival time of a shock from the *Wind* catalogue. The *Wind* intensities in Figure 5 show a slight increase after shock passage, similar to that seen in the 26 December 2001 event (Figure 1). At the higher GOES energies in Figure 6, there is no particle increase associated with this shock; instead the shock marks an inflection point in the time profiles, after which the intensities begin to drop rapidly. However, this shock may be related to the backside CME only by coincidence.

As seen in Figure 5, background levels prior to the event at L1 were much larger than in the December event. Nevertheless, the onset and initial Fe/O enhancement are clear at

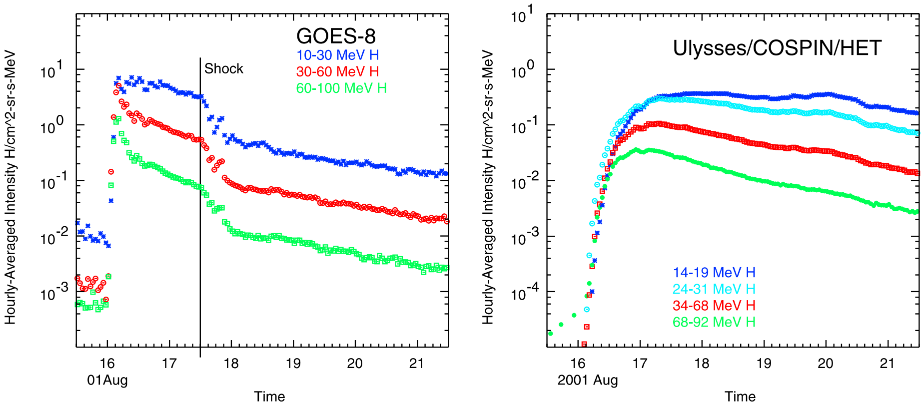
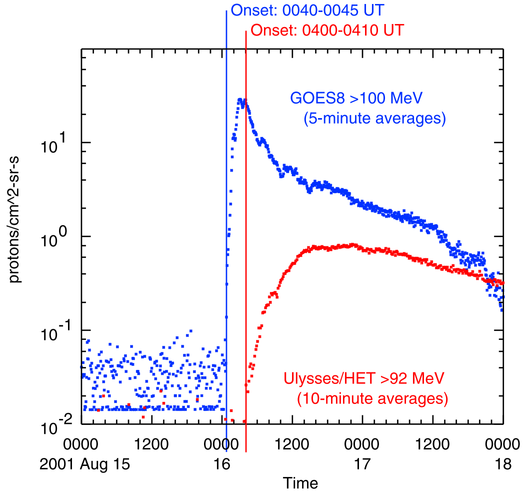


**Figure 6** Like Figure 2, but for the 16 August 2001 event.

**Figure 7** Like Figure 3, but for the 16 August 2001 event.



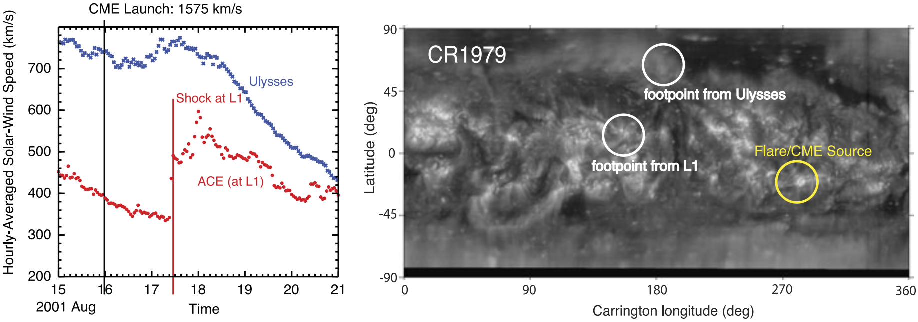


**Figure 8** Like Figure 4, but for the 16 August 2001 event. The yellow circle reflects uncertainty in the location of the backside flare, which was not directly observed.

