First near-relativistic solar electron events observed by EPD onboard Solar Orbiter


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ABSTRACT

Context. Solar Orbiter, launched in February 2020, started its cruise phase in June 2020, in coincidence with its first perihelion at 0.51 au from the Sun. The in situ instruments onboard, including the Energetic Particle Detector (EPD), operate continuously during the cruise phase enabling the observation of solar energetic particles.

Aims. In situ measurements of the first near-relativistic solar electron events observed in July 2020 by EPD are analyzed and the solar origins and the conditions for the interplanetary transport of these particles investigated.

Methods. Electron observations from keV energies to the near-relativistic range were combined with the detection of type III radio bursts and extreme ultraviolet (EUV) observations from multiple spacecraft in order to identify the solar origin of the electron events. Electron anisotropies and timing as well as the plasma and magnetic field environment were evaluated to characterize the interplanetary transport conditions.

Results. All electron events were clearly associated with type III radio bursts. EUV jets were also found in association with all of them except one. A diversity of time profiles and pitch-angle distributions was observed. Different source locations and different magnetic connectivity and transport conditions were likely involved. The July 11 event was also detected by Wind, separated 107 degrees in longitude from Solar Orbiter. For the July 22 event, the Suprathermal Electron and Proton (STEP) sensor of EPD allowed for us to not only resolve multiple electron injections at low energies, but it also provided an exceptionally high pitch-angle resolution of a very anisotropic beam. This, together with radio observations of local Langmuir waves suggest a very good magnetic connection during the July 22 event. This scenario is challenged by a high-frequency occultation of the type III radio burst and a nominally non-direct connection to the source; therefore, magnetic connectivity requires further investigation.

Key words. acceleration of particles– Sun: particle emission – Sun: activity

1. Introduction

One of the science goals of the Solar Orbiter (SoO) mission is the analysis of the mechanisms by which solar eruptions produce energetic particle radiation that fills the heliosphere (Müller et al. 2020). This entails a deep understanding of how and where solar energetic particles (SEPs) are accelerated and how these particles are released and distributed into the interplanetary medium. SoO, which was launched on 2020 February 10, enables in situ observations of SEPs from heliocentric distances <1 au, hence minimizing the transport effects undergone by the particles that often hinder the identification of their solar sources.

Solar electrons are closely associated with type III radio bursts and often with 3He-rich ion emissions (e.g., Wang et al. 2012). Due to their fast propagation, near-relativistic (NR) electrons are particularly useful for the identification of SEP sources at the Sun. There is a rich literature on the relationship between NR electron events and solar activity, with diverging results. While the early onset of electron events was reported to be closely related in time with the onset of radio emission and especially type III bursts produced by electron beams (Kallenrode & Wibberenz 1991), later work from 1 au frequently found significant delays in the electrons observed in space (Krucker et al. 1999; Haggerty & Roelof 2002; Wang et al. 2016). There is also no simple relationship between energy spectra of electrons observed in space and thick-target energy spectra derived from solar hard X-ray emission (Dröge 1996; Krucker et al. 2007). The frequent detection of electrons at widely separated spacecraft (s/c) is a third issue that is not adequately understood, and it involves various transport processes in the corona and/or the heliosphere (Kallenrode et al. 1992; Wibberenz & Cane 2006; Dressing et al. 2014; Gómez-Herrero et al. 2015; Xu et al. 2020; Zhang et al. 2021).

While HELIOS observations from the inner heliosphere addressed some of these questions (see Pacheco et al. 2019, and references therein), SoO provides a new view due to the better coverage of the energy spectrum of the electrons and the existing complementary electromagnetic observations. The present
Electron flux increases, some of them comprising several injections: July 8-25. The bottom panel shows the heliocentric distance and time profiles measured by STEP at the lower energy range, from each with a 30° conical FOV.

2. Observations and data analysis

2.1. NR electron events during the SoO cruise phase

Although SoO started its cruise phase during the solar minimum between solar cycles 24 and 25, a number of NR electron events were observed in July 2020. Out of the four sensors of the EPD suite, the EPT-Sun, the Electron Proton Telescope (EPT), and the Electron Proton telescope (EPT). The electron increase was also observed near Earth by the EPT-Sun aperture, pointing sunward along the nominal Parker spiral direction (Fig. A.1 in Appendix A). The electron increase was observed above 70 keV. No significant increase above 100 keV.

- 2020 July 11. The 58 keV electron flux observed by EPT started to rise at 20:40 UT ± 10 min. The highest intensity and earliest onset were observed by the northward-looking EPT telescope, pointing closer to pitch-angle 0° (Fig. A.2). No significant increase was observed above 100 keV.

