

## Influence of large-scale interplanetary structures on the propagation of solar energetic particles: The multi-spacecraft event on 2021 October 9

D. LARIO,<sup>1</sup> N. WIJSEN,<sup>2</sup> R. Y. KWON,<sup>3</sup> B. SÁNCHEZ-CANO,<sup>4</sup> I. G. RICHARDSON,<sup>5,1</sup> D. PACHECO,<sup>6</sup> E. PALMERIO,<sup>7</sup> M. L. STEVENS,<sup>8</sup> A. SZABO,<sup>1</sup> D. HEYNER,<sup>9</sup> N. DRESING,<sup>10</sup> R. GÓMEZ-HERRERO,<sup>11</sup> F. CARCABOSO,<sup>12,1</sup> A. ARAN,<sup>13</sup> A. AFANASIEV,<sup>10</sup> R. VAINIO,<sup>10</sup> E. RIIHONEN,<sup>10</sup> S. POEDTS,<sup>2,14</sup> M. BRÜDEN,<sup>6</sup> Z. G. XU,<sup>6</sup> AND A. KOLLHOFF<sup>6</sup>

<sup>1</sup>*Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

<sup>2</sup>*Centre for mathematical Plasma-Astrophysics, Department of Mathematics, KU Leuven, B-3001 Leuven, Belgium*

<sup>3</sup>*Korea Astronomy and Space Science Institute, Daejeon, Republic of Korea*

<sup>4</sup>*School of Physics and Astronomy, University of Leicester, Leicester, UK*

<sup>5</sup>*Department of Astronomy, University of Maryland, College Park, MD 20742, USA*

<sup>6</sup>*Institut für Experimentelle und Angewandte Physik (IEAP), Christian-Albrechts-Universität zu Kiel, 24118 Kiel, Germany*

<sup>7</sup>*Predictive Science Inc., San Diego, CA 92121, USA*

<sup>8</sup>*Center for Astrophysics—Harvard & Smithsonian, Cambridge, MA 02138, USA*

<sup>9</sup>*Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Braunschweig, Germany*

<sup>10</sup>*Department of Physics and Astronomy, University of Turku, Finland*

<sup>11</sup>*Universidad de Alcalá, Space Research Group, Alcalá de Henares, 28805 Alcalá de Henares, Spain*

<sup>12</sup>*The Catholic University of America, Washington, DC 20064, USA*

<sup>13</sup>*Department of Quantum Physics and Astrophysics, Institute of Cosmos Sciences (ICCUB), Universitat de Barcelona (UB-IEEC), Spain*

<sup>14</sup>*Institute of Physics, University of Maria Curie-Skłodowska, 20-031 Lublin, Poland*

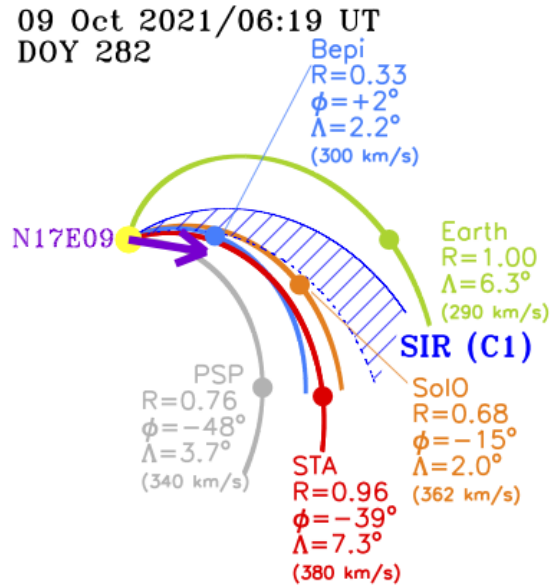
(Received; Revised; Accepted)

Submitted to ApJ

### ABSTRACT

An intense solar energetic particle (SEP) event was observed on 2021 October 9 by multiple spacecraft distributed near the ecliptic plane at heliocentric radial distances  $R \lesssim 1$  au and within a narrow range of heliolongitudes. A stream interaction region (SIR), sequentially observed by Parker Solar Probe (PSP) at  $R=0.76$  au and  $48^\circ$  east from Earth ( $\phi=E48^\circ$ ), STEREO-A (at  $R=0.96$  au,  $\phi=E39^\circ$ ), Solar Orbiter (SolO; at  $R=0.68$  au,  $\phi=E15^\circ$ ), BepiColombo (at  $R=0.33$  au,  $\phi=W02^\circ$ ), and near-Earth spacecraft, regulated the observed intensity-time profiles and the anisotropic character of the SEP event. PSP, STEREO-A and SolO detected strong anisotropies at the onset of the SEP event, which resulted from the fact that PSP and STEREO-A were in the declining-speed region of the solar wind stream responsible for the SIR, and from the passage of a steady magnetic field structure by SolO during the onset of the event. By contrast, the intensity-time profiles observed near-Earth displayed a delayed onset at proton energies  $\gtrsim 13$  MeV and an accumulation of  $\lesssim 5$  MeV protons between the SIR and the shock driven by the parent coronal mass ejection (CME). Even though BepiColombo, STEREO-A, and SolO were nominally connected to the same region of the Sun, the intensity-time profiles at BepiColombo resemble those observed near Earth, with the bulk of low-energy ions also confined between the SIR and the CME-driven shock. This event exemplifies the impact that intervening large-scale interplanetary structures, such as corotating SIRs, have in shaping the properties of SEP events.

*Keywords:* Solar energetic particles (1491); Interplanetary shocks (829); Solar coronal mass ejections (310); Interplanetary magnetic fields (824)



**Figure 1.** Schematic representation of the nominal interplanetary magnetic field configuration in the ecliptic plane as seen from the north, showing field lines connecting the Sun to the locations of Earth (green symbol), BepiColombo (Bepi; blue symbol), Solar Orbiter (SolO; orange symbol), STEREO-A (STA; red symbol), and Parker Solar Probe (PSP; gray symbol) on 2021 October 9 (day of year 282) at the time of the start of the SXR flare associated with the SEP event commencing on this day. Nominal Parker spiral magnetic field lines have been plotted using the solar wind speed indicated next to the HEEQ coordinates of each spacecraft. The solar wind speed values come from plasma measurements at the onset of the SEP event, except for Bepi where a nominal value of  $300 \text{ km s}^{-1}$  has been adopted since no solar wind data from this spacecraft were available. The purple arrow identifies the longitude of the solar flare. The blue hatched region indicates a stream interaction region (SIR) including compressed magnetic field (C1) that controlled the properties of the SEP event at each location.

## 1. INTRODUCTION

The intensity-time histories of solar energetic particle (SEP) events detected by instruments aboard spacecraft are determined by the mechanisms that accelerate and inject particles into the interplanetary medium as well as the processes undergone by the particles as they propagate from their source to the spacecraft (e.g., Meyer et al. 1956; Beeck et al. 1987; Klein & Dalla 2017, and references therein). Energetic particle transport throughout the heliosphere is controlled by the properties of the interplanetary magnetic field (e.g., Jokipii 1971). In the absence of transient interplanetary structures of solar origin, such as interplanetary coronal mass ejections (ICMEs), and corotating solar wind stream interaction regions resulting from the interaction of solar wind streams of different speed (e.g. Richardson 2018), the field-aligned energetic particle transport results from pitch-angle scattering processes combined with the focusing effect of the outwardly decreasing interplanetary magnetic field (Roelof 1969). However, when present, these structures can have a substantial effect on the transport of energetic particles. These effects include the mirroring of particles by compressed magnetic field regions acting as reflecting barriers, the confinement of particles in closed magnetic field structures or in converging enhanced magnetic field regions, the enhancement of particle drifts by strong magnetic field gradients and curvatures, and the intensification of the pitch-angle scattering processes undergone by the particles as the level of magnetic field turbulence increases in these structures (e.g., Barouch & Burlaga 1976; Richardson & Cane 1996; Bieber et al. 2002; Lario et al. 2008, 2013; Luhmann et al. 2017; Wijzen et al. 2020).

On 2021 October 9, an intense SEP event was detected by multiple spacecraft distributed in the inner heliosphere. The solar origin of this event was associated with a fast ( $\sim 983 \text{ km s}^{-1}$ )<sup>1</sup> coronal mass ejection (CME) and a M1.6/2B X-ray/H $\alpha$  solar flare from NOAA Active Region (AR) 12882 at N17 $^{\circ}$ E09 $^{\circ}$  with soft X-ray (SXR) emission starting at 06:19 UT and peaking at 06:38 UT, together with a metric type III radio burst starting at 06:30 UT<sup>2</sup>. Figure 1 shows the spatial distribution of several spacecraft located at heliocentric radial distances  $R \lesssim 1 \text{ au}$  on 2021 October

<sup>1</sup> CME speed reported by the Space Weather Database of Notifications, Knowledge, Information (DONKI) at [ccmc.gsfc.nasa.gov/DONKI/](http://ccmc.gsfc.nasa.gov/DONKI/) using the measuring technique SWPC\_CAT (ID CME activity 2021-10-09T07:09-00-CME-001)

<sup>2</sup> [ftp.swpc.noaa.gov/pub/indices/events/](http://ftp.swpc.noaa.gov/pub/indices/events/)

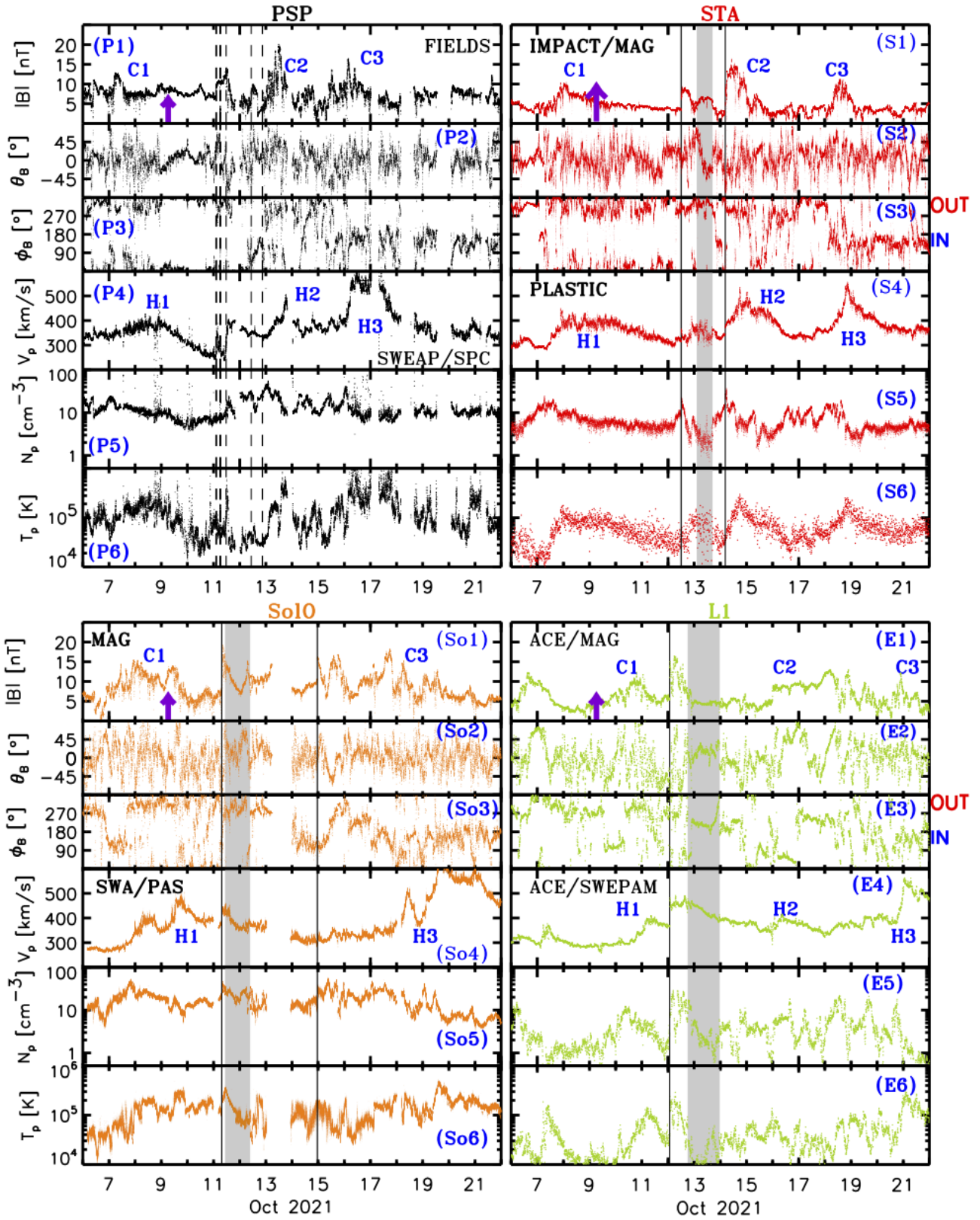
9 as seen from the north ecliptic pole. The solid circles (not to scale) indicate the locations of the Sun (yellow), Parker Solar Probe (PSP; [Fox et al. 2016](#)) (gray), the A spacecraft of the Solar Terrestrial Relations Observatory (STEREO-A; [Kaiser et al. 2008](#), STA hereafter) (red), Solar Orbiter (SolO; [Müller et al. 2020](#)) (orange), BepiColombo (Bepi; [Benkhoff et al. 2021](#)) (blue), and Earth (green). The legend next to each symbol provides the heliocentric radial distance  $R$ , and the heliographic longitude  $\phi$  and latitude  $\Lambda$  in Heliocentric Earth Equatorial (HEEQ) coordinates. Nominal magnetic field lines connecting each one of these locations with the Sun have been plotted assuming a Parker spiral and the solar wind speed observed at each location, indicated in the legend next to each symbol. The dark blue hatched region indicates the presence of a stream interaction region (SIR) labeled C1 that, as will be discussed below, played an essential role in shaping the properties of the SEP event at each spacecraft.

The distribution of spacecraft in this time interval, close to the longitude of the solar flare (indicated by the purple arrow) and covering a range of radial distances, is very opportune to demonstrate the effects that intervening large-scale solar wind structures have on the intensity-time profiles and anisotropy properties of the 2021 October 9 SEP event observed at the different spacecraft. As will be discussed below, some observations are contrary to expectations. For example, we might expect that the nominal magnetic connection between Bepi and STA shown in [Figure 1](#) would lead to similar intensity-time profiles observed by both spacecraft. We might also expect that Bepi and near-Earth spacecraft would observe similar particle intensity enhancements associated with the passage of the interplanetary (IP) shock driven by the CME propagating radially outward from the Sun (not shown in [Figure 1](#)), as both locations, separated just by  $\sim 2^\circ$  in longitude, will intercept the same portion of the shock front, albeit at different helioradii. However, the presence of the SIR corotating from east to west, together with the CME-driven shock, shaped the observed properties of the SEP event at the different spacecraft. We observe a remarkable similarity between the low-energy ion intensity-time profiles measured by Bepi and near-Earth spacecraft, despite being on well-separated magnetic field lines. This similarity is observed for a long time interval prior to the arrival of the shock (more than  $\sim 24$  hours in the case of Earth and more than  $\sim 8$  hours in the case of Bepi). This resulted from the interplay between the CME-driven shock and the SIR C1 preceding the arrival of the CME-driven shock at these spacecraft.

The structure of the paper is as follows. In [section 2](#), we present the interplanetary context during the development of the SEP event based on simulations from the European Heliospheric FORecasting Information Asset (EUHFORIA) model ([Pomoell & Poedts 2018](#)) and solar wind and magnetic field measurements from PSP, STA, SolO, and the Advanced Composition Explorer (ACE; [Stone et al. 1998](#)) located at the Sun-Earth Lagrangian point L1. In [Section 3](#), we describe the solar eruption associated with the SEP event as seen in ExtremeUltraviolet (EUV) and white-light (WL) measurements from STA, the Solar Dynamics Observatory (SDO; [Pesnell et al. 2012](#)) and the Solar and Heliospheric Observatory (SOHO; [Domingo et al. 1995](#)). In [Section 4](#), we describe energetic particle measurements from PSP, STA, SolO, Bepi, and the near-Earth spacecraft ACE, SOHO and Wind ([Wilson et al. 2021](#)), paying especial attention to the anisotropic character of the onset of the event. In [Section 5](#), we address the relationship between the estimated release time of high-energy protons and relativistic electrons with the solar eruption. In [Section 6](#), we summarize the main results of this analysis emphasizing the role that the interceding SIR had in shaping the properties (intensity-time profiles and anisotropy character of the event) at each spacecraft. Finally, the main conclusions of this work are presented in [Section 7](#).