L1. *Ulysses* was at 64°N heliographic latitude and at 1.65 AU radial distance from the Sun. *Ulysses* ion statistics are poor at the onset, and the Fe/O enhancement becomes clearly observable only ∼24 hours into the event. Figure 7 shows a delay of more than three hours between the GOES-8 and *Ulysses* onsets. Part of this delay may be due to directionality in the expansion of the CME-driven shock, similar to what has been reported from recent observations by the *Solar TErrestrial RElations Observatory* (STEREO; Rouillard *et al.*, 2012).

Figure 8 shows the solar-wind speed profiles at the time of this event and the relevant SOHO/EIT Carrington map. Although the solar-wind speed profiles are highly dynamic, it is clear that L1 and *Ulysses* were in different solar-wind streams for at least the first 30 hours of the event. Footpoint locations at the start of the event are shown in the Carrington map and given in Table 2. The angular separation between the flare location and the L1 footpoint is 126° (124° in longitude). The angular separation between the flare and the *Ulysses* footpoint is 112° (97° in longitude). In this event, neither L1 nor *Ulysses* is magnetically well-connect to the flare site.

## 4. Comparison of Fe/O Evolution at L1 and at *Ulysses*

How do we expect the temporal evolution in Fe/O at L1 and at *Ulysses* to compare?

In general, the time-scale of SEP evolution depends on heliocentric distance $R$. In the context of a simple radial diffusion model (Parker, 1963), in which the effective radial mean free path is proportional to $R^{\beta}$, the time scale for SEP evolution is proportional to $R^{(2-\beta)}$. Zwickl and Webber (1977) modeled ∼20 SEP events observed by *Pioneer 10* and *Pioneer 11* as they traveled from 1 to 5 AU in 1972 – 1974. Using a numerical convection-diffusion model with mean free path proportional to $R^{\beta}$, they deduced $\beta = 0.0 \pm 0.3$ for protons at 3.4 – 5.2 MeV and 24 – 30 MeV. In a similar study using *Pioneer* data from other instruments but based on fewer events and with a somewhat different theoretical approach, Hamilton (1977) found $\beta = 0.4 \pm 0.2$ for 11 – 20 MeV and 30 – 67 MeV protons, consistent with the Zwickl and Webber (1977) results to within uncertainties.

In the same radial diffusion model, with energetic particles injected at the Sun as a delta function at time $t = 0$ and with the mean free path of species $i$ independent of time. If we explicitly display the radial-dependence of the scattering mean free path for species $i$ as

$$\lambda_i = \Lambda_i R^{\beta}, \tag{3}$$

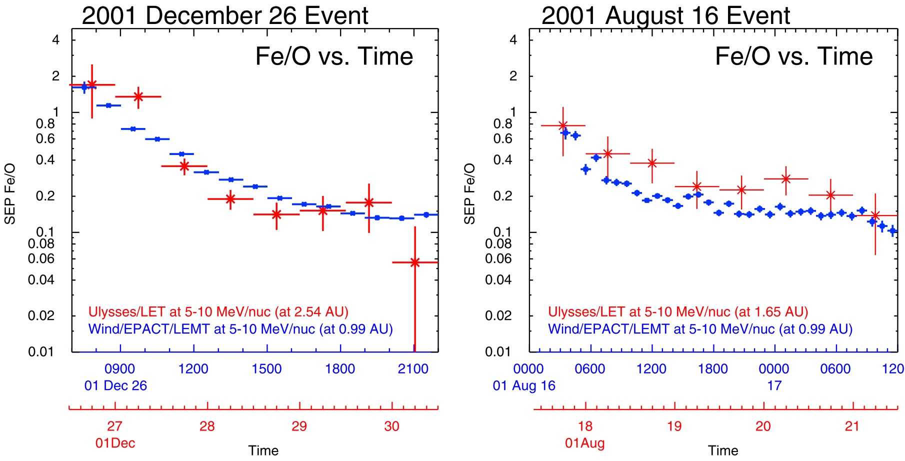


**Figure 9** Temporal evolution in the Fe/O ratio from *Wind* at L1 (blue) and from *Ulysses* (red) in the 26 December 2001 (left) and the 16 August 2001 (right) events. Note that the time scales for the *Ulysses* data (shown in red, below the plots) have been compressed by factors of $R^2$. See text for details.