- 2020 July 21. This event comprises at least three consecutive, partly overlapping electron injections, with electron on-
sets at 01:25, 03:05, and 06:25 UT ± 10 min (determined at 58 keV). The increases were progressively more intense and energetic, reaching ~1 MeV (observed by the High Energy Telescope (HET) of EPD, not shown). The peak flux was reached at ~08:30 UT on July 21 and the decay phase lasted until mid-July 22. EPT directional intensities revealed measurable anisotropies, but smaller than during the previous event (Fig. A.2).

- 2020 July 22. EPT observed a very anisotropic electron event reaching energies slightly above 100 keV. The spike-like time profile, similar to the events described by Klassen et al. (2011), showed a sharp onset with clear velocity dispersion, starting at 23:40 UT ± 10 min at 58 keV. This period was cleanly observed by STEP at lower energies, which revealed additional spike-like injections preceding and following the event observed by EPT. The EPD pitch-angle coverage for this event was nearly optimal (Figs. A.3 and A.5).

The events on July 19, 20, 21, and probably July 22 resulted in an extended period with observable 3He/4He fluxes and enhanced 3He/4He ratios measured by the Suprathermal Ion Spectrograph (EPD/SIS), which spanned from mid-July 19 to July 25 (cf. Fig. 3 in Mason et al. 2021). Anisotropies during the events are discussed in further detail in Appendix A. In situ magnetic field and plasma observations by the Magnetometer (MAG, Horbury et al. 2020) and the Solar Wind Analyser suite (SWA, Owen et al. 2020) onboard SolO are presented and discussed in Appendix B.

The main observational characteristics of the NR electron events are summarized in Table 1. The first row numbers the events in sequential order. The event date and the observed onset time at 58 keV are listed in the second and third row, respectively. The timing of type III radio bursts and coronal EUV jets likely associated with each event are listed in the fourth and fifth row, respectively (see Sects. 2.2 and 2.3 for further details). The sixth and seventh row describe the s/c observing the EUV jet and its approximate position angle (PA, counter-clockwise from the solar north), respectively. The times listed for the type III radio bursts and the EUV jets are the times at which these phenomena were observed locally by the listed s/c. The eighth row shows the 1-hour averaged solar wind speed at the onset of the NR electron event (see Appendix B). This value was used to estimate the Corrington Longitude (CL) of the footpoint of the s/c along an ideal Parker spiral (ninth row). Some additional remarks are described in the last row.

The bottom panel in Fig. 3 shows an inverse-speed versus time plot (typically used for velocity dispersion analysis) for the July 22 event, combining STEP and EPT electron data. The color scale represents the intensity, normalized to the maximum value for each energy (speed) channel. The black line is a linear fit to electron arrival times, indicating the solar particle release time. The energy interval used for the fit is marked with a solid line (see text for details).

Fig. 3. Top: SolO/RPW radio dynamic spectrum observed in association with the electron event with an onset in late July 22. The magenta line is the spectral flux at the local plasma frequency, where the peaks indicate locally generated Langmuir waves. Bottom: Electron c/v versus time plot. The color scale corresponds to the particle intensity, normalized to the maximum value for each energy (speed) channel. The black line is a linear fit to electron arrival times, indicating the solar particle release time. The energy interval used for the fit is marked with a solid line (see text for details).

2.2. Radio observations

Radio dynamic spectra from STEREO/SWAVES (Bougeret et al. 2008), Wind/Waves (Bougeret et al. 1995), and SolO/RWP were examined for the period under analysis. Type III radio bursts were found in association with all the electron events presented here (Table 1). None of the electron events were accompanied by type II radio bursts.

The top panel of Fig. 3 shows the dynamic spectrum observed by SolO/RWP during the electron event starting in late July 22. The magenta line shows the spectral flux around the local plasma frequency. The distinct peaks are due to Langmuir waves locally generated when the electron beam causing the type III radio emission reached the s/c location. We note the coincidence of the intensity increase with the detection of few keV electrons by STEP. These observations support the existence of a direct magnetic connection to the solar source of the electrons.
The attenuation of the type III burst observed at high frequencies suggests the source was partially occulted as viewed from SolO, while STEREO-A saw it entirely (not shown). Furthermore, the lack of a clear type III detection from PSP (not shown) places the most probable location near the east limb from STEREO-A and behind the west limb from SolO (for reference, see Fig. 1).

The type III burst seen by STEREO-A/SWAVES corresponds to fundamental emission, while SolO/RPW observed harmonic emission. According to Thejappa et al. (2012), fundamental emission in type III radio bursts is more directive than the second harmonic, which explains why SolO observed the weaker second harmonic emission, while STEREO-A, with direct visibility of the source, observed the fundamental emission.

