Interplanetary transport of solar near-relativistic electrons on 2014 August 1 over a narrow range of heliolongitudes

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Abstract – We study two consecutive solar near-relativistic (>50 keV) electron events observed on 2014 August 1 by both STEREO spacecraft with a longitudinal separation of only about 35° . The events were unambiguously associated with a solar source location and not accompanied by type II radio bursts or coronal mass ejections. Despite their close location, the two spacecraft were embedded in different solar wind streams and the electron intensities observed by the two STEREOs showed clear differences in onset times, peak intensities and pitch-angle distributions. The apparently better connected spacecraft, STEREO B, observed a smaller and more isotropic intensity increase and a later event onset time than STEREO A. Since the interplanetary transport conditions of solar energetic particles (SEPs) have a direct influence on the characteristics of the observed temporal profiles and the particle anisotropies at the spacecraft location, our aim is to understand if the observations on 2014 August 1 could be explained by different interplanetary transport conditions along each flux tube connecting the spacecraft with the solar source. For that purpose, we use a Monte Carlo interplanetary transport model combined with an inversion procedure to fit the in-situ observations of the two near-relativistic multi-spacecraft electron events. This allows us to obtain the injection profiles at the Sun and infer the transport conditions, which are characterized by the electron radial mean free path, λ_r . We obtain an almost simultaneous release of electrons for both spacecraft in both events. The release is consistent with the timing and duration of the type III radio burst emission and it is larger for STEREO B, the better connected spacecraft. In addition, we obtain different transport conditions in different solar wind streams. We find that the stream in which STEREO B was embedded was more diffusive ($\lambda_r = 0.1$ AU for Event I and $\lambda_r = 0.06$ AU for Event II) than the stream in which STEREO A was embedded ($\lambda_r = 0.31$ AU for Event I and $\lambda_r = 0.37$ AU for Event II). These different transport regimes are sufficient to explain the early onset for the worse connected spacecraft, STEREO A, and the observation of larger and more anisotropic intensities.

Keywords: solar energetic particles / interplanetary transport / Sun / solar flares

1 Introduction

Several studies of solar energetic particle (SEP) events have assumed that the longitudinal distribution of particle peak intensities at 1 AU follows a Gaussian distribution with respect to the longitudinal separation between the flare site and the nominal magnetic footpoint of the spacecraft (Wibberenz and Cane, 2006; Lario *et al.*, 2006, 2013; Richardson *et al.*, 2014; Dresing *et al.*, 2014; Gómez-Herrero *et al.*, 2015). This is also predicted by simulations assuming uniform turbulence conditions in the interplanetary medium or, e.g., a symmetric

Gaussian distribution of particles released close to the Sun (Dröge *et al.*, 2010; Strauss and Fichtner, 2015). In two recent studies, Klassen *et al.* (2015) and Klassen *et al.* (2016) reported the observation of non-symmetric intensity distributions of electrons at 1 AU for several events examined over relatively narrow angular intervals. The approach of the STEREO mission to the solar conjunction provided us with the opportunity to study SEP events at 1 AU when the two STEREO spacecraft had nominally nearly the same magnetic connection to the Sun and explore how the interplanetary transport conditions can change over narrow angular intervals.

We study two consecutive solar near-relativistic electron events observed by the Solar Electron Proton Telescope (SEPT, Müller-Mellin *et al.*, 2008) on board STEREO A and STEREO B

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on 2014 August 1, when the longitudinal separation between the two spacecraft was of only $\sim 35^\circ$ (Klassen *et al.*, 2016). Despite their close location, the two STEREO spacecraft were embedded in different solar wind streams. The solar eruptions associated with these events were two flares located in the same active region (Klassen *et al.*, 2016). There were no signatures of shock waves. The particle events observed by STEREO A and STEREO B showed strong differences in terms of onset, peak intensities and evolution of the measured angular distributions. The spacecraft with the better nominal magnetic connection to the flare detected a later arrival of electrons than the worse connected one, and a lower peak intensity by a factor ~ 5 (Klassen *et al.*, 2016). The authors hypothesized that the unexpected particle distributions detected at 1 AU could be attributed to a rippled peak intensity distribution at 1 AU formed by narrow peaks (“fingers”) superposed on a quasi-uniform Gaussian distribution (Klassen *et al.*, 2016). In this scenario, open magnetic field lines from the flaring region would provide prompt access of SEPs and form the fingers, while large-scale “closed” magnetic fields around the active region and/or coronal holes with stronger turbulence would inhibit perpendicular diffusion and partially shield the penetration of particles inside these regions, providing the valleys.