then the Fe/O ratio at time $t$ for particles with speed $v$ is given[4] by

$$\begin{aligned}\mathrm{Fe/O} &= (N_{\mathrm{Fe}}/N_{\mathrm{O}})(\Lambda_{\mathrm{O}}/\Lambda_{\mathrm{Fe}})^{3/(2-\beta)}\exp\bigl\{3R^{(2-\beta)}(1/\Lambda_{\mathrm{O}}-1/\Lambda_{\mathrm{Fe}})/\bigl[(2-\beta)^2 vt\bigr]\bigr\} \quad (4)\\ &= (N_{\mathrm{Fe}}/N_{\mathrm{O}})(\Lambda_{\mathrm{O}}/\Lambda_{\mathrm{Fe}})^{3/(2-\beta)}\exp(\tau/t), \quad (5)\end{aligned}$$

where $N_i$ is the number density of species $i$ in the seed population and

$$\tau = 3R^{(2-\beta)}(1/\Lambda_{\mathrm{O}}-1/\Lambda_{\mathrm{Fe}})/\bigl[(2-\beta)^2 v\bigr]. \quad (6)$$

Thus, given a radial mean free path that is independent of $R$ (*i.e.*, with $\beta = 0$), we expect that the temporal decay of Fe/O ratios to follow a simple $R^2$ scaling. This notion is tested in Figure 9, in which the horizontal (time) axes have been shifted so as to make the peak Fe/O values at L1 and at *Ulysses* coincide and the time scales at L1 have been dilated by factors of $R^2 = (2.54/0.99)^2$ and $(1.65/0.99)^2$ for the December and August events, respectively. The *Ulysses* statistical uncertainties prevent a definitive conclusion. Nevertheless, the correspondence in the Fe/O profiles after application of the time-dilation factor is quite good. Deviations from this simple model are not surprising, when one remembers that:

i) particles at these energies are injected over a period of time by the CME-driven shock, and not impulsively at the Sun;
ii) proton-amplified Alfvén waves can introduce both temporal and radial dependence into the scattering mean free paths;
iii) observations over these extended time periods sweep over many flux tubes, potentially with different scattering conditions and different histories in the shock parameters.

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[4] From Equation C3 in Ng, Reames, and Tylka (2003). A typographical error in the exponent of $R$ in their Equation C3 is corrected here.

## 5. Discussion

In this work, we have shown that transient, initial enhancements in SEP Fe/O are not restricted to observers that are magnetically "well-connected" to the flare site. One important consideration here is how large the angular separation between the flare site and the observer's footpoint can be before the observer is no longer deemed "well-connected". A statistical study of single-point observations of $^3$He-rich impulsive events (Reames, 1999; see also Nitta *et al.*, 2006) indicated a longitude distribution centered about the nominal Sun–Earth footpoint with an rms width of $\sim 20°$. According to Reames (1999), the width of the distribution is driven primarily by variations in solar-wind speed, along with a small contribution due to the random walk of field lines resulting from footpoint motion. A multi-spacecraft study of $^3$He-rich events in the *Helios* era also favored a narrow cone of emission (Reames, Kallenrode, and Stone, 1991).

Wiedenbeck *et al.* (2010) have examined this question anew, using simultaneous multi-spacecraft observations with the more sensitive particle instruments on the STEREO spacecraft. They reported one example of an impulsive SEP event in which $^3$He-increases were observed at two locations, one $\sim 20°$ ahead and the other $\sim 20°$ behind the longitude of the associated active region. This result, according to Wiedenbeck *et al.* (2010), is consistent with the earlier statistical studies.