### 2.3. Associated solar activity and source locations

During the period under analysis, remote-sensing instruments onboard SolO were not active. EUV and coronagraph observations from SDO/AIA (Lemen et al. 2012), SOHO/LASCO (Brueckner et al. 1995), and STEREO-A/SECCHI (Howard et al. 2008) have been examined in order to explore solar activity phenomena and source regions potentially associated with the electron events observed by EPD.

For all the events except the weak event on July 19, sequences of multiple narrow ejections were found in 171, 195, and 304 Å EUV images, with appearance times very close to the in situ electron onsets. None of the events were associated with large CMEs. Some small flux-rope ejections were seen, but there was no time coincidence with the electron events analyzed here.

The times, locations, and observing s/c of the jets are listed in Table 1. They were observed above the west limb on SDO (July 11) and the east limb from STEREO-A (July 20, 21, and 22). When comparing the observation times of these EUV jets at 1 au and the type III radio bursts at SolO, it should be taken into account that the light travel time to STEREO-A and SDO is 2-3 minutes longer than to SolO.

Fig. 4 shows two STEREO-A/EUVI running difference images at 171 Å, around the time of the type III radio burst associated with the July 22 event. We note the agreement with the timing of the type III radio burst and the electron release time inferred from a velocity dispersion analysis (Fig. 3). The jet showed a strongly non-radial propagation trajectory toward the equator (projected onto the plane of the sky), likely reflecting the non-radial magnetic field configuration around the source region, as described by Klassen et al. (2018) and Bučík et al. (2018).

### 3. Summary and conclusions

In spite of the solar minimum conditions, after its first perihelion, SolO detected several NR electron events during 2020 July 11-24. All of them were clearly associated with type III radio bursts observed by multiple s/c. EUV jets were observed above the east limb from STEREO-A for the July 20, 21, and 22 events and above the west limb from SDO for the July 11 event, with good time coincidence with the type III radio bursts. While velocity dispersion analysis results should always be treated with caution (e.g., Lintunen & Vainio 2004; Sáiz et al. 2005; Kahler & Ragot 2018), the evidence points toward a strong association between type III radio bursts and NR electron events.

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**Table 1. Electron events observed by EPD during July 2020.**

<table>
<thead>
<tr>
<th>Event</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
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<td>July 19</td>
<td>July 20</td>
<td>July 21</td>
<td>July 22</td>
</tr>
<tr>
<td>Onset (UT)</td>
<td>02:33 ± 5 min</td>
<td>11:00 ± 1 h</td>
<td>20:40 ± 10 min</td>
<td>01:25 ± 10 min</td>
<td>23:40 UT ± 10 min</td>
</tr>
<tr>
<td>Type III (UT)</td>
<td>02:21</td>
<td>10:27</td>
<td>20:13</td>
<td>01:16</td>
<td>23:33</td>
</tr>
<tr>
<td>EUV jet</td>
<td>02:21</td>
<td>no</td>
<td>20:20 – 20:56</td>
<td>01:16 – 01:36</td>
<td>23:33</td>
</tr>
<tr>
<td>EUV jet observer</td>
<td>SDO/AIA</td>
<td>N/A</td>
<td>STA/EUVI</td>
<td>STA/EUVI</td>
<td>STA/EUVI</td>
</tr>
<tr>
<td>EUV jet PA (°)</td>
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<td>N/A</td>
<td>~70</td>
<td>~70</td>
<td>~70</td>
</tr>
<tr>
<td>V_sw (km/s)</td>
<td>No data</td>
<td>264</td>
<td>284</td>
<td>275</td>
<td>320</td>
</tr>
<tr>
<td>Remarks</td>
<td>Multiple injections</td>
<td>Multiple injections</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Notes.** (a) Determined at 58 keV using the telescope showing earliest onset. For multiple injections, the first onset is listed. (b) Onset at 2 MHz on SolO/RPW data for events 1, 3, 4, and 5 and Wind/Waves for event 2. (c) Series of type III bursts along the day. (d) Series of jets. (e) Position angle of the jet(s) observed over the solar limb, counter-clockwise from the solar north pole. (f) No SWA data are available, footpoint was obtained assuming V_sw=350 km/s.
2006), the results presented here suggest that this method provides a reasonable estimation of the solar release time for SEP events in the inner heliosphere under low-scattering conditions. As commonly happens for impulsive SEP events, EPD/SIS detected several \(^3\)He and heavy ion enhancements during the same time interval (Mason et al. 2021). The period was not disturbed by major CMEs nor shocks (Appendix B).

Examination of NR electron observations from instruments onboard STEREO, near-Earth s detected several /... 2019-000918-M). The RPW team thanks the French space agency CNES, the Center Na... the ESA PRODEX programme and NASA.