## 2. INTERPLANETARY CONTEXT

During October 2021, a series of solar wind streams was sequentially observed by PSP, STA, SolO and spacecraft orbiting the Sun-Earth Lagrangian point L1 such as ACE and Wind. [Figure 2](#) shows magnetic field and solar wind parameters from 2021 October 6 to 2021 October 22 as measured by PSP (top left panels in black), STA (top right panels in red), SolO (bottom left panels in orange) and ACE (bottom right panels in green). In particular, the panels (P1)-(P6) show, from top to bottom, the magnetic field (P1) magnitude  $|B|$ , (P2) elevation angle  $\theta_B$ , and (P3) azimuth angle  $\phi_B$  in the spacecraft-centered Radial-Tangential-Normal (RTN) coordinate system as measured by the fluxgate magnetometers of the FIELDS suite of instruments ([Bale et al. 2016](#)) on board PSP; and the proton solar wind (P4) speed  $V_p$ , (P5) density  $N_p$ , and (P6) temperature  $T_p$  as measured by the Solar Probe Cup (SPC; [Case et al. 2020](#)) of the Solar Wind Electrons Alphas and Protons (SWEAP) experiment ([Kasper et al. 2016](#)) on PSP. The panels (S1)-(S6) show, from top to bottom, (S1)  $|B|$ , (S2)  $\theta_B$  and (S3)  $\phi_B$  in RTN coordinates as measured by the magnetometer ([Acuña et al. 2008](#)) of the In situ Measurements of Particles And CME Transients (IMPACT) suite of instruments ([Luhmann et al. 2008](#)) on board STA; (S4)  $V_p$ , (S5)  $N_p$  and (S6)  $T_p$  as measured by the Plasma and



**Figure 2.** Magnetic field and solar wind plasma measurements from 2021 October 6 to 2021 October 22 measured by (top left) PSP, (top right) STA, (bottom left) SoLo, and (bottom right) ACE. Each panel shows, from top to bottom, magnetic field magnitude  $|B|$ , magnetic field elevation angle  $\theta_B$ , magnetic field azimuthal angle  $\phi_B$  in spacecraft-centered RTN coordinates, solar wind proton speed  $V_p$ , solar wind proton density  $N_p$ , and solar wind proton temperature  $T_p$ . See text for the specific instruments that collected these measurements. The solid vertical lines indicate the passage of shocks and the gray columns the possible passage of ICMEs. C1, C2, C3 indicate the passage of magnetic field compression regions preceding the passage of the solar wind streams labeled H1, H2 and H3. The purple arrows indicate the onset time of the SXR emission of the solar flare associated with the origin of the SEP event shifted back to the Sun by the light transit time to 1 au.

Suprathermal Ion Composition experiment (PLASTIC; Galvin et al. 2008) on STA<sup>3</sup>. The panels (So1)-(So6) show, from top to bottom, (So1)  $|B|$ , (So2)  $\theta_B$  and (So3)  $\phi_B$  in RTN coordinates as measured by the magnetometers on board SoO (Horbury et al. 2020), and (So4)  $V_p$ , (So5)  $N_p$  and (So6)  $T_p$  as measured by the Proton and Alpha particle Sensor (PAS) of the Solar Wind Analyzer (SWA; Owen et al. 2020) on board SoO. The panels (E1)-(E6) show, from top to bottom, (E1)  $|B|$ , (E2)  $\theta_B$  and (E3)  $\phi_B$  in RTN coordinates as measured by the magnetometer on board ACE (Smith et al. 1998), and (E4)  $V_p$ , (E5)  $N_p$  and (E6)  $T_p$  as measured by the Solar Wind Electron Proton Alpha Monitor (SWEPAM; McComas et al. 1998) on ACE. The purple arrow in panels (P1), (S1), (So1) and (E1) identify the occurrence of the SXR flare associated with the origin of the SEP event. The solid vertical lines indicate the passage of IP shocks identified by discontinuous increases of magnetic field magnitude and solar wind parameters. The shaded gray bars indicate the possible passage of ICMEs<sup>4</sup> identified using signatures typically observed in these structures (e.g., Zurbuchen & Richardson 2006) as described below.

The sequence of solar wind streams observed by PSP, STA, SoO and near-Earth spacecraft was more clearly seen by the spacecraft at the highest heliolatitude, i.e.  $\Lambda=7.3^\circ$  for STA. Figure 2(S4) shows the observation by STA of three solar wind streams with speeds  $\gtrsim 400$  km s<sup>-1</sup> labeled H1, H2 and H3. These solar wind streams were preceded by the compressed magnetic field regions labeled C1, C2 and C3 in Figure 2(S1). As indicated in Figure 2(S3), the magnetic field polarity observed during the solar wind streams H1 and H2 was mostly outward (i.e., positive polarity), whereas for H3 it was inward (i.e., negative polarity). Interspersed between the decay of H1 and before the arrival of H2, an IP shock (first solid vertical line) was observed by STA at 12:02 UT on 2021 October 12. Following this shock, a period with enhanced magnetic field, with a clear rotation in  $\theta_B$  and low density suggests the presence of an ICME, although not all signatures typical of an ICME (Zurbuchen & Richardson 2006) are evident. In particular, a depression of  $T_p$  is not apparent and no suprathermal bidirectional electrons (BDEs) were observed<sup>5</sup>. A possible interpretation is that the main magnetic obstacle of this ICME was not fully intercepted by STA, and instead there was just a glancing encounter with its flank or the disturbed medium surrounding the ICME. The compressed field region C2 formed in front of H2 was preceded by an IP shock at 04:33 UT on 2021 October 14 (second vertical solid line) formed in the wake of the prior ICME structure.

The solar wind speed profile at PSP (Figure 2(P4)) also shows the passage of the solar wind streams H1, H2 and H3, although the speed enhancement seen at H1 was much more gradual than at STA, the speed increase associated with H2 was much briefer, and the passage of H3 more apparent. Note that PSP was at a heliolatitude  $\Lambda=3.7^\circ$  (i.e., a few degrees to the south of STA). Interspersed between the decay of H1 and prior to the arrival of H2, PSP observed a sequence of structures indicated by dashed vertical lines in Figure 2: (1) First an abrupt increase of  $|B|$  by a factor of  $\sim 1.4$  at 02:12 UT on 2021 October 11 accompanied by an increase of just  $\sim 10$  km s<sup>-1</sup> in  $V_p$ ,  $\sim 2$  cm<sup>-3</sup> in  $N_p$ , and no significant increase in  $T_p$ . (2) An increase of  $V_p$  by  $\sim 80$  km s<sup>-1</sup> at  $\sim 02:45$  UT, coinciding with a change of magnetic field orientation, but no changes in  $|B|$ ,  $N_p$  or  $T_p$ . (3) A crossing of the heliospheric current sheet with an abrupt magnetic field depression between 05:49 UT and 06:36 UT. (4) A gradual increase of  $V_p$  between 10:45 UT and 13:12 UT on 2021 October 11 reaching  $\sim 400$  km s<sup>-1</sup> associated with a gradual decrease of  $|B|$  and  $N_p$ . (5) An increase of  $|B|$  with some hints of rotation in  $\theta_B$  between 10:33 UT and 20:53 UT on 2021 October 12 (details of these structures numbered 1 through 5 will be found in Figure 7 below). Throughout this period no clear signatures of bidirectional suprathermal electrons (not shown here) were observed. Therefore, no clear signatures of an ICME passage were observed during this time interval. We interpret this complex sequence of structures propagating in the wake of H1 as a result of the interplay between the approaching solar wind stream H2, the eastern flank of the same ICME as observed by STA, and a small solar wind stream formed between H1 and the upcoming H2 discernible in Figure 3(d) as discussed below.

Figure 2(So4) shows that SoO, located closer to the Sun at  $R=0.68$  au and at lower latitudes ( $\Lambda=2.0^\circ$ ), observed only two main solar wind streams. Based on the magnetic field polarity and the corotation delay with respect to STA, we identify these two solar wind streams with H1 and H3. The increase of solar wind speed in the stream H1 occurred in two steps, resulting in a more structured increase in the magnetic field magnitude than that observed at STA. At the expected arrival time of H2 at SoO (i.e., around 2021 October 15-16), no significant increase of  $V_p$  was observed, although a period with compressed magnetic field is evident following the passage of an IP shock at 23:12 UT on 2021

<sup>3</sup> Level-2 preliminary moments derived from 1D Maxwellian fits are used in Figures 2(S4)-(S6) as retrieved from [https://ssc.nascom.nasa.gov/data/ins\\_data/plastic/level2/Protons/Derived\\_from\\_1D\\_Maxwellian/](https://ssc.nascom.nasa.gov/data/ins_data/plastic/level2/Protons/Derived_from_1D_Maxwellian/)

<sup>4</sup> Here we use the term ICME to identify the magnetically dominated region (historically called ejecta, e.g., Cane et al. 1997) that is usually (but not always) preceded by a dense sheath and an IP shock, whereas other researchers use ‘ICME’ to refer to the shock, sheath and ejecta as a whole (e.g., Temmer et al. 2021)

<sup>5</sup> [stereo.irap.omp.eu/plots.php](https://stereo.irap.omp.eu/plots.php)

October 14 during which the magnetic field changed from inward to outward polarity and then gradually changed back to inward polarity before the arrival of H3. During the decay of H1, an IP shock was observed by SolO at 07:32 UT on 2021 October 11, followed by an interval with signatures indicative of an ICME, such as a smooth magnetic field evolution with some rotation and a  $T_p$  depression. This interval is indicated by the gray shaded bar in the SolO panel of Figure 2, although the actual boundaries of the ICME are uncertain.

Considering observations at L1, Figure 2(E4) shows that the solar wind stream H1 started to arrive at L1 on 2021 October 11, preceded by the compressed field region C1 on 2021 October 10. However, the complete passage of H1 was interrupted by the arrival of an IP shock observed by ACE at 01:42 UT on 2021 October 12. This shock was followed by a period of  $\sim 29.5$  hours with signatures typical of the passage of an ICME (indicated by the gray shaded bar in the L1 panel of Figure 2). After the passage of the ICME, a slight increase of  $V_p$  on 2021 October 16 with outward magnetic field polarity could be associated with the solar wind stream H2. Finally on 2021 October 21, an inward-polarity solar wind speed increase can be identified with the passage of H3.

Assuming that the IP shocks observed by STA at 12:02 UT on 2021 October 12, by SolO at 07:32 UT on 2021 October 11, and by ACE at 01:42 UT on 2021 October 12 were associated with the CME on 2021 October 9, we infer an average transit speed of the shock to travel from the Sun to each spacecraft of  $\sim 512$  km s $^{-1}$  to STA,  $\sim 573$  km s $^{-1}$  to SolO, and  $\sim 615$  km s $^{-1}$  to ACE (assuming the onset time of the SXR emission of the solar flare with the corresponding time-light shift of 8.33 minutes was the time when the shock formed). However, if the abrupt magnetic field increase observed by PSP at 02:12 UT on 2021 October 11 were associated with the CME, this would imply a higher average transit speed for the shock to travel from the Sun to PSP of  $\sim 717$  km s $^{-1}$ . This higher speed would appear to be inconsistent with the greater longitudinal separation between PSP and the site of the parent solar flare than for the other spacecraft (Figure 1) and the expectation that shock speeds decrease with increasing distance from the nose of the shock (e.g., Smart & Shea 1985).

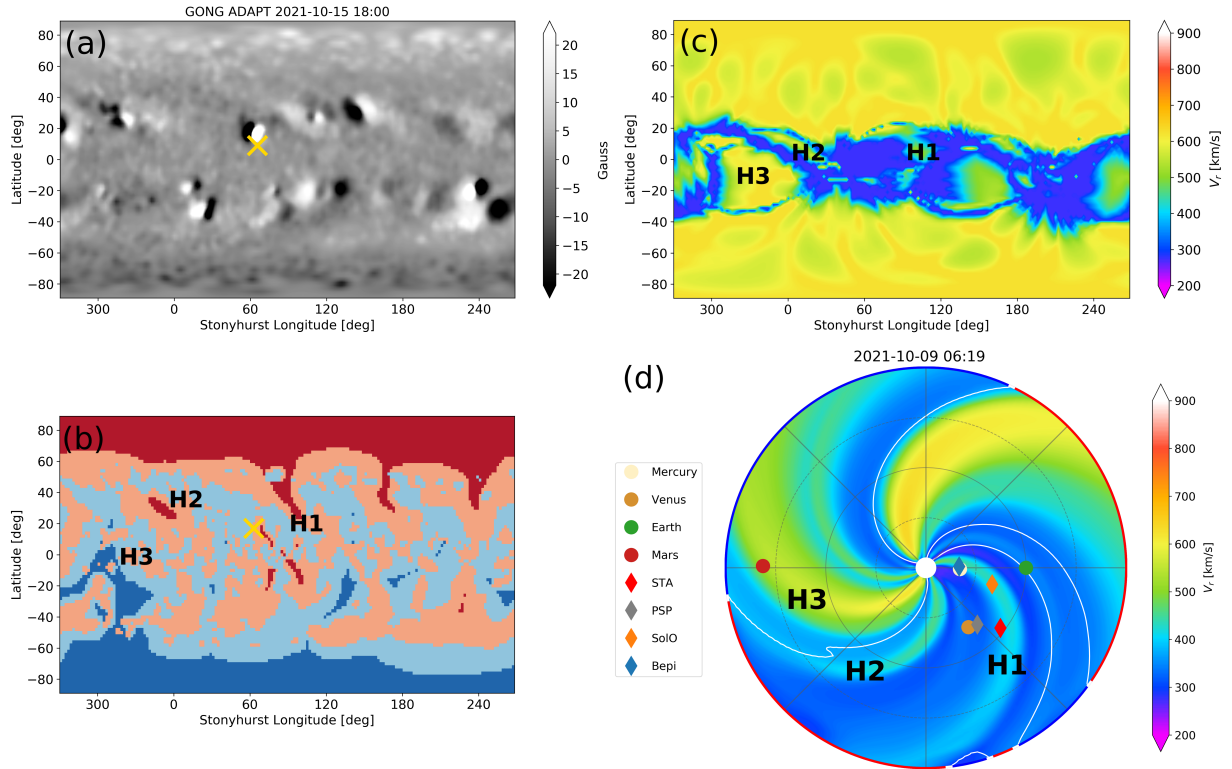
Large-scale MHD simulations of the inner heliosphere using the EUHFORIA model support our identification of the solar wind streams that are sequentially observed by these spacecraft. EUHFORIA<sup>6</sup> is a 3D MHD code that simulates the large-scale structure of the solar wind above a heliocentric distance of 0.1 au, by solving ideal MHD equations using boundary conditions derived from solar magnetograms in a semi-empirical manner (Pomoell & Poedts 2018). In particular, here we use the output provided by the Wang–Sheeley–Arge (WSA) model (Arge et al. 2004). The WSA model uses synoptic solar magnetic field maps derived from these magnetograms to create a coronal hole (CH) map coupling the potential field source surface (PFSS) and the Schatten current sheet models of the solar corona (Schatten et al. 1969; Schatten 1971). The use of empirical relationships between the solar wind radial velocity and magnetic field expansion factor that depend on the distance of a solar wind source region from the nearest CH boundary (Arge et al. 2004) allows us to infer the solar wind speed at the inner boundary of EUHFORIA. As input for the WSA model, we use an intermediate step based on applying first the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) to the GONG magnetogram (Arge et al. 2010; Henney et al. 2012; Hickmann et al. 2015). ADAPT produces an ensemble of 12 model realizations that are based on varying the model parameters used in the photospheric magnetic flux transport within a range of uncertainties that accounts for photospheric flows. These provide 12 synchronic maps of the Sun’s surface magnetic field that are used by WSA as boundary conditions to derive the coronal field out to 0.1 au. Field line tracing from 0.1 au down to the photosphere is used to determine open and closed field regions at  $1 R_\odot$  and thus generate CH maps (Wallace et al. 2019).

Here, we use the synoptic magnetogram map at 18:00 UT on 2021 October 15 provided by the National Solar Observatory (NSO) Global Oscillation Network Group (GONG)<sup>7</sup>. Figure 3(a) shows this GONG magnetogram map, where the yellow cross identifies the site of the solar eruption that generated the SEP event. The use of a magnetogram taken a few days after the occurrence of the solar flare allows us to accurately reproduce the solar wind streams H2 and H3 that originated in coronal holes located east of Earth at the time of the solar eruption.