More recently, ACE and the two STEREO spacecraft observed an impulsive $^3$He-rich SEP event that began on 7 February 2010, when the STEREO spacecraft were separated by $\sim 136°$ in longitude (Wiedenbeck *et al.*, 2012). At $\sim 3$ MeV/nucleon, the $^3$He onset at STEREO-A occurred $\sim 18$ hours after the onset at STEREO-B, whose nominal magnetic footpoint was close to the flare site. This long delay is a critical difference between this recent study and earlier work: Reames (1999) and Nitta *et al.* (2006) also examined $^3$He enhancements at a few MeV/nucleon. However, for a valid association, they required the flare to have occurred no more than 5 hours before the SEP onset; an appropriate time window, given that it takes $\sim 2$ hours for a $\sim 3$ MeV/nucleon ion to travel scatter-free along the nominal Parker spiral from Sun to Earth. The Wiedenbeck *et al.* (2012) observation at STEREO-A would have been excluded by this time-window criterion. Making the long-delayed association between the flare and the STEREO-A $^3$He increase in this event was possible only because of the extraordinarily low level of flaring activity in early 2010.

The apparent cross-longitude transport processes implied by the 7 February 2010 event are too weak and too slow to explain what was seen in our events. First, in this impulsive event, the peak intensity at the farthest remove from the flare site (STEREO-A) was smaller by a factor of $\sim 50$ from that observed at the well-connected location (STEREO-B). By contrast, if we conservatively use a factor of $R^2$ to correct for the difference in peak intensity caused by radial distance (Lario *et al.*, 2007), the (corrected) peak Fe and O intensities at *Ulysses* longitudes were smaller than those at *Wind* by only a factor of three or four (see Figures 1 and 5). Similar ratios are found when comparing intensities in the first hour of the events. Second, in the impulsive event, $\sim 3$ MeV/nucleon ions took at least 20 hours to disperse over the $\sim 120°$ longitudinal separation between the flare site and the magnetic footpoint of STEREO-A. That is the same longitudinal separation between the flare/CME site and the magnetic footpoint of *Wind* at L1 in the 16 August 2001 event studied here (see Table 2). But in the 16 August 2001 event, the onset of $\sim 3$ MeV/nucleon ions at *Wind* was no more than 5 hours after the CME launch and the (presumed but unobserved back-side) flare.

Thus, in our study, only the L1 observation of the 26 December 2001 event can conceivably be construed as sufficiently "well-connected" to include direct flare contribution to

SEPs at the start of the event. One might therefore posit that the initial Fe/O enhancement at *Wind* in this event had a direct flare origin, whereas the same phenomenon observed at *Ulysses* was a transport effect. However, if two different mechanisms were involved, the remarkably good radial scaling shown in Figure 9 would be surprising. A simpler and more likely explanation is that particle transport is responsible for the initial Fe/O enhancement at both locations.

In the case of the 16 August 2001 event, the angular separation between the flare site and the magnetic footpoints is greater than 110° both for *Wind* and for *Ulysses*. These separations are too large to be explained away by inaccuracy in the PFSS calculations. In this event, it is likely that neither L1 nor *Ulysses* was "well-connected" to the flare site. Given the large longitudinal separation of both observers from the flare site, expansion of the CME-driven shock becomes an important factor in understanding the details of the particle timelines. Nevertheless, in this event, both transient Fe/O enhancements are most likely due to rigidity-dependent transport.