In the present work, we investigate under which circumstances the STEREO observations could be explained by different transport conditions in different solar wind streams connecting each STEREO spacecraft back to the Sun. In Section 2 we review the characteristics of the two consecutive SEP events observed on 2014 August 1. In Sections 3 and 4 we describe the modeling tools we used to study these events and present the results. Finally, we summarize this work in Section 5.

2 Observations

We study two consecutive electron events observed with only a few hours of delay by the STEREO twin spacecraft on 2014 August 1. On that date, the longitudinal separation between the spacecraft was of only $\sim 35^\circ$ (see Fig. 11 in Klassen *et al.*, 2016). Thus, the longitudinal separation between the nominal footpoints of the two spacecraft was very small, of less than 9° (assuming that the large scale interplanetary magnetic field (IMF) is a Parker spiral consistent with the solar wind speed measured in situ by each spacecraft).

We use particle measurements provided by the SEPT experiment on board the two STEREO spacecraft that measures electrons from 45 to 400 keV. SEPT consists of four identical detectors mounted to cover four fields of view, which are pointing to the ecliptic north, to the ecliptic south, along the nominal Parker spiral towards the Sun (named as Sun) and in the opposite direction (Antisun). We complement this information with IMF measurements by STEREO/MAG (Acuña *et al.*, 2008) to determine the particle pitch-angle distributions and particle anisotropies and with solar wind observations from the PLasma and SupraThermal Ion Composition experiment (PLASTIC, Galvin *et al.*, 2008), to study the in situ characteristics of the plasma. In addition, we use measurements by the STEREO Radio and Plasma Wave Investigation (SWAVES, Bougeret *et al.*, 2008) to study the radio emission spectra at frequencies lower than 16 MHz.

Both particle events showed a significant intensity enhancement, that is, peak intensities were at least one order of magnitude higher than the pre-event background intensities, in the energy ranges 45–65 keV and 65–105 keV. The upper panels of Figure 1 show the omni-directional intensities (solid curves) for 45–65 keV (top panel) and 65–105 keV (second panel) electrons measured by STEREO A (red) and STEREO B (blue). Dotted (dashed) curves correspond to the intensities measured by the Sun (Antisun) fields of view (orange curves for STEREO A and gray curves for STEREO B). The following panels in Figure 1 show the solar wind speed, density and temperature, and the IMF intensity, latitude and longitude angles in the RTN reference frame, as measured by STEREO A (red) and STEREO B (blue). Table 1 summarizes the main characteristics of the 2014 August 1 electron events.

Despite the close location of the two spacecraft, for both events, the electron intensities observed by STEREO A and STEREO B showed clear differences in terms of onset time, peak intensity and evolution of the pitch-angle distributions. The events observed by STEREO A started to rise up to 20 min earlier than at STEREO B, and the peak intensity was about a factor 5 higher at STEREO A. STEREO B observed more isotropic pitch-angle distributions signaled the observation of similar profiles by the four fields of view of SEPT (see also the pitch-angle distribution at the bottom panel of Fig. 10 in Klassen *et al.*, 2016). On the other hand, the intensity profiles observed by STEREO A were very different, being the most intense intensities recorded by the Sun field of view, which signals more anisotropic pitch-angle distributions (note the difference between the orange profiles in Fig. 1).

Interestingly, as can be seen in the third panel of Figure 1, on 2014 August 1, STEREO A was embedded in a slow solar wind stream, while STEREO B was inside a fast stream region, due to a coronal hole (Klassen *et al.*, 2016). The mean solar wind speeds, computed during the first hour after the event onset, are given in Table 1. The longitudinal separation between the nominal footpoints of the two spacecraft (computed assuming a Parker spiral) was very small, of less than 9° . In fact, given the estimated uncertainties in determining the magnetic connection (i.e., 10° as estimated by Nolte and Roelof 1973a, b, or even 20° , depending on the method employed, e.g., Lario *et al.*, 2014), one could even claim that the footpoints of STA and STB are the same.