Figure 3(b) shows the CH map used in these simulations where red (blue) indicates the outward (inward) polarity of the magnetic field at the CHs. Whereas the solar wind streams H1 and H2 originated in outward polarity CHs, H3 originated in an inward polarity CH. Figure 3(c) shows the solar wind speed map generated by the WSA-ADAPT model that is used as input to the EUHFORIA code at its inner boundary. Figure 3(d) shows solar wind speed contours obtained from the EUHFORIA simulation at the time of the onset of the SXR flare associated with the origin of the

<sup>6</sup> euhforia.com

<sup>7</sup> gong.nso.edu/

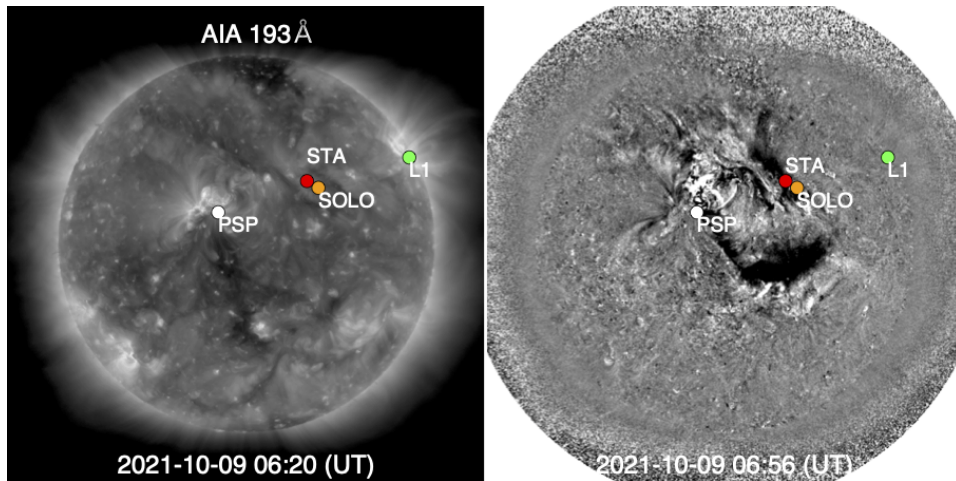


**Figure 3.** (a) GONG magnetogram at 18:00 UT on 2021 October 15 used in the EUHFORIA simulations. (b) Coronal hole map obtained from the ADAPT-WSA model using as input the synoptic magnetograms shown in panel (a). The red and blue regions indicate the outward and inward polarity of the CHs, respectively. (c) Velocity map at 0.1 au obtained by the WSA model and used as input for the EUHFORIA code. (d) Solar wind speed contour obtained from the EUHFORIA simulation at the time of the onset of the SXR solar flare (06:19 UT on 2021 October 9) at the Earth’s latitude ( $\Lambda=6^\circ$ ). The blue and red portions of the outer boundary (at 2 au) of the speed contour in panel (d) indicate the polarity of the magnetic field, and the white lines indicate the location of the heliospheric current sheet. The different symbols in panel (d) indicate the position of planets and spacecraft indicated in the legend. The yellow crosses in panels (a) and (b) indicate the site of the solar eruption origin of the SEP event. The letters H1, H2, and H3 indicate, in panel (b) the CHs that are the origin of the solar wind streams identified in Figure 2, in panel (c) the solar wind injected from each one of these CHs, and in panel (d) the structure of the solar wind streams as they corotate with the Sun.

209 SEP event and at the Earth’s latitude (i.e.,  $\Lambda=6^\circ$ ). The red and blue portions of the outermost circle of the solar wind  
 210 contour identify the field polarity, with H1 and H2 being outward polarity (red) and H3 inward (blue). According  
 211 to this simulation, at that time, PSP was located in the rarefaction region of H1, STA was in the tail of H1, SolO  
 212 and Bepi were within H1, and Earth was in a slow solar wind region ahead of the arrival of H1 that did not occur  
 213 until early on 2021 October 11. The EUHFORIA simulation agrees with the sequential observation of the solar wind  
 214 streams at the different spacecraft. Note that whereas the CH that is the origin of H1 extends close to the equator  
 215 with a fragmented structure, the CH associated with H2 is more concentrated at northern latitudes above  $\gtrsim 20^\circ$ , while  
 216 that associated with H3 is predominantly at southern latitudes (Figure 3b). The fact that the speed stream H3 was  
 217 more clearly observed for the spacecraft at lower heliolatitudes (PSP and SolO), and that the solar wind stream H2  
 218 was better observed at STA agrees with the EUHFORIA results. In fact, SolO at just  $\Lambda=2.0^\circ$  might have missed the  
 219 solar wind stream H2 although the magnetic field increases that were observed at that time might have been evidence  
 220 of an associated compression region. Additionally, Figure 3(d) also displays a faint solar wind stream between H1 and  
 221 H2 that could have contributed to the complex sequence of structures seen by PSP on 2021 October 11-12.

### 222 3. SOLAR ORIGIN: EUV AND WHITE LIGHT CORONAGRAPH OBSERVATIONS

223 The left panel of Figure 4 is a 193 Å bandpass image from the Atmospheric Imaging Assembly on board the Solar  
 224 Dynamics Observatory (SDO/AIA, Lemen et al. 2012) taken at 06:20 UT on 2021 October 9 prior to the occurrence of  
 225 the solar eruption that generated the SEP event. The white, red, orange, and green symbols indicate the locations of

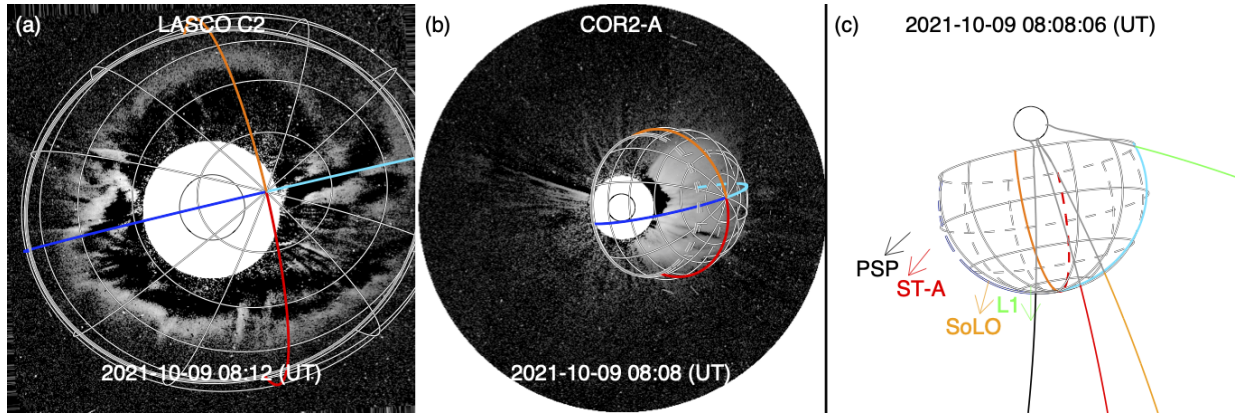


**Figure 4.** *Left panel:* SDO/AIA 193 Å image taken at 06:20 UT on 2021 October 9. The white, red, orange and green symbols indicate the footpoints of the field lines connecting to PSP, STA, SoLo and L1, respectively, assuming nominal Parker spiral field lines down to  $2.5 R_{\odot}$  and then a coronal field configuration obtained from the PFSS model. *Right panel:* Running difference image computed from SDO/AIA 193 Å intensity images taken at 06:56 UT and 06:52 UT on 2021 October 09 showing the limited extent of the EUV wave due to surrounding CHs.

the footpoints of the field lines connecting to PSP, STA, SoLo, and near-Earth spacecraft, respectively. These field lines have been computed assuming a nominal Parker spiral with the solar wind speeds listed in Figure 1 down to a distance of  $2.5 R_{\odot}$ , and then using the open field lines resulting from the potential field source surface (PFSS) model applied to a synoptic magnetogram obtained by the Helioseismic and Magnetic Imager on board SDO (SDO/HMI, Scherrer et al. 2012) at 06:04 UT on 2021 October 9. Note that the footpoint of the field line connecting to Bepi is not shown in Figure 4 for clarity purposes but is located in the same region as those of SoLo and STA. We have also considered the connections using a hypothetical solar wind speed of  $800 \text{ km s}^{-1}$  to mimic the sub-Parker field configuration found in the rarefaction regions formed in the tail of high-speed solar wind streams, where the magnetic field tends to be more radial than a nominal Parker spiral (e.g., Lario & Roelof 2010, and references therein). According to Figures 1, 2, and 3(d), this may be the case for PSP and STA. However, owing to the focusing of field lines spreading out from the CHs obtained from the PFSS model, the location of the PSP footpoint does not change with respect to that shown in Figure 4, whereas the footpoint of STA moves to the site of the PSP footpoint indicated in Figure 4. Moreover, during the decay of solar wind speed observed by PSP and STA at the time of the SEP event (Figures 2(P4) and 2(S4)), the magnetic footpoints of these spacecraft did not change their location as both spacecraft were in a solar wind “dwell” (Nolte & Roelof 1973). Hereafter, we will consider the spacecraft footpoints to be as depicted in Figure 4, and will indicate in each case the uncertainty in their location introduced by the possible sub-Parker magnetic fields in the tail of solar wind stream H1.

The animated version of Figure 4 (see also Figure 14 in Appendix A), has been built using 193 Å images from SDO/AIA and 195 Å images from the Extreme Ultraviolet Imager (EUVI, Wuelser et al. 2004) of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) on board STA, and shows the evolution of the EUV wave that expanded away from AR 12882 mostly to the west. The first signs of the initiation of an EUV eruption started after  $\sim 06:26$  UT. A well-formed EUV wave was seen to reach the PSP footpoint at  $06:32 \text{ UT} \pm 2 \text{ min}$ , then arrive at the footpoints of STA and SoLo at  $06:38 \text{ UT} \pm 2 \text{ min}$ . The expansion of the EUV was limited by coronal structures including coronal holes. Figure 3b shows the location of AR 12882 (yellow cross) and the CHs that limited the propagation of the EUV wave near the solar surface, including that associated with stream H1 northwest of the AR, the outward polarity CH extending southwest from the AR, and the southern inward (blue) polarity CH at Stonyhurst longitudes  $120^{\circ}$ - $140^{\circ}$ . The right panel of Figure 4 is a running-difference image computed from the 193 Å SDO/AIA intensity images taken at 06:56 UT and 06:52 UT on 2021 October 9. The darkest regions in the right panel of Figure 4 result from wave reflections at the east by the CH where PSP is connected, at the west by the CH where both STA and SoLo are connected, and at the south by the additional blue CH seen in Figure 3b. Details of the EUV reflections and the limited expansion of the EUV wave near the solar surface can be seen in the





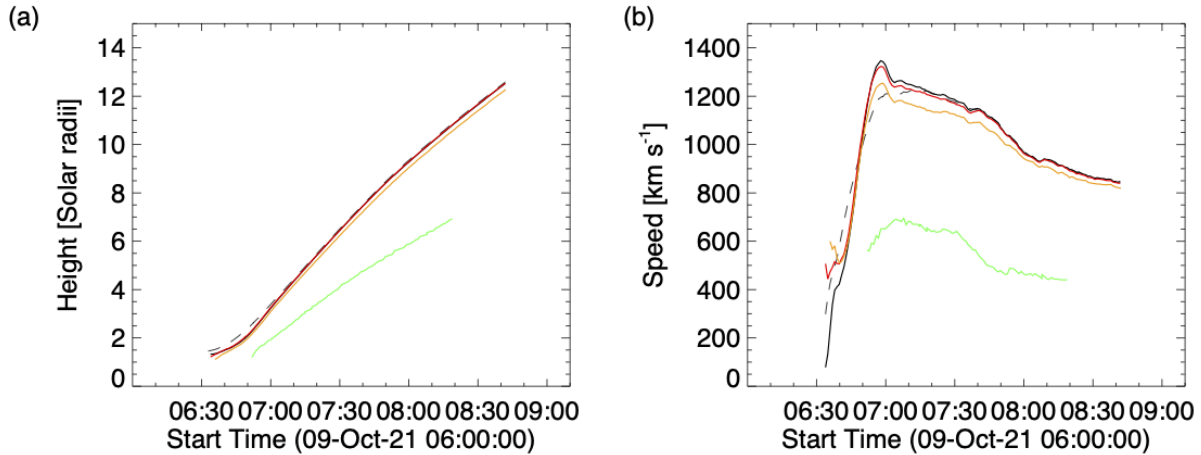
**Figure 5.** Running difference images from SOHO/LASCO/C2 (left panel) and STA/SECCHI/COR2 (middle panel) showing the CME and the ellipsoid (grid of lines with the red, orange, blue and cyan lines indicating each quadrant) fitting the outermost front of the CME. The right panel shows the ellipsoid shock front in the ecliptic plane as seen from the north ecliptic pole at 08:08 UT on 2021 October 9. The black, red, orange and green lines indicate the magnetic field lines connecting to PSP, STA, SoLO and L1, respectively, computed assuming nominal Parker field lines above  $2.5 R_{\odot}$  and the PFSS configuration below  $2.5 R_{\odot}$  (gray color is used for the portion of the field line inside the modeled ellipsoid). The black, red, orange, and green arrows indicate the radial direction to PSP, STA, SoLO and L1, respectively.

257 animated version of Figure 14 (Appendix A). A consequence of this limited EUV wave extent is that the wave was  
 258 not observed to reach the nominal magnetic footpoint for spacecraft at L1.

259 The distribution of spacecraft at the time of this solar eruption (Figure 1) was not optimal to determine the evolution  
 260 of the 3D structure of the shock driven by the CME at high altitudes. The two most distant coronagraphs in terms of  
 261 heliolongitude were on board SOHO and STA. The longitudinal separation of these two spacecraft was just  $\sim 39^{\circ}$ , which  
 262 does not provide us with a complete perspective of the expanding shock. Nevertheless, we have used WL observations  
 263 from the coronagraphs C2 and C3 of the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995)  
 264 on board SOHO, and from the COR1 and COR2 coronagraphs of SECCHI on board STA, in combination with the  
 265 EUV observations from SDO/AIA and STA/SECCHI/EUVI, to fit the large-scale structure of outermost front of the  
 266 CME identified as the coronal shock wave driven by the CME. We have applied the method developed by Kwon et al.  
 267 (2014) that uses an ellipsoid centered at a certain altitude  $h_E$  to describe the outermost front driven by the CME.  
 268 The first time when it was possible to fit an ellipsoid is 06:32 UT by using first the EUV observations. The last time  
 269 is when the outermost front of the CME reached the outer boundary of the COR2 field of view at 08:42 UT.

270 Figure 5 shows the shock wave as fitted by the ellipsoid overplotted on running difference images taken by (a)  
 271 LASCO/C2 and (b) STA/SECCHI/COR2. The fitted ellipsoid is shown by the grid of lines with the red, orange, blue,  
 272 and cyan colors indicating each quadrant. The geometric parameters of the ellipsoid are determined at each time step  
 273 by iterative fitting of the shock wave using all available EUV and WL observations selected as co-temporal as possible.  
 274 In order to obtain the best geometric parameters, such iterative fits are independently applied to different time steps.  
 275 The final parameters defining the ellipsoid are confirmed when their changes with time are smooth and the derived  
 276 quantities, such as the shock speed, are physically reasonable. At the beginning of the eruption (until  $\sim 06:45$  UT  $\pm 2$   
 277 minutes), the intersection of the ellipsoid with the solar surface spatially coincided with the EUV wave front. For later  
 278 times, the EUV wave expansion was limited, as indicated in Figure 4, whereas the shock seen in WL expanded to a  
 279 broader range of longitudes and latitudes. Eventually, the CME became a halo CME as seen from LASCO at around  
 280  $\sim 07:23$  UT, whereas from the STA point of view it propagated mostly over the west limb.

281 Figure 5c shows the ellipsoid projection on the ecliptic plane as seen from the north ecliptic pole. Note that, whereas  
 282 the longitude of the parent AR was at E09 $^{\circ}$ , the central axis of the fitted shock was directed toward a longitude E03 $^{\circ}$   
 283 at  $\sim 06:33$  UT, then shifted further westward, being along W09 $^{\circ}$  at  $\sim 08:32$  UT. In Figure 5(c) we have also plotted  
 284 field lines connecting to PSP (black), STA (red), SoLO (orange), and L1 (green) estimated using the nominal Parker  
 285 spiral lines down to a heliocentric distance of  $2.5 R_{\odot}$  and then using the PFSS model within this distance. Note that  
 286 the field line connecting to Bepi practically coincides with the SoLO nominal field line, and for clarity purposes, it  
 287 is not displayed in Figure 5c. PSP, STA, SoLO and Bepi connected close to the nose of the fitted shock, while L1  
 288 connected closer to the western flank of the shock. To determine the angular width of the shock, we use projections of



**Figure 6.** *Left panel:* Height versus time of the PSP (black), STA (red), SolO (orange) and L1 (green) cobpoints and the nose of the shock (dashed black line). *Right panel:* Shock speed versus time at the cobpoints of PSP (black), STA (red), SolO (orange) and L1 (green) and at the nose of the shock (dashed black line).