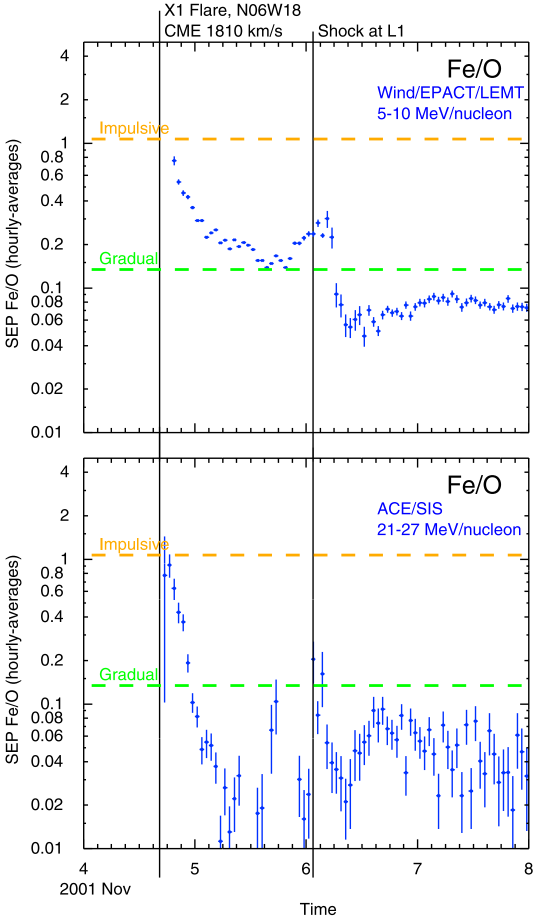
In a paper entitled "Two Components in Major Solar Particle Events", Cane *et al.* (2003) used oxygen and iron time-intensity profiles to divide a sample of 29 large events into three groups: i) flare-dominated; ii) shock-dominated, and iii) a "combination". According to Cane *et al.* (2003), "the 4 November 2001 event typifies… the third grouping. The profiles are basically a combination of those of the previous two groupings, *i.e.*, *a Fe-rich component at the time of the flare* (emphasis added) and later, a shock-associated component with a lower Fe/O ratio." Figure 10 shows the Fe/O evolution from *Wind*/EPACT/LEMT and from the *Solar Isotope Spectrometer* (SIS; Stone *et al.*, 1998) on ACE for this archetypal event. This particular event was caused by a CME launched from near central meridian (W18), so that the shock was still accelerating particles as it approached Earth. Except for the rebound in the Fe/O ratio as the shock neared L1, the behavior of Fe/O in this event is very similar to that seen at L1 in Figures 1 and 5. In fact, it is difficult to see any difference in the evolution of the Fe/O ratio in the first day of this event that would necessitate an explanation other than transport.

An initial flare contribution to a large, gradual SEP event is a logical hypothesis. However, it is a logical error to cite an initial Fe/O enhancement as evidence for a flare contribution. Given that initial Fe/O enhancements are seen at widely separated spacecraft, even when one or both is not magnetically well-connected to the flare site, it is likely that the initial Fe/O enhancement is generally a transport effect. Based on the results of this study, we expect to see initial Fe/O enhancements on multiple spacecraft (the STEREOs and/or ACE/*Wind* at L1) when the SEP events of Cycle 24 become sufficiently large.

On the other hand, the possibility of a direct flare contribution component is certainly not ruled out by this study. Measurements of iron charge states in the first few hours of the gradual event might serve to do so. For flare-accelerated particles at ∼MeV/nucleon energies, iron and oxygen ions are nearly fully ionized. In this circumstance, iron has only a small transport advantage over oxygen; transport therefore cannot cause an enhancement. Observations of highly charged Fe while the Fe/O is enhanced would favor a flare origin. However, it would still be possible that these Fe ions were flare remnants subsequently energized by the shock (Tylka and Lee, 2006). To date, however, instruments for measuring charge states in the ∼MeV/nucleon energy range have had too little collecting power to extract meaningful measurements during the small intensities at the onset of an event.

Finally, the observations presented here are also potentially relevant to the controversy concerning how SEPs reach high heliolatitude. One school of thought claims that the CME-driven shocks are broad in latitude as well as longitude; when the shock intercepts the Sun-*Ulysses* field line, shock-accelerated particles are injected on to that field line, along which

**Figure 10** Temporal evolution in the Fe/O ratio from *Wind* at 5 – 10 MeV/nucleon (top) and from ACE/SIS at 21 – 27 MeV/nucleon (bottom) for the 4 November 2001 event.



they travel outward to *Ulysses* (Malandraki *et al.*, 2009). The observations presented here are consistent with this scenario. Other researchers, however, suggest that particle acceleration occurs only in the ecliptic, with SEP access to high heliolatitude arising from subsequent cross-field diffusion (*e.g.* Dalla *et al.*, 2003a, 2003b). The Fe/O data presented here provide a new opportunity to test cross-field diffusion models. In particular, if the *Ulysses* Fe/O observations in Figure 9 are ascribed to cross-field diffusion, the cross-field transport must have rigidity dependence very similar to that found in the radial diffusion of particles observed at L1, at least in the rigidity range of these observations.

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