According to Klassen *et al.* (2016), the first electron event was associated with a jet appearing at S22W55, as seen from STEREO B, at 16:13 UT. It was associated with a type III radio burst detected 9 min later, at 16:22 UT. The second electron event, was associated with a solar flare from the same active region occurring at 23:16 UT and followed by a type III radio burst at 23:24 UT. No type II radio bursts or coronal mass ejections (CMEs) were observed in association with any of the two events.

The connection angle, defined as the angular difference between the flare source and the spacecraft nominal footpoint, was larger for STEREO A than for STEREO B. The apparently better connected spacecraft, STEREO B, observed a smaller intensity increase and a later event onset time than STEREO A. In the next section, we explore if this can be due to different electron transport conditions along the flux tube connecting each spacecraft back to the Sun.

Fig. 1. In situ measurements by STEREO A (red) and STEREO B (blue). Electron omni-directional (solid curves) intensities are shown for 45–65 keV (top panel), and for 65–105 keV (second panel). Intensities for the Sun (STEREO A orange-dotted, STEREO B gray-dotted) and Antisun (STEREO A orange-dashed, STEREO B gray-dashed) fields of view are also displayed for both spacecraft in these two panels. The solar wind velocity, plasma density and temperature are shown from the third to the fifth panels, respectively. Finally, the last three panels display the magnetic field strength and its direction (latitudinal and azimuthal angles in the RTN reference frame).

Table 1. Main characteristics of the 2014 August 1 electron events (based on Klassen *et al.*, 2016).

Properties		Event I	Event II
Type III burst onset [UT]		16:22	23:24
Type II burst onset [UT]		No	No
CME		No	No
Connection angle [°]	STA-flare	27	26
	STB-flare	18	22
Electrons onset time [UT]	STA	16:34	23:45
	STB	16:54	23:54
Delay STB vs. STA [min]		20	9
Peak intensity ratio, STA/STB		5.5	4.0
V_{sw} [km s ⁻¹]	STA	349	328
	STB	557	584

3 Modeling

*SEPServer*¹ currently hosts a database of results of a Monte Carlo interplanetary transport model (Agueda *et al.*, 2008) to aid the study of near-relativistic (>50 keV) electron events observed by STEREO/SEPT (Agueda *et al.*, 2012). The transport model solves the focused transport equation (Roelof, 1969; Ruffolo, 1995), including the effects of particle streaming along the magnetic field lines, adiabatic focusing by the diverging magnetic field (Roelof, 1969), interplanetary scattering by magnetic fluctuations frozen into the solar wind (Jokipii, 1966; Dröge, 2003), convection with scattering fluctuations, and adiabatic deceleration resulting from the interplay of scattering and focusing (Ruffolo, 1995; Kocharov *et al.*, 1998).

¹ <http://server.sepsserver.eu>.

Fig. 2. Omni-directional 45–65 keV electron intensities expected at 1 AU under two interplanetary transport scenarios assuming that $\lambda_r = 0.37$ AU (red) and $\lambda_r = 0.10$ AU (blue). The release of particles was assumed to occur at $t=0$ for 10^{30} electrons in both cases. The particle event starts later and peaks at lower intensities for small values of the mean free path (more turbulent interplanetary transport conditions).

The model assumes a static source of particles at two solar radii following a power law in energy, and an Archimedean spiral magnetic flux tube connecting the Sun and the spacecraft. In situ observations of the solar wind speed and the spectra at the peak intensity help us constrain the curvature of the Archimedean spiral and the source spectrum, respectively.

In this work, diffusion perpendicular to the average magnetic field is neglected. The pitch-angle diffusion coefficient is given by $D_{\mu\mu} = \frac{v}{2}(1 - \mu^2)$, where the scattering frequency $\nu(\mu)$ adopts the form (Agueda et al., 2008), $\nu(\mu) = \nu_0 \left(\frac{1-\mu^2}{1+\mu^2} + \varepsilon \right)$, that allows us to model a range of scattering conditions, from quasi-isotropic ($\varepsilon \gtrsim 1$) to fully pitch-angle dependent ($\varepsilon = 0$). The case of isotropic pitch-angle scattering is obtained by taking $\nu(\mu) = \nu_0$ (see details in Agueda et al., 2008 and Agueda and Vainio 2013 for a comparison of the ε -scattering model with the modified standard model). Once the form of the pitch-angle scattering frequency is fixed, the radial mean free path, λ_r , is the only free parameter that describes the amount of pitch-angle scattering processes undergone by the energetic particles. It is related to the parallel mean free path by $\lambda_{\parallel} = \lambda_r \sec^2 \psi$, where ψ is the angle between the radial direction and the local magnetic field.