289 the ellipsoid structure onto the plane of the images such that a satisfactory fit to the outermost front shock is found  
 290 (see details in Figure 2 of Kwon & Vourlidas 2017). The arrows in Figure 5(c) indicate the radial direction to each  
 291 spacecraft. Note that at the passage of the shock, there is likely to be a change in the direction of the field lines;  
 292 therefore we plot the field lines in gray when they remain inside the fitted ellipsoid, whereas the colored portions of  
 293 the field lines in Figure 5(c) indicate the field configuration found upstream of the shock as it expanded away from the  
 294 Sun. Whereas Figure 5 shows the structure of the fitted shock for a given time, the animated version of Figure 5 (see  
 295 also Figure 15 in Appendix A) shows the evolution of the fitted ellipsoid as the CME was seen to expand using first  
 296 EUV observations, and then observations from STA/SECCHI/COR1, SOHO/LASCO/C2, STA/SECCHI/COR2, and  
 297 SOHO/LASCO/C3.

298 By using the field lines depicted in Figure 5c, we can estimate when the fitted shock intercepted these field lines, and  
 299 hence estimate the height of the intersection point between the fitted shock and the field lines. This point is known  
 300 as the Connecting with the OBserver point, or “cobpoint” (after Heras et al. 1995). The left panel of Figure 6 shows,  
 301 as a function of time, the heliocentric radial distance of the cobpoints of PSP (black), STA (red), SolO (orange), and  
 302 L1 (green), as well as the heliocentric distance of the nose of the shock (dashed black line). Owing to the coincidence  
 303 between the nominal field lines connecting to Bepi and SolO, the cobpoint of Bepi coincides with that of SolO. We  
 304 estimate that PSP established magnetic connection with the fitted shock shortly after the solar eruption at a time  
 305  $<06:33$  UT, STA at  $06:34$  UT  $\pm 1$  min, SolO and Bepi at  $06:36$  UT  $\pm 1$  min. The error bars assigned to these connection  
 306 times are based on the assumption that there is an uncertainty of  $\sim 7\%$  in the geometry of the ellipsoid (see Kwon  
 307 et al. 2014). Because L1 connected close to the shock flank, the L1 connection time is also subject to the uncertainty  
 308 in the shock angular width, in addition to the general uncertainty in the shock geometry. We determine that the fitted  
 309 shock intercepted the field line connecting to L1 as early as  $06:50$  UT when considering the upper uncertainty values  
 310 of the shock geometry, but delayed to  $07:02$  UT when considering a more conservative approach, that is a few minutes  
 311 before the WL shock front started extending around the far side of the Sun with respect to the site of the parent  
 312 eruption (see animated version of Figure 15 in Appendix A).

313 The time-height profiles shown in the left panel of Figure 6 allow us to estimate the speed of the shock at the  
 314 cobpoints. The right panel of Figure 6 shows that the shock expanded quite slowly ( $\lesssim 500$  km s<sup>-1</sup>) at the beginning of  
 315 its expansion, until  $\sim 06:40$  UT when it accelerated, reaching a maximum speed of  $\sim 1250$  km s<sup>-1</sup> at about  $\sim 07:10$  UT,  
 316 and then it gradually decelerated. L1 spacecraft established magnetic connection with the western flank of the shock,  
 317 where the speed was much slower ( $\lesssim 700$  km s<sup>-1</sup>) and decayed faster than for the other cobpoints. The uncertainty in  
 318 the magnetic footpoint site for STA, allowing for possible sub-Parker field structure in the tail of stream H1 moving  
 319 the footpoint to the site of the PSP footpoint, does not significantly change the height and speed of the cobpoint, due  
 320 to the similarity between the red (STA) and black (PSP) lines in Figure 6.

## 4. ENERGETIC PARTICLE OBSERVATIONS

## 4.1. PSP energetic particle observations

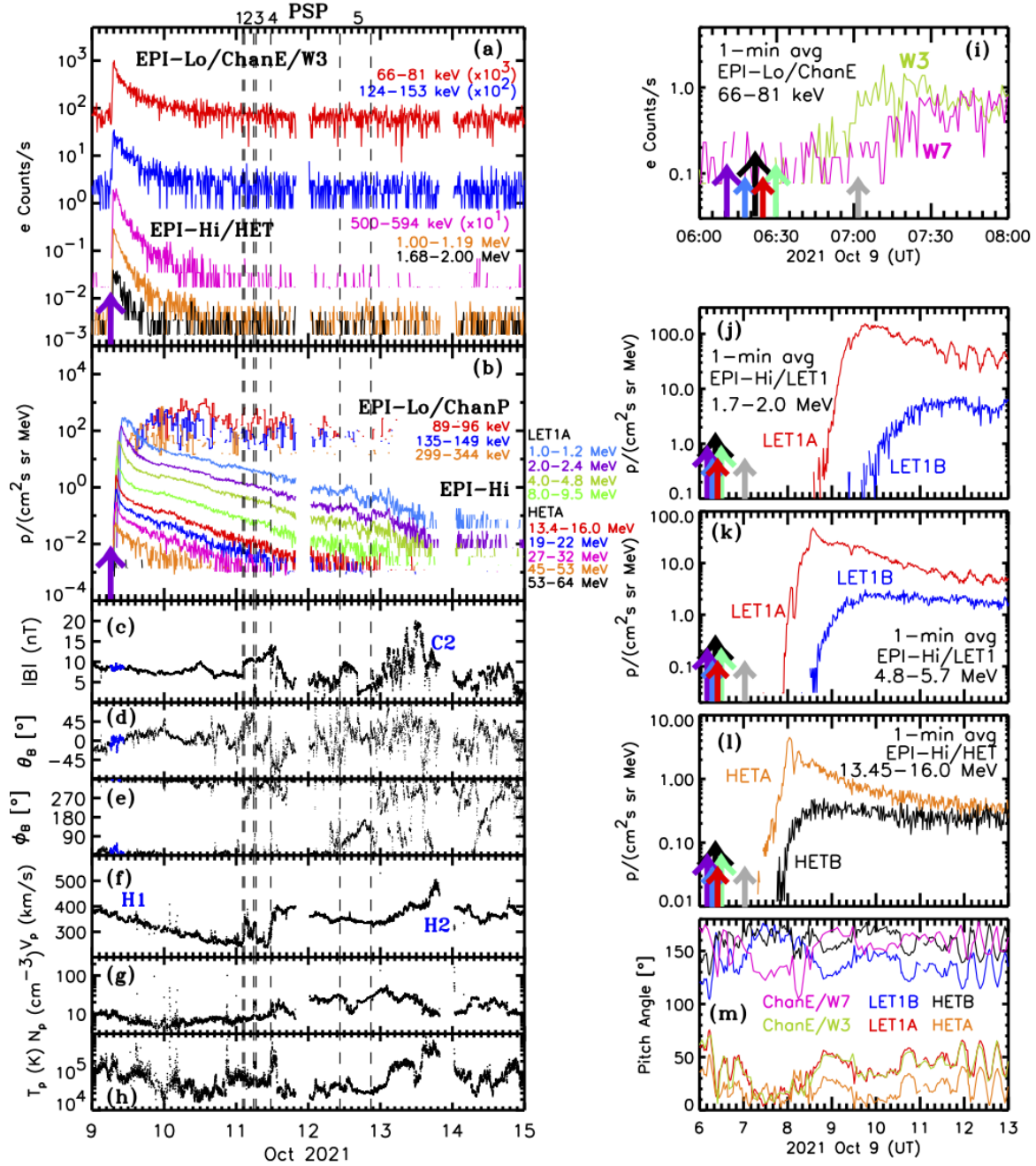
Figure 7 shows PSP in-situ measurements during the SEP event. We use data from the Energetic Particle Instruments (EPs) of the Integrated Science Investigation of the Sun (IS $\odot$ IS; McComas et al. 2016) on board PSP, the magnetometers from FIELDS and solar wind moment fits from SWEAP/SPC. IS $\odot$ IS consists of two energetic particle instruments: (1) EPI-Lo, which comprises 80 apertures separated into 8 wedges and measures particles using the time-of-flight versus energy technique, and determines the composition, spectra, and anisotropies of particles with energies from  $\sim 20$  keV nucleon $^{-1}$  to several MeV nucleon $^{-1}$  (Hill et al. 2017), and (2) EPI-Hi, which comprises three telescopes and uses the dE/dx versus residual energy technique to measure particles over the energy range of  $\sim 1$ –200 MeV nucleon $^{-1}$  (Wiedenbeck et al. 2017). In particular, we use electron intensities (ChanE data product) measured by EPI-Lo in the wedges 3 and 7, and proton intensities measured by the triple coincidence data system (ChanP data product) of EPI-Lo (Hill et al. 2017). We also use proton intensities measured by the double-ended Low Energy Telescope (LET1) and the double-ended High Energy Telescope (HET) of EPI-Hi.

The left column of Figure 7 shows, from top to bottom, (a) 10-minute averages of near-relativistic electron intensities measured by the wedge 3 of EPI-Lo/ChanE (two top traces) and the side A of the HET telescope of EPI-Hi (three bottom traces), (b) 30-minute averages of the proton intensities measured by EPI-Lo/ChanP averaged over all the apertures of the instrument (except for the apertures 3 and 10 blocked by EPI-Hi, 11 and 12 due to partial effects of the EPI-Hi blockage, and those affected by dust impacts as listed in IS $\odot$ IS release notes<sup>8</sup>), 10-minute averages of the proton intensities measured by the side A of EPI-Hi/LET1 (i.e., LET1A) and by the side A of EPI-Hi/HET (i.e., HETA), (c) the magnetic field magnitude, (d) the elevation angle of the magnetic field vector in RTN coordinates, (e) the azimuth angle of the magnetic field vector in RTN coordinates, and the proton solar wind (f) speed, (g) density, and (h) temperature.

The onset of the SEP event occurred during the decay of the solar wind speed observed in the tail of stream H1 (Figure 7f). During this period, radial outward-polarity magnetic field was constantly observed (Figure 7e) until the arrival of the complex sequence of structures on 2021 October 11 described in Section 2 (vertical dashed lines in Figures 7a-h). During this period of radial magnetic field, as typically observed during the tail of high-speed solar wind streams (e.g., Lario & Roelof 2010), the magnetic field also exhibits a decay in the amplitude of its fluctuations (e.g., Borovsky & Denton 2016; Carnevale et al. 2022). Figure 4 shows that the site of the PSP magnetic footpoint before the solar eruption was very close to AR 12882. As seen from PSP, AR 12882 was at a longitude W39 $^{\circ}$ . The nose of the fitted shock described in Section 3 shifted from W45 $^{\circ}$  to W57 $^{\circ}$  with respect to PSP during its first stages of propagation. Therefore, the observation of particle intensities reaching a peak shortly after the occurrence of the parent solar event followed by gradual decay, is consistent with the typical intensity-time profiles observed at 1 au for SEP events originating from western longitudes (e.g., Cane et al. 1988). The arrival of the interplanetary structures on 2021 October 11 described in Section 2 (dashed vertical lines in Figures 7a-h with the numbers 1 through 5 on the top) did not result in any significant change in the rate of decay of the  $\gtrsim 1$  MeV proton intensities.

Figures 7i-l focus just on a few hours around the onset of the SEP event as seen by the EPI-Lo and EPI-Hi telescopes used here. In particular, Figure 7i shows the ChanE 66-81 keV electron intensities measured in wedges 3 (green) and 7 (pink) of EPI-Lo from 06:00 UT to 08:00 UT on 2021 October 9. Figures 7j-l show measurements of proton intensities from 06:00 UT to 13:00 UT on 2021 October 9. In particular, Figures 7j and 7k show the enhancement of the 1.7-2.0 MeV and 4.8-5.7 MeV proton intensities, respectively, as measured by side A (red) and side B (blue) of EPI-Hi/LET1. Figure 7l shows the enhancement of 13.45-16.0 MeV proton intensities measured by side A (orange) and side B (black) of EPI-Hi/HET. Because of their orientations, these telescopes were scanning different regions of the sky with respect to the magnetic field direction and hence detecting particles with different pitch angles. Figure 7m shows the pitch angles along the direction of the geometric center of the wedges 3 and 7 of EPI-Lo (see Mitchell et al. 2021, for details of the individual field of views (FOVs) of the EPI-Lo apertures with respect to the geometric center of each wedge), and of the central axis of each side of the EPI-Hi telescopes using the same color code as in Figures 7i-l. In Appendix B we provide details of the pitch angles scanned by the ten apertures of the wedges 3 and 7 of EPI-Lo and by the whole aperture of the sides A and B of EPI-Hi/LET1 and EPI-Hi/HET. When considering the apertures of the telescopes, the range of pitch angles extend over a wider region than those plotted in Figure 7m but centered

<sup>8</sup> spp-isois.sr.unh.edu/Release-Notes.html



**Figure 7.** PSP measurements of the SEP event. *Left column:* (a) near-relativistic electron intensities measured by the wedge 3 of EPI-Lo (two top traces), and EPI-Hi/HET-A (three bottom traces), (b) 30-min averages of the energetic proton intensities measured by EPI-Lo/ChanP (three top traces), 10-min averages of the proton intensities measured by EPI-Hi/LET1A (four next traces) and by EPI-Hi/HETA (five bottom traces), (c) magnetic field magnitude, (d) magnetic field elevation angle, (e) magnetic field azimuthal angle in spacecraft-centered RTN coordinates, (f) solar wind proton speed, (g) solar wind proton density, and (h) solar wind proton temperature. H1 indicates the tail of the first solar wind stream and C2 the passage of the magnetic field compression region preceding the passage of the solar wind stream H2. The dashed vertical lines indicate the passage of different IP structures numbered from 1 to 5 described in Section 2. *Right column:* (i) 1-minute averages of the 66–81 keV electron intensities measured by the wedges 3 (green) and 7 (pink) of EPI-Lo (ChanE product), 1-minute averages of (j) 1.7–2.0 MeV and (k) 4.8–5.7 MeV proton intensities measured by the double-ended LET1 telescope (LET1A in red and LET1B in blue), (l) 1-minute averages of 13.45–16.0 MeV proton intensities measured by the double-ended HET telescope (HETA in orange and HETB in black), (m) pitch-angle scans by the central axis of each side of LET1 (red and blue), HET (orange and black) and the geometric center of the wedges W3 and W7 of EPI-Lo (green and pink). The purple arrows in panels (a–b) and (i–l) indicate the onset time of the SXR emission of the solar flare associated with the origin of the SEP event. The blue, black, green, red and gray arrows in panels (i–l) indicate the time when the first EUV wave activity was detected, the onset of the metric type III radio burst, the peak of the SXR flare was observed, the fitted ellipsoid magnetically connected to PSP, and the fitted shock reached its maximum speed, respectively (all these times are shifted back to the Sun by the light transit time to 1 au).

around the lines in Figure 7m. While the orientation of the magnetic field was relatively constant during this time interval (indicated by blue portion of the magnetic field traces in Figures 7c-e), the scanned pitch angles also vary due to maneuvers performed by the spacecraft, especially between 06:15 UT and 06:26 UT and during a sequence of rolls starting at  $\sim 11:00$  UT. Despite these maneuvers, LET1A, HETA and wedge 3 of EPI-Lo predominantly scanned small pitch angles, whereas LET1B, HETB and wedge 7 of EPI-Lo scanned large pitch angles (see also Figure 16 in Appendix B for the complete pitch angle coverage of each telescope). Therefore, the observations suggest that the onset of the SEP event at PSP was highly anisotropic, with small pitch angle particles traveling away from the Sun being predominant. In fact, the event was so anisotropic that the changes of pitch angle scanned by LET1A due to the spacecraft maneuvers starting at  $\sim 11:00$  UT led to oscillations in the intensities measured by LET1A (Figures 7j-k).