References


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Appendix A: Electron anisotropies

Directional intensities from EPT telescopes can be combined with the magnetic field vector data in order to produce electron PADs. The PAD quality for a particular event (i.e., the coverage of the pitch-angle space) is conditioned by the relative orientation of the magnetic field vector and the sensor apertures. Figs. A.1, A.2, and A.3 summarize the 40.9–46.2 keV electron anisotropy information provided by EPT for the July 11, July 19-21, and July 22 events, respectively. We note that on July 19, EPT pitch-angle coverage goes through sharp and periodic changes, coinciding with most of event 2 due to s/c rotations. Fig. A.4 shows the evolution of the PAD, directional intensities, and anisotropy index of 30-50 keV electrons observed by Wind/3DP during the July 11 event.

Moreover, the pixelated FOV of STEP can provide improved angular resolution for a limited range of pitch angles. Fig. A.5 shows the electron pitch-angle distribution obtained from STEP data for three different energy ranges during the July 22 event. For this event, EPT and STEP observed very anisotropic fluxes, which were resolved in two different beams at low energies (Fig. 3). The interplanetary magnetic field and solar wind observations showed very stable conditions during the whole interval and during most of the event the magnetic field vector was almost aligned with the STEP and the EPT-Sun sensor apertures, providing a nearly optimal pitch-angle coverage of the two narrow field-aligned electron beams observed by STEP below 30 keV. We note that before 23:40 UT, the electron beam was not aligned with the FOVs, which is probably the cause of the abrupt start of the first electron beam, and hinders the detection of the higher energy electrons by EPT, in case they were present.

Appendix B: Interplanetary context

For the same period shown in Fig. 2, Fig. B.1 shows from top to bottom the solar wind proton speed ($V_p$), density ($n_p$), and temperature ($T_p$) as measured by SWA and the interplanetary magnetic field (IMF) magnitude ($B_{IMF}$) and direction in the s/c centered radial tangential normal (RTN) coordinates (polar angle $\theta_{IMF}$ and azimuthal angle $\phi_{IMF}$) as measured by MAG. The vertical lines indicate the onset time of the NR electron events listed in Table 1. SWA observations were only available for the
last part of the period, showing predominantly slow solar wind conditions.

The onset of event 1 occurred after the passage of a compressed magnetic field without clear shock discontinuities at its boundaries. The occurrence of a low-energy ion intensity enhancement in coincidence with this IMF structure as observed by both STEP and EPT (Fig. 2), with the suprathermal proton enhancement seen earlier than the more energetic ions detected by EPT, suggests that this IMF enhancement is most likely the signature of a stream interaction region (SIR).

The onset of event 2 occurred during spacecraft rolling maneuvers (from 4:00 UT to 16:00 UT on July 19) that affected SWA data, exhibiting large oscillations in density and temperature, which were removed from Fig. B.1. Nevertheless, event 2 developed during a period characterized by low $T_p$ and low $V_p$ ($< 270 \text{ km s}^{-1}$) embedded between the decay of the fast ($\sim 450 \text{ km s}^{-1}$) stream (observed earlier on July 15) and an approaching solar wind stream characterized by enhanced values of $n_p$ and low values of $V_p$, $T_p$, and $B_{IMF}$. The onset of events 3 and 4 occurred during this period and in coincidence with IMF rotations. These conditions suggest that a non-compressive density enhancement reached SoIO, indicating a possible small eruption from the Sun (Gosling et al. 1977; Diego et al. 2020). The passage of a SIR-like magnetic structure started on July 21 and coincides with the observed low-energy ion event (middle panel in Fig. 2). Finally, event 5 occurred in a period with more stable plasma and IMF parameters, which may facilitate the scatter-free propagation of NR electrons toward SoIO.

**Fig. A.4.** Summary of Wind/3DP observations of 30-50 keV electrons during the electron event on July 11. From top to bottom: Electron PAD, pointing for each pitch-angle bin, intensities observed by each pitch-angle bin, and anisotropy index (calculated as described in Dresing et al. (2014)).

**Fig. A.5.** Electron PAD observed by STEP at three different energy bands during the July 22 event. The time scale is the same as the one used in Figs. 3 and A.1. We note that in this case, the Y-axis covers the interval 0-90°.

**Fig. B.1.** Summary of the solar wind and interplanetary magnetic field measurements by the SWA/PAS and MAG instruments in July 2020. From top to bottom: Solar wind speed, density, and temperature as well as IMF intensity, and IMF polar and azimuthal angles in RTN coordinates. Vertical lines mark the onset times of the five NR-electron enhancements listed in Table 1.