The results of the model are intensity directional distributions of electrons at 1 AU resulting from an instantaneous release of electrons close to the Sun, i.e., the model provides the Green's functions of interplanetary transport. Figure 2 shows the intensities expected at 1 AU under two interplanetary transport scenarios assuming that $\lambda_r = 0.37$ AU and $\lambda_r = 0.10$ AU, and isotropic pitch-angle scattering. It can be seen that for a given injection function at the Sun, the peak intensities expected at 1 AU will be larger for larger values of the radial mean free path, and the pitch-angle distributions more anisotropic (cf. Fig. 2 in Agueda et al., 2012 or Fig. 5 in Strauss et al., 2017 for 2 GV protons). In addition, the event onset time will appear earlier for larger values of the radial mean free path. Another interesting aspect under the assumptions of the focused transport model is

that for an injection function at the Sun that scales in heliolongitude following a Gaussian distribution and under the assumption of uniform interplanetary transport conditions (same radial mean free path in contiguous solar wind streams), the peak intensities expected at 1 AU will follow a Gaussian distribution.

We use the *SEPinversion* software available in *SEPServer* to infer the release time history and the interplanetary transport conditions of near-relativistic electrons for each event in our sample. *SEPinversion* makes use of a database of results of an interplanetary transport model to fit spacecraft observations at 1 AU. The fitting is done using the most direct form of directional data provided by the spacecraft (i.e. intensities recorded in four fields of view for STEREO/SEPT). *SEPinversion* assumes that the particle detector is a conical aperture and integrates the intensities for all the pitch angles in the detector aperture range according to the angular response of the telescope (Agueda et al., 2012). The software uses an inversion approach to fit the observations (Agueda et al., 2008), that is, it computes the intensities expected at 1 AU for a set of multiple consecutive instantaneous injection episodes (also refereed as Green's functions) and then solves a least-square problem to find out what should be the relative weight of each injection episode to best fit the intensities measured at 1 AU.

To find out the best fit scenario for each event, we considered: (i) the two options available in *SEPServer* for the description of the pitch-angle diffusion coefficient (isotropic and pitch-angle dependent with $\varepsilon = 0.01$), (ii) a wide range of interplanetary conditions covering 25 values of the radial mean free path, logarithmically spaced between 0.05 to 2.77 AU; and (iii) five values of the spectral index of the electron source (between 2.0 and 4.0, with step intervals of 0.5). Also, from the solar wind speed options available in the database, we selected the value from the discrete list (of 50 km/s steps) closest to the values shown in Table 1, at the onset of each event.

For each transport scenario, the best possible release time history was obtained. The goodness of the fit for each case was

Fig. 3. Two upper panels: Observed (thin curves) directional 45–65 keV electron intensities by STEREO A (left column) and STEREO B (right column) for Event I (top row) and Event II (bottom row). The intensity profiles for each field of view are identified by different colors as indicated in the inset (Sun and Antisun fields of view at the top panels; North and South fields of view at the second panels). Thick lines are the corresponding model fits. Bottom panels show the evolution of the pitch-angle cosine measured at the center of each field of view (color curves). The gray area shows the pitch-angle range covered by the telescopes. Each title shows the inferred value of the mean-free path for each case.

then evaluated by comparing the observations and the modeled data (see [Agueda et al., 2009](#), for more details). Each energy channel was fitted separately.

4 Results

We selected the time intervals between 16:20–19:00 UT for STEREO A and 16:35–20:25 UT for STEREO B to fit Event I, and 23:25–01:15 UT for STEREO A and 23:35–05:00 UT for

STEREO B to fit Event II. The start time of these intervals was chosen to take into account the onset of the particle event, for each spacecraft. The end times for STEREO A correspond to the time when the particle intensity had decreased one order of magnitude from the peak intensity. For STEREO B, with events showing slowly decreasing intensities, we chose the end time in a way that the results of the fits and the inferred parameters did not vary under minor time changes. The two upper panels of [Figure 3](#) show for each event (Event I, top row; Event II, bottom row), the 45–65 keV electron intensity-time

Fig. 4. Release functions inferred for Event I (*left*) and Event II (*right*). For each event, from top to bottom: Radio spectra observed by STEREO B/WAVES mirrored in the y-axis, electron source profile deduced at $2R_{\odot}$ for STEREO A and STEREO B in two energy channels, 45–65 keV (red) and 65–105 keV (blue), and radio flux observed by STEREO A/WAVES. Injection times are shifted by 500 s for comparison purposes with electromagnetic emissions.