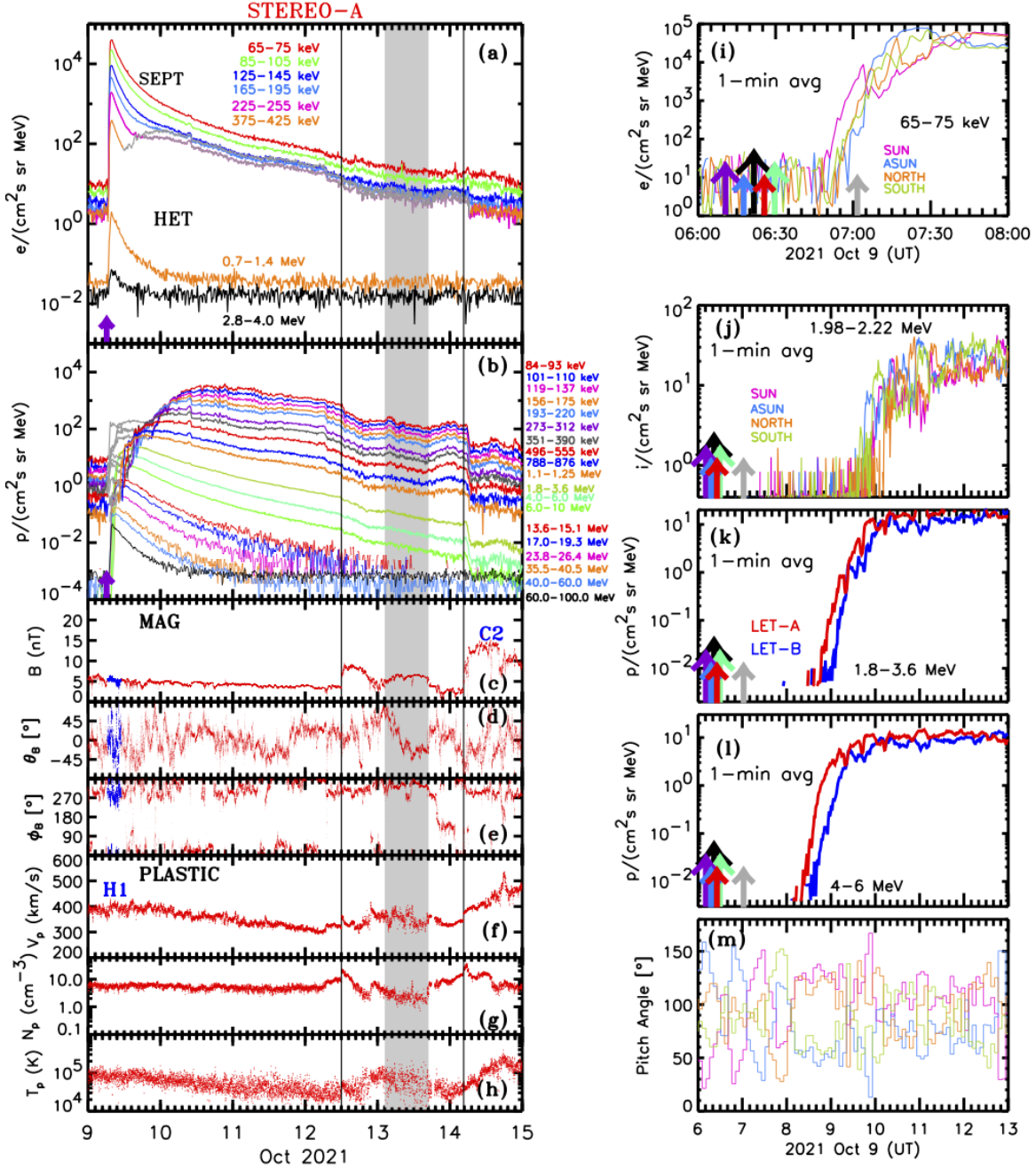
#### 4.2. STEREO-A energetic particle observations

Figure 8 shows in detail STA in-situ data during the SEP event. We use energetic particle observations made by the Solar Electron and Proton Telescope (SEPT; Müller-Mellin et al. 2008), the Low-Energy Telescope (LET; Mewaldt et al. 2008), and the High Energy Telescope (HET; von Rosenvinge et al. 2008) of the IMPACT suite of instruments on board STA; magnetic field measurements from the IMPACT magnetometer, and solar wind plasma measurements from PLASTIC.

From top to bottom, the left column of Figure 8 shows (a) near-relativistic electron intensities as observed by STA/SEPT (six top traces at energies below 425 keV) and by STA/HET (two bottom traces at energies above 700 keV), (b) ion intensities observed by STA/SEPT (ten top traces at energies below 1.25 MeV), proton intensities observed by STA/LET (three greenish lines at energies between 1.8 MeV and 10 MeV) and by STA/HET (six bottom traces at energies above 13.8 MeV), (c) the magnetic field magnitude  $|B|$ , (d) the elevation angle  $\theta_B$  of the magnetic field vector in RTN coordinates, (e) the azimuth angle  $\phi_B$  of the magnetic field vector in RTN coordinates, and the proton solar wind (f) speed  $V_p$ , (g) density  $N_p$ , and (h) temperature  $T_p$ . The gray portion of the SEPT electron traces in Figure 8(a) indicate periods when electron intensities measured by STA/SEPT were most likely contaminated by ions, whereas the gray portion of the ion SEPT traces in Figure 8(b) indicate periods at the onset of the event when ion intensities were most likely contaminated by penetrating electrons (Wraase et al. 2018). The solid vertical lines in Figures 8(a-h) indicate the passage of two IP shocks, at 12:02 UT on 2021 October 12, and 04:31 UT on 2021 October 14. It is unlikely that the second shock was associated with the CME on 2021 October 9 since this would imply an average transit speed of just  $\sim 338$  km s $^{-1}$ . Instead, the time profiles of  $V_p$ ,  $N_p$  and  $T_p$  observed after the passage of this shock (Figures 2(S4)-(S6)) suggest that the shock was most likely driven by the compression region C2 formed in front of stream H2, which is evident on October 14. On the other hand, the first shock was followed by a period reminiscent of an ICME (gray shaded bar in Figures 8a-h) that could be related to a glancing encounter with the CME that generated the SEP event. The passage of this ICME-related structure at STA lasted only  $\sim 14.5$  hours, which is comparable to the  $\sim 14.3$  hours duration of the sheath. This is consistent with STA intercepting just the flank of the ICME as the sheath usually increases in thickness from the nose of the ICME towards the flanks (Kilpua et al. 2017).

As seen from STA, the parent AR 12882 was at a longitude W30 $^\circ$ , and the nose of the fitted shock described in Section 3 shifted from W36 $^\circ$  to W48 $^\circ$  with respect to STA. Therefore, as expected, the energetic particle intensity-time profile at STA is typical of SEP events originating from western longitudes (e.g., Cane et al. 1988), reaching peak intensity shortly after the occurrence of the parent solar event followed by a gradual decay. This decay was much faster at proton energies  $\gtrsim 2$  MeV than at lower energies. This is probably because the approaching shock was still able to inject particles on its way to STA, although the scattering of low-energy protons throughout their transport toward the spacecraft may also have contributed to their slower intensity decay. There was no increase in the energetic particle intensities in the vicinity of the shock at 12:02 UT on 2021 October 12, suggesting that there was no local acceleration at the shock, at least at the energies displayed in Figure 8b.

Similarly to PSP, the onset of the SEP event occurred during the decay of the solar wind speed  $V_p$  in solar wind stream H1 (Figure 8f) where the magnetic field polarity was mostly outward, with some periods being close to the radial direction (Figure 8e). Figures 8i-l show in detail just a few hours around the onset of the SEP event as seen by STA/SEPT and STA/LET. In particular, Figures 8i and 8j show, respectively, the 65-75 keV electron and the  $\sim 2$  MeV ion intensity enhancements as measured by the STA/SEPT. The SEPT instrument comprises two double-ended telescopes with a total of four apertures pointing in different directions, termed SUN, ASUN, NORTH and SOUTH (Müller-Mellin et al. 2008). Because STEREO-A made a roll of 180 $^\circ$  about the spacecraft-Sun line on 2015 July 20, the SUN aperture, that originally pointed toward the Sun along the direction of the nominal Parker spiral direction,



**Figure 8.** STA measurements of the SEP event. *Left column:* (a) near-relativistic electron intensities measured by STA/SEPT (first six top traces), and STA/HET (two bottom traces), (b) energetic ion intensities measured by STA/SEPT (ten top traces), proton intensities measured by STA/LET (three green traces) and by STA/HET (six bottom traces), (c) magnetic field magnitude, (d) magnetic field elevation angle, (e) magnetic field azimuthal angle in RTN coordinates, (f) solar wind proton speed, (g) solar wind proton density, and (h) solar wind proton temperature. The solid vertical lines indicate the passage of shocks and the gray shaded bar the structure reminiscent of an ICME. H1 indicates the tail of the first solar wind stream and C2 the passage of the magnetic field compression region preceding the passage of the solar wind stream H2. Gray traces in panels (a) indicate periods when the electron intensities are most likely contaminated by ions, whereas gray traces in panels (b) indicate periods when ion intensities are most likely contaminated by electrons. *Right column:* (i) 65-75 keV electron and (j)  $\sim 2$  MeV ion intensities measured by the different apertures of STA/SEPT at the onset of the SEP event, (k-l) proton intensities measured by the side-A (red) and side-B (blue) of STA/LET at two energy channels, (m) pitch-angle scanned by the central axis of each aperture of STA/SEPT using the same color code as in (i) and (j). The purple arrows in panels (a-b) and (i-l) indicate the onset time of the SXR emission of the solar flare associated with the origin of the SEP event. The blue, black, green, red and gray arrows in panels (i-l) indicate the time when the first EUV wave activity was detected, the onset of the metric type III radio burst, the peak of the SXR flare was observed, the fitted ellipsoid magnetically connected with STA, and the fitted shock reached its maximum speed, respectively (all these times are shifted by the light transit time to 1 au).

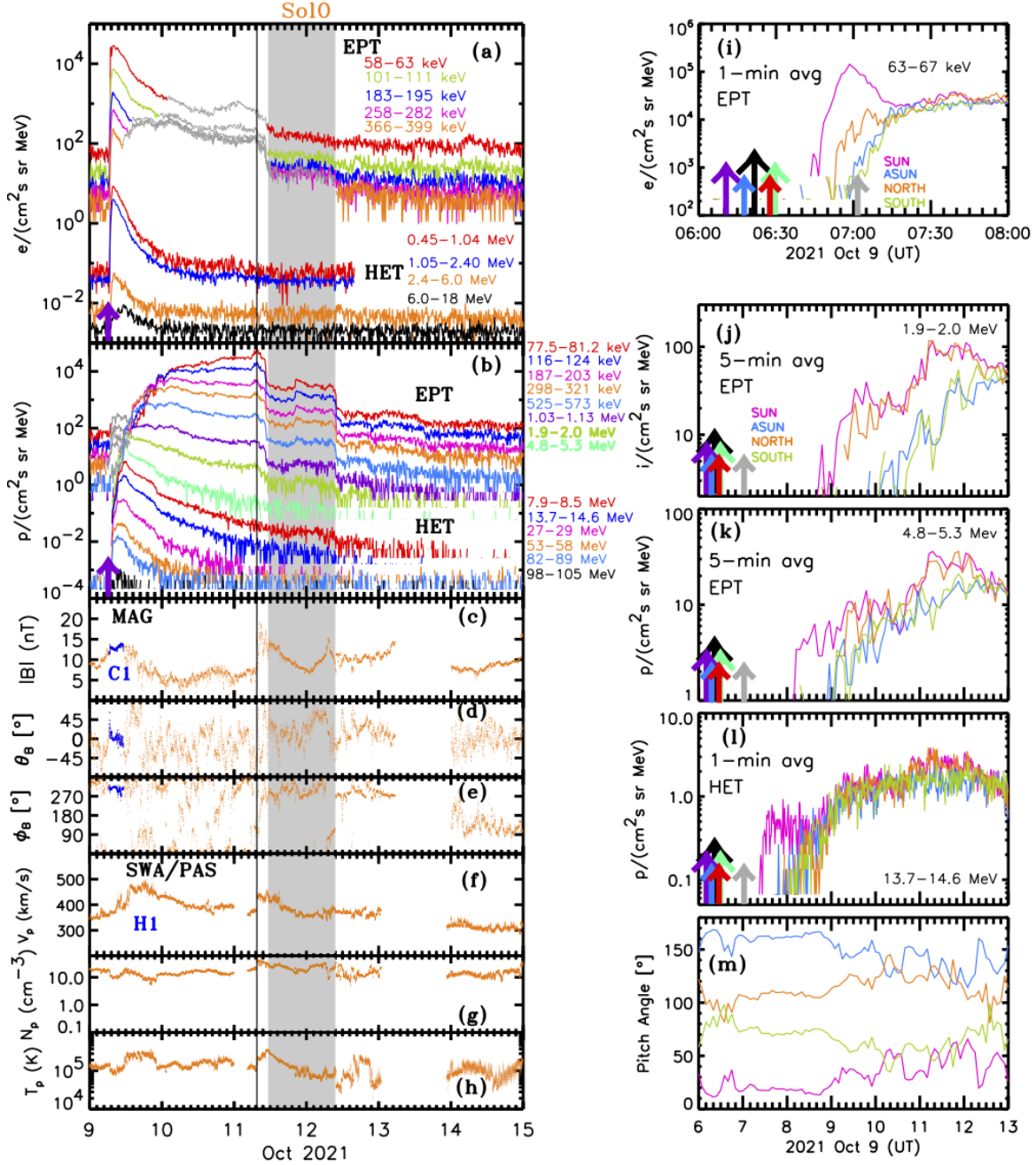
on 2021 October 9 pointed perpendicular to the nominal Parker spiral direction in the ecliptic in the [-R,-T] quadrant, whereas the ASUN aperture happened to point in the opposite direction in the [+R,+T] quadrant. The NORTH and SOUTH apertures of STA/SEPT pointed perpendicular to the ecliptic plane in the south and north direction, respectively. The colored lines in Figure 8m show the pitch-angles associated with the directions of the central axis of each STA/SEPT apertures, indicating that pitch-angles around  $0^\circ$  and  $180^\circ$  (i.e., parallel/anti-parallel to the magnetic field direction) were poorly scanned. The complete range of pitch angles scanned by the whole field of view (FOV) of each one of the four SEPT apertures is provided in Appendix B. The fluctuations in the scanned pitch angles are a consequence of the oscillating magnetic field orientation (mainly in  $\theta_B$ ) as shown by the highlighted blue intervals in Figures 8c-e. Figures 8m and 16(S1) show that the STA/SEPT configuration during the event on 2021 October 9 was not ideal for detecting the first arriving particles if they were propagating along the magnetic field direction. Note also that the gray portion of the intensity time profiles in Figure 8b at the onset of the SEP event (indicating periods when ion intensities may be dominated by electron contributions) prevents the analysis of the onset of the ion event at low energies. Nonetheless, Figure 8i shows that the onset of the event seen in the 65-75 keV electron energy channel was anisotropic, with the first enhancement seen by STA/SEPT/SUN at  $\sim 06:47$  UT $\pm 1$  minute, whereas the intensities at the other apertures increased at 06:52 UT $\pm 1$  minute. Figure 8j shows that the  $\sim 2$  MeV ion intensities increased at around 09:40 UT $\pm 5$  minutes, first in the ASUN and SOUTH apertures, when these two apertures were scanning small pitch angles (Figure 8m).

The STA/LET instrument provides also some anisotropy information (Mewaldt et al. 2008) by measuring sectorized rates in 16 different viewing directions, distributed in two fans each spanning  $129^\circ$  of longitude in the ecliptic and  $\sim 30^\circ$  of latitude out of the ecliptic. In the spacecraft configuration at the time of the solar event, the central axis of one of the fans (side-A) pointed  $45^\circ$  east of the Sun in the [-R,-T] direction (i.e., perpendicular to the nominal Parker spiral direction), whereas the opposite fan (side-B) pointed in the [+R,+T] direction (i.e., still perpendicular to the nominal Parker spiral direction). Since this configuration is similar to that of the SUN and ASUN apertures of SEPT, the pitch angles scanned by the side-A and side-B of STA/LET were similar to those scanned by the SEPT/SUN and SEPT/ASUN apertures, respectively, shown in Figure 8m (see also Figure 16(S2) in Appendix B). Figures 8k-l show the averages of the intensity measured in the 8 sectors of side-A (red) and side-B (blue) of STA/LET. The onset of the event at the energies measured by LET also showed some anisotropy, as suggested by the differences in the particle intensities seen by LET-A and LET-B, but the orientation of LET was not appropriate to infer the time of the first arriving particles and hence their release time at the Sun, because it did not scan small pitch angles corresponding to particles propagating along the magnetic field. STA/HET had a similar orientation to STA/SEPT/SUN, and hence scanned particles with similar pitch angles as the SEPT/SUN aperture. Therefore, it was also not suitably oriented for the detection of the first arriving particles, if they were propagating along the magnetic field. In Section 5 we estimate the release time of the first particles observed by STA/HET, with the caveat that most likely, those particles were not the first to arrive at STA.

#### 4.3. *Solo energetic particle observations*

Figure 9 shows detailed observations of the SEP event at Solo. We use energetic particle data from the Electron and Proton Telescope (EPT) and the High-Energy Telescope (HET) of the Energetic Particle Detector (EPD) instrument suite (Rodríguez-Pacheco et al. 2020) on board Solo, magnetic field data from the magnetometer on Solo and solar wind plasma measurements from Solo/SWA/PAS. Solo/EPT and Solo/HET have each one four apertures, termed SUN, ASUN, NORTH, and SOUTH, that scan different regions of the sky. The corresponding Solo/EPT and Solo/HET apertures share the same orientation, with the center of their FOVs pointing in the same direction but with different opening angles of  $30^\circ$  for Solo/EPT and  $43^\circ$  for Solo/HET (cf. Figure 4 and Table 2 of Rodríguez-Pacheco et al. 2020). The five top traces in Figure 9a show near-relativistic electron intensities measured by Solo/EPT/SUN and the four bottom traces relativistic electron intensities measured by Solo/HET/SUN. The eight top traces of Figure 9b show ion intensities measured by Solo/EPT/SUN and the six bottom traces proton intensities measured by Solo/HET/SUN. As Solo/EPT is very similar in construction as STA/SEPT, it suffers similar cross contamination issues detecting electrons in the ion channels at the onset of the SEP events, as well as  $\gtrsim 400$  keV ions populating the electron channels when these ions become more abundant than electrons (Wimmer-Schweingruber et al. 2021). The periods affected by such contamination are indicated by the gray portions of the intensity traces in Figures 9a and 9b.

The particle intensity-time profiles at Solo are typical of an SEP event generated from longitudes near central meridian (Cane et al. 1988). The longitudinal separation between the site of the parent AR and Solo was just  $6^\circ$ ,



**Figure 9.** SolO measurements of the SEP event. *Left column:* (a) near-relativistic electron intensities measured by SolO/EPT (first five top traces), and SolO/HET (four bottom traces), (b) energetic ion intensities measured by SolO/EPT (eight top traces), and proton intensities measured by SolO/HET (six bottom traces), (c) magnetic field magnitude, (d) magnetic field elevation angle, (e) magnetic field azimuthal angle in RTN coordinates, (f) solar wind proton speed, (g) solar wind proton density, and (h) solar wind proton temperature. The solid vertical line indicates the passage of the CME-driven shock (the passage of the ICME is indicated by the gray shaded bar). H1 indicates the passage of the solar wind stream preceded by the compressed field region C1. Gray traces in panels (a) indicate periods when the electron intensities are most likely contaminated by ions, whereas gray traces in panels (b) indicate periods when ion intensities are most likely contaminated by electrons. *Right column:* (i) 63-67 keV electron and (j)  $\sim 2$  MeV ion intensities measured by the different apertures of SolO/EPT at the onset of the SEP event, (k-l) proton intensities measured by the different apertures of SolO/HET at two energy channels, (m) pitch-angle scanned by the central axis of the SolO/EPT and SolO/HET apertures. The purple arrows in panels (a-b) and (i-l) indicate the onset time of the SXR emission of the solar flare associated with the origin of the SEP event. The blue, black, green, red and gray arrows in panels (i-l) indicate the time when the first EUV wave activity was detected, the onset of the metric type III radio burst, the peak of the SXR solar flare was observed, the fitted ellipsoid magnetically connected with SolO, and the fitted shock reached its maximum speed, respectively (all these times are shifted by the light transit time to 1 au).



whereas the nose of the shock fitted to EUV and WL observations propagated at a longitude that shifted from W12 to W24 with respect to SolO. Both near-relativistic electron intensities and proton intensities at energies above  $\gtrsim 5$  MeV displayed a rapid rise shortly after the occurrence of the parent solar eruption followed by a gradual decay. By contrast, ion intensities at energies  $\lesssim 500$  keV remained flat or kept increasing until the arrival of the shock, presumably driven by the CME, at 07:32 UT on 2021 October 11. A local peak at the time of the shock passage indicates that the shock was most likely still able to accelerate  $\lesssim 2$  MeV ions at its arrival at 0.68 au.

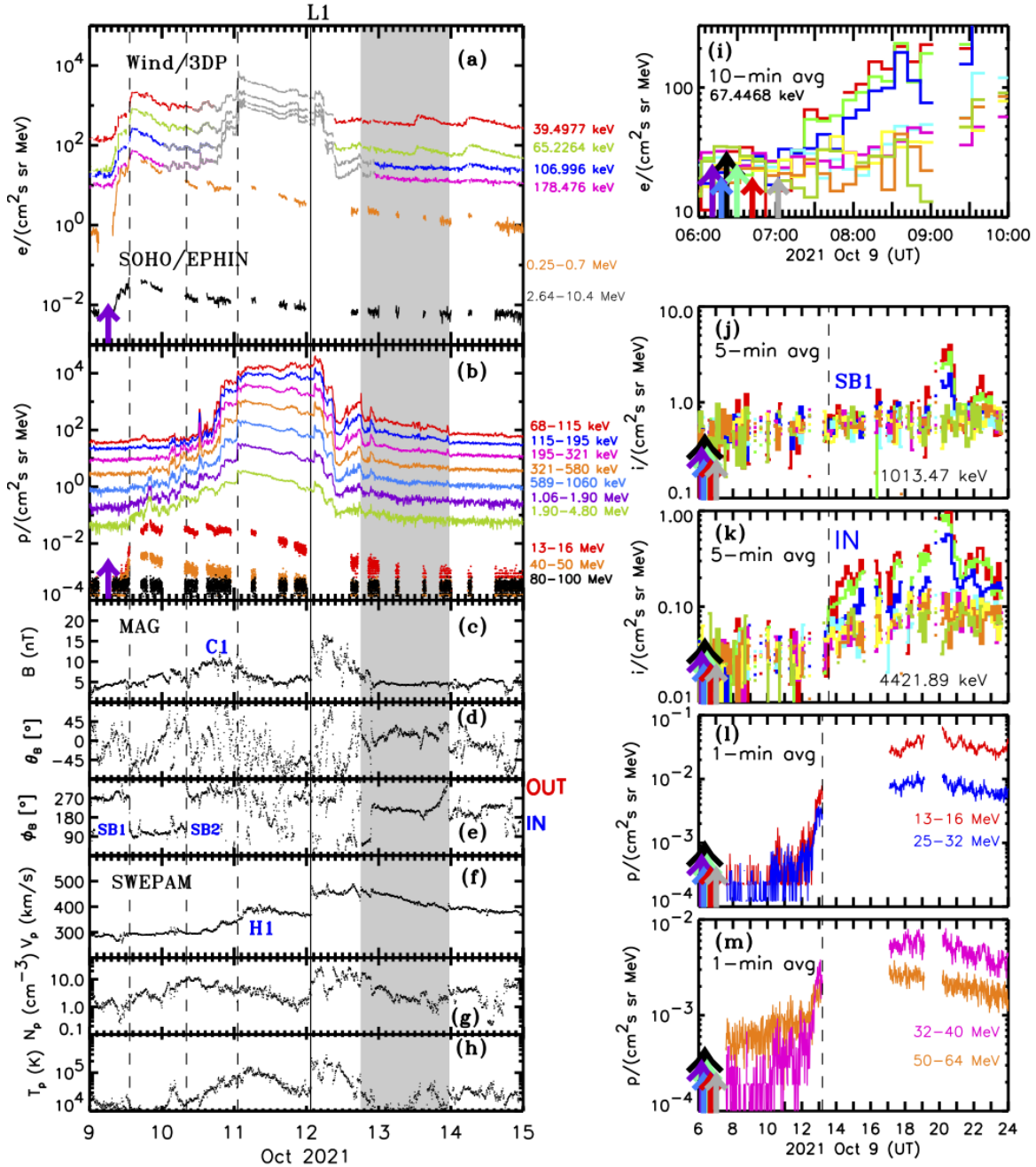
Following the shock passage, ion intensities at energies  $\lesssim 2$  MeV decreased abruptly at  $\sim 11:17$  UT on 2021 October 11. Based also on an abrupt transition from the disturbed fluctuating magnetic field downstream of the shock into a smoother magnetic field period (indicated by the gray shaded bar in Figures 9c-h), we suggest that the shock was followed by an ICME with leading edge at 11:17 UT on 2021 October 11 and trailing edge at  $\sim 09:35$  UT on 2021 October 12. This identification implies that the passage of the ICME sheath region lasted only 3.75 hours, whereas the passage of the ICME lasted  $\sim 22.32$  hours, implying a ratio between the sheath and the ICME durations of 0.17. This inferred sheath duration is relatively short compared to the average duration of sheaths at  $\sim 0.7$  au (i.e.,  $\sim 7.2$  hours, Janvier et al. 2019). By contrast, the ICME duration is longer than the average ICME durations observed at  $\sim 0.7$  au (i.e.,  $\sim 14.4$  hours, Janvier et al. 2019). The small ratio between the sheath and the ICME durations might result from the fact that the ICME propagated into the rarefaction region left behind the solar wind stream H1, favoring the expansion of the ICME and resulting in a longer duration than average.

Similarly to the right columns of Figures 7 and 8, the right column of Figure 9 focuses on a few hours around the onset of the SEP event as observed by the different apertures of SolO/EPT and SolO/HET. The analysis of the onset of the SEP event at ion energies  $\lesssim 1.5$  MeV is affected by the electron contamination in the SolO/EPT low-energy ion channels (gray traces in Figure 9b). Figure 9i shows 63-67 keV electron intensities, and Figures 9j and 9k the  $\sim 2$  MeV and  $\sim 5$  MeV ion intensities as observed by the four SolO/EPT apertures. At this time, SolO was in its original orientation, with the SUN apertures of SolO/EPT and SolO/HET pointing sunward along the nominal Parker spiral field, and the ASUN apertures in the opposite direction (Rodríguez-Pacheco et al. 2020). The onset of the SEP event occurred between the two solar wind speed increases that constituted the arrival of solar wind stream H1 (Figure 2(So4)) and coincided with a period when the magnetic field was quite steady with a constant field orientation, observed from  $\sim 06:50$  to  $\sim 09:00$  UT on 2021 October 9 (indicated in blue in Figures 9c-e). During this period, the SUN apertures scanned particles with pitch angles close to  $0^\circ$  (Figure 9m), allowing the detection of particles arriving along the magnetic field direction (see also Figure 16(So1) in Appendix B). These observations show that the onset of the event during this period of steady magnetic field was anisotropic. Figure 9l shows the onset of the event at  $\sim 14$  MeV proton intensities measured by SolO/HET. Similarly to the lower energy ion intensities, the event onset was observed first in the SolO/HET/SUN aperture, which has a similar viewing direction as SolO/EPT/SUN (cf. Figure 4 in Rodríguez-Pacheco et al. 2020), but after about  $\sim 60$  minutes, the intensities became isotropic, whereas at lower energies the anisotropic intensities lasted longer (Figure 9j), which may result from a more prolonged injection of lower-energy protons than at higher energies (Heras et al. 1994). Therefore, the SEP event onset at SolO was anisotropic, with particle intensities in the SUN apertures increasing much earlier than in the other apertures.

#### 4.4. L1 energetic particle observations

Figure 10 shows detailed observations of the SEP event at L1. We use a combination of data from several near-Earth spacecraft. In particular, we use electron and ion data from the Solid State Telescope (SST) of the Three-Dimensional Plasma and Energetic Particle Investigation suite of instruments on board the Wind spacecraft (3DP; Lin et al. 1995); relativistic electron data from the Electron Proton Helium Instrument (EPHIN) of the Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP; Müller-Mellin et al. 1995) on board SOHO; low-energy ion data from the Low Energy Magnetic Spectrometer (LEMS120) of the Electron, Proton, and Alpha Monitor (EPAM; Gold et al. 1998) on ACE; and proton intensities measured by the Energetic and Relativistic Nuclei and Electron Experiment (ERNE; Torsti et al. 1995) on board SOHO.

The left column of Figure 10 shows, from top to bottom, (a) spin-averaged near-relativistic electron intensities observed by Wind/3DP (four top traces) and relativistic electron intensities observed by SOHO/EPHIN (two bottom traces), (b) spin-averaged ion intensities observed by ACE/EPAM/LEMS120 (eight top traces) and proton intensities observed by SOHO/ERNE (three bottom traces), (c) magnetic field magnitude as observed by ACE/MAG, (d) the elevation angle  $\theta_B$  of the magnetic field vector in RTN coordinates, (e) the azimuth angle  $\phi_B$  of the magnetic field vector in RTN coordinates, the proton solar wind (f) speed  $V_p$ , (g) density  $N_p$ , and (h) temperature  $T_p$  as measured



**Figure 10.** L1 measurements of the SEP event. *Left column:* (a) near-relativistic electron intensities measured by Wind/3DP (first four top traces), and SOHO/EPHIN (two bottom traces), (b) energetic ion intensities measured by ACE/EPAM (eight top traces), and proton intensities measured by SOHO/ERNE (three bottom traces), (c) magnetic field magnitude, (d) magnetic field elevation angle, (e) magnetic field azimuthal angle in RTN coordinates measured by ACE/MAG, (f) solar wind proton speed, (g) solar wind proton density, and (h) solar wind proton temperature measured by ACE/SWEPAM. The solid vertical line indicates the passage of the CME-driven shock, the gray shaded bar the passage of the ICME. The vertical dashed lines indicate discontinuities in either particle intensities or magnetic field (see text for details). H1 indicates the passage of the solar wind stream preceded by the compressed field region C1. Gray traces in panel (a) indicate periods when the electron intensities were most likely contaminated by ions. *Right column:* (i)  $\sim 67$  keV electron, (j)  $\sim 1$  MeV and  $\sim 4.4$  MeV ion intensities measured by Wind/3DP/SST binned in eight different pitch angles. (l-m) proton intensities measured by SOHO/ERNE at four energy channels. The purple arrows in panels (a-b) and (i-m) indicate the onset time of the SXR emission of the solar flare associated with the origin of the SEP event. The blue, black, green, red, and gray arrows in panels (i-m) indicate the time when the first EUV activity was detected, the onset of the type III radio burst, the peak of the SXR solar flare was observed, the fitted ellipsoid magnetically connected with Earth, and the fitted shock reached its maximum speed, respectively (all these times are shifted by the light transit time to 1 au).

by ACE/SWEPAM. The gray traces in Figure 10(a) indicate those periods when intensities in the electron channels of Wind/3DP/SST were most likely contaminated by penetrating  $\gtrsim 400$  keV ions (Lin et al. 1995).

The solid vertical line in Figure 10 identifies the passage of an IP shock at 01:42 UT on 2021 October 12, presumably driven by the ICME. In fact, typical signatures of the ICME, including smooth magnetic field and depressed  $T_p$ , were observed by ACE for a period of  $\sim 29.5$  hours, indicated by the gray shaded bar in Figures 10a-h (namely from 18:00 UT on 2021 October 12 to  $\sim 23:30$  UT on 2021 October 13). This ICME was preceded by the passage of a sheath region of  $\sim 16.3$  hours. The sheath-to-ICME duration ratio is  $\sim 0.55$ , similar to the average ratio observed for ICMEs at 1 au (i.e., 0.5; see Janvier et al. 2019). The long duration of the sheath region at L1 contrasts with the duration of only 3.75 hours at SolO (Figure 9).

The vertical dashed lines in Figure 10 indicate discontinuities in either the particle intensities or the magnetic field. The first vertical dashed line indicates a sector boundary (SB1) observed by ACE at 13:18 UT on 2021 October 9 when the magnetic field polarity switched from outward to inward that coincided with an abrupt increase in the electron intensities shortly following the onset of the SEP event, and the start of a gradual enhancement of the  $\sim 5$  MeV ion intensities. The second vertical dashed line at 08:13 UT on 2021 October 10 indicates a second sector boundary (SB2) when the magnetic field polarity switched from inward to outward. The third vertical dashed line at 01:12 UT on 2021 October 11 coincides with the end of the compressed magnetic field region C1, the arrival of the solar wind stream H1, and an abrupt increase of low-energy  $\lesssim 5$  MeV ion intensities. The bulk of low-energy ( $\lesssim 5$  MeV) ions during the SEP event at L1 were observed during a period of  $\sim 24.5$  hours extending from this third dashed vertical line to the arrival of the shock.