Table 2. Best fit radial mean free path inferred for each event and in situ solar wind speed.

Event	S/C	λ_r [AU]	V_{sw} [km s ⁻¹]
I	STA	0.31	349
	STB	0.06	557
II	STA	0.37	328
	STB	0.10	584

profiles observed by STEREO A (left column) and STEREO B (right column) for the four fields of view (thin colored lines) of the SEPT instrument. The bottom panels show the evolution of the observed pitch-angle cosine, at the center of the telescope for each field of view with the same color code as the directional intensities, and the pitch-angle range (given the aperture of the telescopes of $\sim 50^\circ$) of each field of view (gray area).

The colored thick solid lines in the two upper panels of Figure 3 show the best fit obtained using *SEP inversion*. We can claim that the model is able to reproduce quite well the observations, except some disagreements that could be due to, e.g., the passage of local interplanetary magnetic field structures that invalidate the Parker field model, or other effects not included in the model. The results obtained assuming either the isotropic or the pitch-angle dependent scattering diffusion coefficient yield similar fits, being slightly better over all cases the fits derived by assuming isotropic pitch-angle scattering. The electron radial mean free paths that provide the best fit in each case are listed in Table 2.

In Figure 4, for Event I (left) and Event II (right), the derived injection profiles are shown in the middle panels (STEREO B, upper panel and STEREO A, lower panel) for the two energy channels fitted (45–65 keV, red and 65–105 keV, blue). For each event, the radio spectra recorded by WAVES is shown for STEREO B (top panels) and for STEREO A (bottom panels). Furthermore, injection times are shifted by 500 s for comparison purposes with electromagnetic emissions. For the two events and both STEREOs, we obtain a set of short injection profiles at $2R_{\odot}$ which agree with the timing and duration of the type III radio burst emission by WAVES (with a 5 min uncertainty). The release is almost simultaneous for both spacecraft and it is higher for STEREO B, the better-connected spacecraft, in both cases. Klassen et al. (2016) mentioned that different transport conditions could explain the onset delay and the peak intensity difference between the spacecraft. Our results confirm this idea.

5 Conclusions

We studied two consecutive electron events observed by the STEREO twin spacecraft on 2014 August 1 with only a few hours of delay between the events. Both electron events were associated with an unambiguous type III burst and not accompanied by type II radio bursts or CMEs (Klassen et al., 2016).

On that date, the longitudinal separation between the spacecraft was of only $\sim 35^\circ$. Despite the close location of the two spacecraft, STEREO A was embedded in a slow solar wind

stream, while STEREO B was inside a fast stream region of solar wind, due to a coronal hole.

In addition, for both events, the electron intensities observed by STEREO A and STEREO B showed clear differences in terms of onset time, peak intensity and evolution of the pitch-angle distributions. The events observed by STEREO A started to rise up to 20 min earlier than at STEREO B, and the peak intensity was about a factor 5 higher at STEREO A and more anisotropic (see the two top panels of in Klassen *et al.*, 2016). The apparently better connected spacecraft, STEREO B, observed a smaller intensity increase and a later event onset time than the worse connected spacecraft, STEREO A.

In this paper, we studied if these observations could be explained by different electron transport conditions along the flux tube connecting each spacecraft back to the Sun. We modeled the two events using *SEPinversion* and inferred an almost simultaneous release of electrons for both spacecraft in both events. The release is consistent with the timing and duration of the type III radio burst emission and it is larger for STEREO B, the better connected spacecraft. In addition, we obtained different transport conditions in different solar wind streams, signaled also by different solar wind regimes. We found that the stream in which STEREO B was embedded was more diffusive ($\lambda_r = 0.1$ AU for Event I and $\lambda_r = 0.06$ AU for Event II) than the stream in which STEREO A was embedded ($\lambda_r = 0.31$ AU for Event I and $\lambda_r = 0.37$ AU for Event II). These different transport regimes are sufficient to explain the early onset for the worse connected spacecraft, STEREO A, and the larger intensities as well as the difference in the observed anisotropies. We conclude that the interplanetary transport conditions can vary drastically between nearby solar wind streams.

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