In contrast to STA and SolO, particle instruments on the spin-stabilized Wind spacecraft (with the spin axis perpendicular to the ecliptic plane) are able to scan almost the whole sky and thus infer particle distributions over a wide range of pitch angles. A data product of Wind/3DP consists of particle intensities binned at different pitch angles<sup>9</sup>. Figures 10i-k show for a few hours around the onset of the SEP event these intensities binned into eight pitch angles for three energies, where the red and green lines are for particles with small ( $\lesssim 40^\circ$ ) pitch angles, whereas the brown and olive traces are for particles with large ( $\gtrsim 140^\circ$ ) pitch angles (see Figure 16(E1) in Appendix B). The onset of the  $\sim 67$  keV electron intensities (Figure 10i) was observed at  $\sim 07:20$  UT  $\pm 10$  minutes at small ( $\lesssim 60^\circ$ ) pitch angles, whereas the increase at large pitch angles ( $\gtrsim 140^\circ$ ) was not observed until 08:25 UT  $\pm 10$  minutes. Because of the outward magnetic field polarity during this period, the predominance of electron intensities at small pitch angles indicates a net antisunward flow of particles. In contrast, Figure 10k shows that the  $\sim 5$  MeV ion intensity increased just after the passage of SB1 (observed by Wind at 13:34 UT on 2021 October 9 as indicated by the vertical dashed line), again with larger intensities at small pitch angles. However, the inward polarity of the magnetic field after SB1 indicates that these particles were sunward-directed, although the magnetic field during this period experienced an out-of-the-ecliptic excursion (Figure 10d). Since the suprathermal electron flow observed by Wind/3DP in this region continued to be directed away from the Sun (not shown here), this suggests that these sunward ion flows were not due to particles being guided in looped magnetic fields or in a magnetic field reversal associated with a field line kink. A possible interpretation is that the protons were reflected back towards the Sun by a structure beyond 1 au, perhaps associated with the SIR driven by H1. With the exception of an intensity spike at  $\sim 20:00$  UT with sunward directed flows (Figure 10j), the gradual ion intensity increase at low energies ( $\lesssim 1$  MeV) was mostly isotropic.

The period between the trailing part of the compressed field region C1 and the arrival of the shock (i.e., in the 24.5 hours between the third dashed vertical line and the solid vertical line in Figures 10a-h) was characterized by almost flat low-energy ( $\lesssim 1$  MeV) ion intensities. The low-energy ion intensities during this period were mostly isotropic with just some evidence of slightly outward flows for around 4 hours before the shock arrival and at energies  $\lesssim 2$  MeV (see also Figure 12b below). This anti-sunward flow suggests that, when arriving at L1, the shock was able to accelerate low-energy ( $\lesssim 2$  MeV) ions, but instead of having a localized intensity peak at the shock, the elevated intensities extended for more than 24 hours prior to the shock. The decay of the ion intensities at higher ( $\gtrsim 4$  MeV) energies prior to the shock arrival (Figure 10b) suggests that the shock was less efficient at accelerating particles to these energies when arriving near L1, and hence less capable of filling this region. Following the shock, after an ion peak intensity observed during a depression of the downstream magnetic field, the ion intensities fell abruptly in two steps. Often such steps correspond to entry into the ICME, but in this case, they apparently occurred well before the

<sup>9</sup> [sprg.ssl.berkeley.edu/wind3dp/data/wi/3dp/sfpd/](http://sprg.ssl.berkeley.edu/wind3dp/data/wi/3dp/sfpd/) and [sprg.ssl.berkeley.edu/wind3dp/data/wi/3dp/sopd/](http://sprg.ssl.berkeley.edu/wind3dp/data/wi/3dp/sopd/)

ICME indicated by the gray shading. This suggests that the abrupt particle intensity decreases were associated with structures in the ICME sheath, or that ICME-related structures extended ahead of the region indicated.

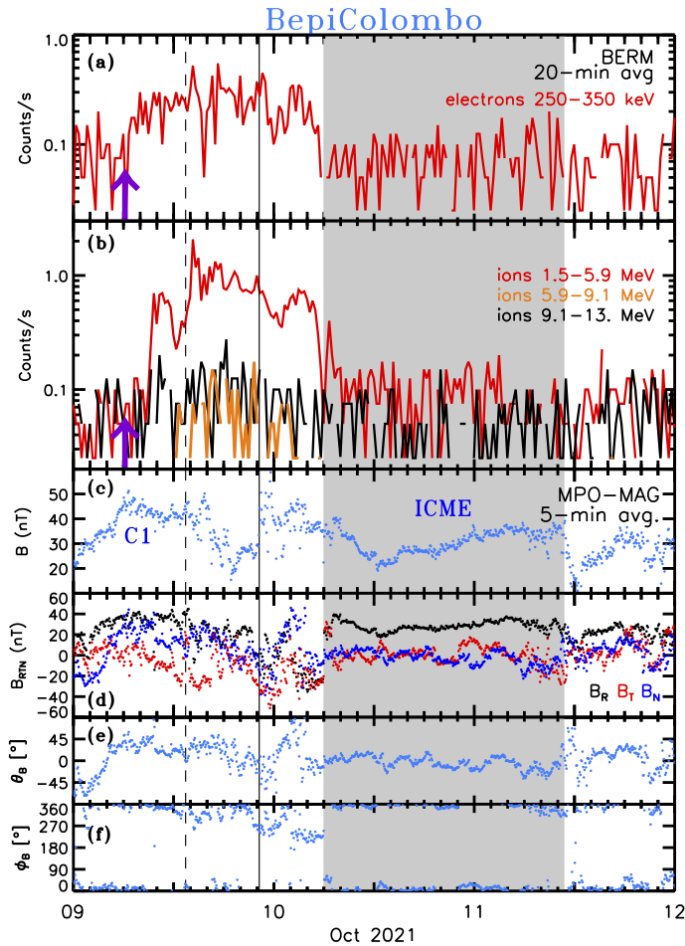
At the time of this SEP event, the SOHO spacecraft was rolled by about  $180^\circ$  and there were several gaps in both SOHO/EPHIN and SOHO/ERNE measurements, including a SOHO/EPHIN data gap that prevented the detection of the onset of the relativistic electron intensity enhancement. Figures 10l-m show proton intensities measured by the High-Energy Detector (HED) of SOHO/ERNE (Torsti et al. 1995) at four different energy channels from 06:00 UT to 24:00 UT on 2021 October 9. The passage of the sector boundary SB1 at SOHO (indicated by the vertical dashed line in Figures 10l-m) is estimated to be  $\sim 6$  minutes earlier than at ACE (considering the location of both spacecraft and a solar wind speed of  $\sim 300 \text{ km s}^{-1}$ ). An initial small enhancement in SOHO/ERNE/HED proton intensities at  $\sim 10:10$  UT was followed by a much more abrupt increase simultaneously at all energies at  $12:34 \text{ UT} \pm 3$  minutes (i.e.,  $\sim 38$  minutes before SB1). There is a SOHO/ERNE data gap at the time of passage of SB1, but the Wind/3DP observations do suggest that there was an abrupt increase in the near-relativistic electron intensities at the passage of SB1 as shown in Figure 10a. Unfortunately, owing to the data gaps in SOHO observations, we cannot completely assess anisotropies at the higher proton energies measured by the position-sensitive strip detectors of SOHO/ERNE/HED (Torsti et al. 1997). From 17:00 UT to 23:00 UT on 2021 October 9, SOHO/ERNE detected weak anisotropies (not shown here), with more flux coming from above the equatorial plane and from the east rather than from the solar direction, whereas, for the rest of the periods with SOHO/ERNE data, the fluxes were nearly isotropic. Note that during this period with anomalous anisotropies at the end of 2021 October 9, the magnetic field experienced an out-of-the-ecliptic excursion (Figure 10d), which may be the cause of these peculiar anisotropies together with the close proximity of the SIR C1 as in the case of the  $\sim 5$  MeV ions detected by Wind/3DP (Figure 10k).

#### 4.5. *BepiColombo Observations*

Bepi was in a privileged location during this period (Figure 1) that allowed the SEP event to be studied at a small heliocentric distance ( $R=0.33$  au) and from a longitude that had a similar nominal magnetic connection to the Sun as STA and SolO but was in close radial alignment with Earth. The two top panels of Figure 11 show the count rates of (a) 250-350 keV electrons and (b) 1.5-13 MeV protons separated into three energy channels as measured by the BepiColombo Radiation Monitor (BERM; Pinto et al. 2022) on board the European Space Agency's Mercury Planetary Orbiter (MPO) of the BepiColombo mission (Benkhoff et al. 2021). BERM is part of the housekeeping suite of instruments on board MPO responsible for monitoring radiation levels during all phases of the BepiColombo mission. The BERM field of view points mostly in the antisunward direction. The calibration of BERM with the other low-energy particle instrument on board Bepi, i.e., the Solar Intensity X-Ray and Particle Spectrometer (SIXS; Huovelin et al. 2020) has not yet been finalized. Unfortunately, SIXS was not operating at the time of the SEP event on 2021 October 9. Therefore, only BERM data in units of count rates are presented in Figure 11. Owing to the poor statistics and, in order to facilitate the visualization of the intensity enhancement associated with the SEP event, we display in Figures 11a-b 20-minute averages of the particle count rates. The only significant increase in the BERM electron channels above the background (dominated by galactic cosmic rays; GCRs) was observed at 250-350 keV. The proton intensities exhibited a clear increase in the 1.5-5.9 MeV energy channel, whereas at the other energy channels most of the counts were observed in the second half of the day on 2021 October 9.

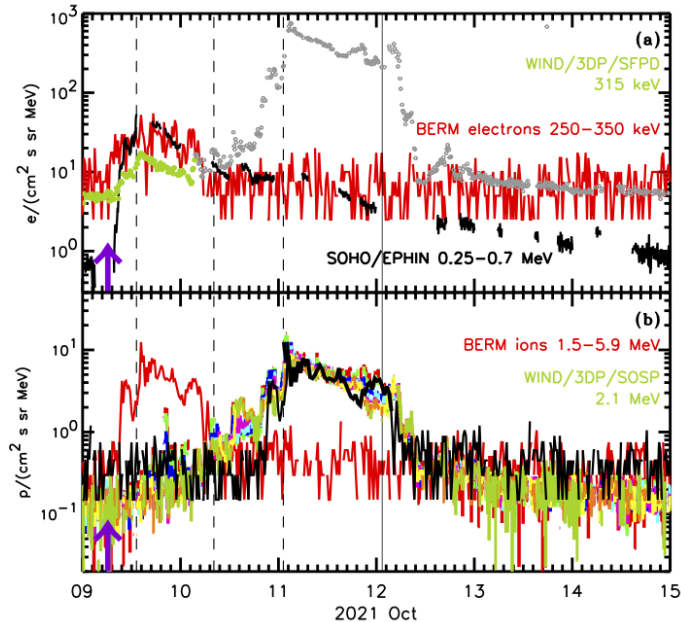
Figures 11c-f show magnetic field data as measured by the magnetometer on board MPO (MPO-MAG; Heyner et al. 2021). The vertical solid line indicates the passage of an IP shock at 22:13 UT on 2021 October 9. No solar wind plasma measurements were available from Bepi, so our identification of the shock is based purely on the increase of the magnetic field magnitude. By assuming that the shock originated at the onset time of the SXR emission from the solar flare associated with the SEP event (with a light-time shift of 8.33 minutes), we estimate an average transit speed for the shock to travel from the Sun to 0.33 au of  $\sim 855 \text{ km s}^{-1}$ .

The gray shaded bar in Figure 11 indicates the passage of an ICME from 05:55 UT on 2021 October 10 to 10:50 UT on 2021 October 11. The identification of the ICME is based on the smooth magnetic field intensity and orientation observed during its passage and the drop of particle intensities at the entry of Bepi into the ICME. This ICME was preceded by a sheath of 7.7 hours duration between the leading edge of the ICME and the IP shock. Whereas the durations of both the ICME passage (28.9 hours) and the sheath passage (7.7 hours) are longer than the average ICME and sheath durations at 0.4 au (7.2 and 2.4 hours, respectively; Janvier et al. 2019), the sheath-to-ICME duration ratio (0.27) is similar to the observed average ratio of 0.33 reported by Janvier et al. (2019). The close radial alignment between Bepi and Earth allows us to conclude that the shock decelerated when propagating from 0.33 au to 1 au since



**Figure 11.** BepiColombo measurements of the SEP event. From top to bottom, (a) near-relativistic electron and (b) proton intensities measured by BERM, (c) magnetic field magnitude, (d) components of the magnetic field vector in the spacecraft-centered RTN coordinates, (e) magnetic field elevation angle, and (f) magnetic field azimuthal angle in RTN coordinates measured by MPO-MAG. The solid vertical line indicates the passage of the CME-driven shock identified by the abrupt increase of magnetic field magnitude. The gray shaded bar indicates the passage of the ICME. The vertical dashed line indicates a discontinuity in the electron and proton intensities that we identify as the end of the compression region C1 (see text for details).

623 the average transit speed diminishes from  $855 \text{ km s}^{-1}$  to  $612 \text{ km s}^{-1}$ . The durations of the sheath and the ICME  
 624 also increased, from 7.7 to 16.3 hours and from 28.9 to 29.5 hours, respectively, between Bepi and Earth. Note also  
 625 that the magnetic field orientation during the ICME passage at Bepi was mostly radial ( $\phi_B \sim 0^\circ$ ), whereas at ACE  $\phi_B$   
 626 was mostly around  $\sim 220^\circ$ , implying that most likely each spacecraft intercepted a different portion of the ICME. It is  
 627 possible that Bepi crossed one of the legs of the ICME close to the axial component of the magnetic field, and ACE  
 628 crossed the main body of the ICME but with a higher impact parameter (see examples in, e.g., [Marubashi & Lepping](#)  
 629 [2007](#); [Owens 2016](#)), and/or that the ICME deflected and/or rotated considerably on its journey between Bepi and  
 630 Earth. In fact, it has been shown that, while most deflections and rotations tend to occur below  $30 R_\odot$ , ICMEs can  
 631 still undergo significant changes in their orientation and trajectory between  $30 R_\odot$  and 1 au (e.g., [Isavnin et al. 2014](#)).  
 632 In the case of the event studied here, it is possible that the fast stream H1 (see e.g. Figure 3d) contributed to the  
 633 observed changes in the magnetic field orientation within the ICME. It has been shown that interactions with large-  
 634 scale solar wind structures, in particular SIRs and high-speed streams, can result in drastic changes in the magnetic  
 635 configuration of ICMEs measured at different heliocentric distances in the inner heliosphere ([Winslow et al. 2021](#)).  
 636 The fact that the IP shock driven by the 2021 October 9 CME impacted Earth shortly after the arrival of H1 makes  
 637 this interaction scenario a plausible reason for the orientation change. Additionally, multi-point studies of the flux



**Figure 12.** *Top panel:* 250-350 keV electron count rates measured by BERM (red traces), spin-averaged  $\sim 315$  keV electron intensities measured by Wind/3DP/SST (green symbols) and 250-700 keV electron intensities measured by SOHO/EPHIN (black trace). The gray symbols indicate those periods when the electron Wind/3DP intensities were contaminated by low-energy ions. *Bottom panel:* 1.5-5.9 MeV proton count rates measured by BERM (red traces), and  $\sim 2.1$  MeV ion intensities binned at different pitch angles as measured by Wind/3DP/SST (colored traces). The black traces are the BERM 1.5-5.9 MeV proton intensities translated and stretched in time as described in the text. The solid vertical line indicates the passage of the IP shock by L1 and the dashed vertical lines the same discontinuities as in Figure 10.

rope structure of CMEs have shown that, for some events, the axis direction can change drastically from one location to the next, suggesting the presence of a highly-distorted flux rope (e.g., Mulligan et al. 1999).

The onset of the SEP event at Bepi occurred during the passage of a compressed magnetic field region that, according to Figures 1 and 3d, could be associated with the SIR preceding the solar wind stream H1 (this compression region is therefore labeled C1 in Figure 11c). The BERM electron count rate increased above the GCR background at 06:38 UT $\pm$ 20 minutes, whereas the BERM 1.5-5.9 MeV proton count rate displayed a first increase at 07:18 UT $\pm$ 20 minutes, followed by a more prominent increase at 08:38 UT $\pm$ 20 minutes. Similarly to the low-energy ion intensity-time profiles observed at L1 (Figure 10b), the bulk of 1.5-5.9 MeV protons at Bepi were found between the trailing edge of C1 and the interplanetary shock. The vertical dashed line in Figure 11 at 13:25 UT $\pm$ 20 minutes indicates a discontinuity at which the particle intensities increased and the magnetic field started to decrease. A possible interpretation is that these low-energy ions were confined between C1 and the approaching shock.

In order to demonstrate the similarities between the intensity-time profiles at L1 and at Bepi, Figure 12(a) shows BERM electron count rates (red traces) together with the spin-averaged  $\sim 315$  keV electron intensities measured by Wind/3DP/SST (green symbols) and the 250-700 keV electron intensities measured by SOHO/EPHIN (black trace). The gray symbols indicate those periods when the electron Wind/3DP intensities were most likely contaminated by penetrating ions. Note that BERM electron count rates have been scaled by a factor  $10^2$  to compare with the electron intensities from the other two instruments. BERM electron count rate enhancement exhibits a similar profile as the electron intensity-time profiles at L1 with a fast rise followed by a gradual decay.

In Figure 12(b) we plot BERM 1.5-5.9 MeV proton count rates scaled by a factor of 60 (red trace), and compare them with the  $\sim 2$  MeV ion intensities binned at different pitch angles as measured by Wind/3DP/SST (colored traces) in order to point out some remarkable similarities between the observations at the two spacecraft. The bulk of  $\sim 2$  MeV ions measured by Wind/3DP were observed for a period of  $\sim 24.5$  hours between the third dashed vertical line and the arrival of the shock. The Wind/3DP ion intensities were mostly isotropic with the exception of about  $\sim 4$  hours prior to the shock arrival, when the colored traces separate and are dominated by the intensities at small pitch angles, indicating that particles were flowing away from the shock and most likely locally accelerated by the approaching shock

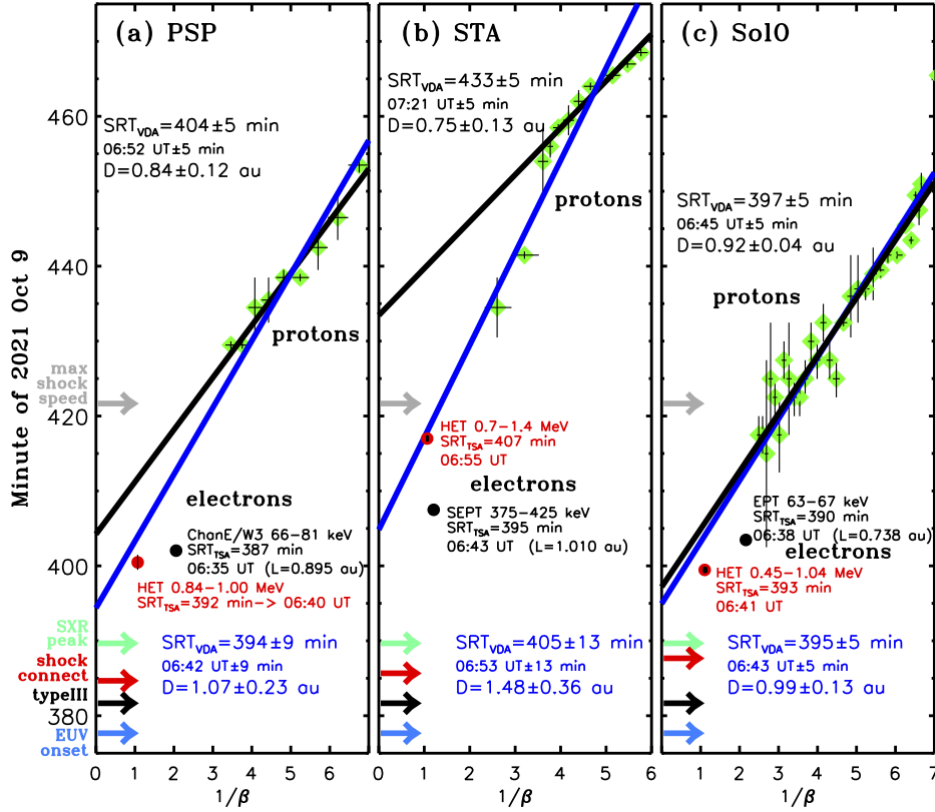
when arriving at 1 au. Unfortunately, BERM does not provide anisotropy information to determine the local effect of the shock when passing by Bepi. The black trace in Figure 12(b) is built by (1) shifting the BERM 1.5-5.9 MeV count rates prior to 13:25 UT on 2021 October 9 later by 1.5 days, (2) shifting and stretching the subsequent period with BERM elevated particle intensities (i.e., from 13:25 UT on 2021 October 9 to 05:20 UT on 2021 October 10) by a factor of 1.75 in time, and (3) shifting the rest of BERM particle data by 1.9 days. The shifted and stretched BERM data overlaps with the  $\sim 2$  MeV ion intensities measured by Wind/3DP between the third dashed vertical line and the entry of this spacecraft into the ICME. This coincidence of intensity-time profiles suggests that low-energy intensities observed at Bepi and at L1 were similarly affected by the compression region C1, the approaching interplanetary shock, and the sheath region preceding the arrival of the ICME. On the other hand, and perhaps contrary to expectations, the particle intensity-time profiles at Bepi were quite different from those at STA (Figure 8) and SolO (Figure 9) on similar field lines (Figure 1).

## 5. COMPARISON BETWEEN PARTICLE RELEASE TIMES AND CONNECTION TIMES

In this section, we compare the estimated release times at the Sun of the first particles measured by the different spacecraft with several manifestations related to the solar eruption. The colored arrows in Figures 7(i-l), 8(i-l), 9(i-l), and 10(i-m) indicate, the onset of the SXR emission of the M1.6 solar flare (i.e., 06:19 UT $\pm$ 1min, purple arrow), the time when the first signs of EUV activity occurred (i.e., 06:26 UT $\pm$ 2 min, blue arrow), the onset time of the metric type III (i.e., 06:30 UT $\pm$ 1 min, black arrow), the time when the fitted ellipsoid established magnetic connection with each respective spacecraft along the nominal Parker spiral+PFSS field lines (i.e., 06:33 UT for PSP, 06:34 UT $\pm$ 1 min for STA, 06:36 UT $\pm$ 1 min for SolO, and 06:50 UT for L1 when considering the early time case, red arrow), the time of the SXR solar flare peak emission (i.e., 06:38 UT $\pm$ 1 min, green arrow), and the time when the fitted shock reached its maximum speed (07:10 UT, gray arrow, cf. Figure 6). When plotting these arrows in Figures 7(i-l), 8(i-l), 9(i-l), and 10(i-m) we have shifted the listed times back to the Sun by subtracting the light transit time to 1 au.

In order to associate these times with the production of the observed SEPs, it is necessary to estimate when the first detected particles were injected into the interplanetary medium. The release times of SEPs at the Sun (Solar Release Time; SRT) are usually estimated by either time-shifting the observed onset times of the particle enhancements assuming scatter-free propagation along a given path length, or by performing a velocity dispersion analysis (VDA) assuming that the first-arriving particles are injected simultaneously at all energies and propagate scatter-free with a pitch angle of  $0^\circ$  along a common path. Under these assumptions, the time-shift analysis (TSA) provides a release time as  $SRT_{TSA}(E) = t_{onset}(E) - 8.33 \frac{min}{au} L/\beta(E)$  where  $t_{onset}(E)$  is the first time in minutes when the intensities of particles with a kinetic energy  $E$  start to increase,  $1/\beta(E) = c/\gamma(E)$  is the inverse speed of the particles with kinetic energy  $E$ , and  $L$  is the path length in au units that usually is assumed to be the nominal length of the Parker spiral computed for the solar wind speed measured at the onset of the SEP event. The VDA method consists of plotting the particle onset times at different energies versus  $1/\beta$ , and performing a least-square fit to the onset times at different energies given by the expression  $t_{onset}(E_i) = SRT_{VDA} + 8.33 \frac{min}{au} D/\beta_i$ , where  $t_{onset}(E_i)$  is the onset time in the energy channel detecting particles of kinetic energy  $E_i$  (usually considered to be the geometrical mean of the energy window of the channel),  $SRT_{VDA}$  is the release time of the particles at the Sun, and  $D$  is the apparent distance traveled by these particles (see Vainio et al. 2013, and references therein, for a critical discussion of the use of these methods).

Figure 13 shows the results of VDA performed for the high-energy particle intensities observed by (a) PSP, (b) STA and (c) SolO. The green diamonds in Figure 13 indicate the onset times in the proton channels of (a) PSP/EPI-Hi/HETA over the energy range 9.5-45.2 MeV, (b) STA/HET over the energy range 13.6-100 MeV, and (c) SolO/HET/SUN over the energy range 10.6-89.5 MeV. The red circles indicate the onset times of the event as seen in (a) the 0.84-1.0 MeV electron channel of PSP/EPI-Hi/HETA, (b) the 0.7-1.4 MeV electron channel of STA/HET, and in (c) the 0.45-1.04 MeV electron channel of SolO/HET/SUN. The black circles indicate the onset times of the event in (a) the 66-81 keV ChanE electron channel of the wedge 3 of EPI-Lo, (b) the 375-425 keV electron channel of STA/SEPT/SUN, and (c) the 63-67 keV electron channel of SolO/EPT/SUN. All these onset times have been obtained by visual inspection of 1-minute averages of the intensity-time profiles, or longer time averages when necessary. The prompt increase of the SEP event and the clean instrumental backgrounds of the HET telescopes on the three spacecraft (Figures 7a-b, 8a-b and 9a-b) facilitates this identification. The value of  $\beta$  assumed in Figure 13 corresponds to the geometrical mean of the energy window of each energy channel. The blue straight lines are least-square fits to the onset times of the protons and relativistic electrons (red data point), whereas the black straight lines are linear-square fits to proton data in the energy range (a) 9.5-45.2 MeV of PSP/EPI-Hi/HETA, (b) 13-40 MeV of STA/HET, and (c)



**Figure 13.** Velocity dispersion analysis of the onset of the SEP event at (a) PSP, (b) STA, and (c) SolO. The green diamonds with black error bars identify the proton onsets. The black circles identify the onset times measured at (a) the 66-81 keV ChanE electron channel of the wedge 3 of EPI-Lo, (b) the 375-425 keV electron channel of STA/SEPT, and (c) the 63-67 keV electron channel of SolO/EPT. The red circles identify the onset times measured at (a) the 0.84-1.00 MeV electron channel of EPI-Hi/HETA, (b) the 0.7-1.4 MeV electron channel of STA/HET, and (c) the 0.45-1.04 MeV electron channel of SolO/HET/SUN. The blue straight lines are linear regression fits to all proton data points (green diamonds) and relativistic electron data points (red circles). The black straight lines are linear regressions to proton data points over the energy range (a) 9.5-45.2 MeV, (b) 13-40 MeV, and (c) 10.6-89.5 MeV, as measured by PSP/EPI-Hi/HETA, STA/HET, and SolO/HET/SUN, respectively. The legends give the values of  $SRT_{VDA}$  in units of minutes (in UT when shifted by the light transit time to 1 au to compare with remote-sensing observations) and the estimated path length ( $D$ ) obtained from VDA. For the electron data points, the figure also provides  $SRT_{TSA}$  in units of minutes of the day (in UT when shifted by the light transit time to 1 au to compare with remote-sensing observations). The horizontal arrows indicate the times when (blue) the first EUV wave activity was detected, (black) the onset of the metric type III burst was observed, (red) the shock fitted to EUV and WL observations established magnetic connection with each spacecraft, (green) the peak of the SXR flare was observed, and (gray) the fitted shock reached its maximum speed (all these times have been shifted back to the Sun by the light transit time).

714 10.6-89.5 MeV of SolO/HET. The values of the estimated release time  $SRT_{VDA}$  (in minutes of the day) and apparent  
 715 path length  $D$  (in au) inferred from each of the two VDA fits using electrons and protons are shown in each panel of  
 716 Figure 13. We also include the release time in UT obtained by adding the light transit time to 1 au, to compare with  
 717 the remote-sensing observations described in Section 3.

718 Figure 13a shows that the estimated release time of the first-arriving particles observed by PSP inferred using either  
 719 TSA or VDA occurred between the time that the fitted shock established magnetic connection with the spacecraft  
 720 (red arrow) and the time when the fitted shock reached maximum speed (gray arrow). The electron release times  
 721 inferred from TSA (06:35 or 06:40 UT) are close to the time when the SXR solar flare reached its maximum emission  
 722 (i.e., 06:38 UT; green arrow) and also close to the time when the fitted shock accelerated (06:40 UT), but delayed by  
 723 a few ( $\lesssim 10$ ) minutes with respect to the onset of the metric type III (i.e., 6:30 UT; black arrow). The VDA method  
 724 when using only proton data provides a SRT that is delayed several minutes with respect to either the main phase of  
 725 the SXR solar flare emission or when the fitted shock established magnetic connection with PSP. When including the



relativistic electron data point,  $SRT_{VDA}$  occurs earlier but the quality of the fit is poorer suggesting that protons and relativistic electrons could have been injected at different times or propagated differently toward PSP.

Figure 13b shows that the onsets of the proton event at STA at energies below  $\sim 40$  MeV ( $\beta^{-1} > 3.5$ ) depart from the linear dependence inferred from the straight blue line, suggesting that either the  $< 40$  MeV protons were injected earlier than both the  $> 40$  MeV protons and relativistic electrons or that they did not follow the same path length. However, the black line in Figure 13b (for energies 13-40 MeV) implies an apparent path length shorter than the heliocentric distance of STA. Therefore, the assumptions made in the VDA method are not valid in this case, i.e., possibly because the first detected protons at different energies were not simultaneously released, they did not propagate along a common path, or their transport was not scatter free. The TSA technique applied to the STA electron onsets, assuming a path length  $L=1.01$  au estimated using the solar wind speed listed in Figure 1, provides a release time of 06:55 UT for 0.7-1.4 MeV electrons and 06:43 UT for 375-425 keV electrons. Both of these times represent a significant delay with respect to the onset of the SXR flare, the initiation of the EUV wave (blue arrow), the onset of the type III radio burst (black arrow), the peak of the SXR flare (green arrow), and the time when the fitted ellipsoid magnetically connected to STA (red arrow), but are earlier than the time when the fitted ellipsoid reached the maximum speed (gray arrow, see also Figure 8c). TSA applied to the highest energy proton channel (60-100 MeV) provides a release time of 07:08 UT  $\pm 2$  minutes that, within the error bars, agrees with the time when the fitted shock reaches the maximum speed. However, this does not mean that the shock needs to reach this speed to accelerate 60-100 MeV protons. Based on comparison with the SRTs inferred for PSP and SolO (see below), we suggest that the delay of the SRT for the first particles observed by STA is a consequence of the orientation of particle instruments on STA that was not appropriate to detect the first particles arriving at the STA location, assuming that these particles arrived anisotropically along the magnetic field at STA (as inferred from the observations made by other instruments in different directions shown in Figures 8i-l). Thus, the lack of appropriate scanning of small pitch angles (Figure 8m), preventing the observation of the first-arriving particles, may have led to inaccurate inferred SRTs.

Considering observations by SolO, Figure 13c shows that the VDA technique applied to either the  $> 10$  MeV proton onsets (black straight line) or to the 0.45-1.04 MeV electron (red data point) plus the  $> 10$  MeV proton onsets (blue straight line) provides SRTs of 06:45 and 06:43 UT that are consistent to within the 5 minute errors. On the other hand, the TSA technique applied to 63-67 keV and 0.45-1.04 MeV electrons provides release times of 06:38 UT  $\pm 1$  minutes and 06:41 UT  $\pm 1$  minutes, respectively. Therefore, the release times of the first-arriving particles observed by SolO are significantly delayed with respect to the onset of the SXR flare and the initiation of the EUV wave, and are within  $\sim 15$  minutes of the onset of the metric type III radio burst, and within  $\sim 10$  minutes of both the time when the fitted ellipsoid established magnetic field connection with SolO and the time of the SXR peak. These SRTs are also within the time when the fitted shock accelerated, but are much earlier than the time when the fitted shock reached its maximum speed.

The estimation of particle onset times at Bepi is affected by the low statistics provided by the BERM count rates and the instrumental background which is dominated by GCRs. Considering 20-minute averages of the Bepi/BERM intensities, the onset of the 300-620 keV electron enhancement would agree with a release time that is consistent with the time when the fitted shock established magnetic connection with the spacecraft (i.e., 06:35 UT  $\pm 2$  min as in the case of SolO and STA) and with the main phase of the SXR flare emission. In contrast, the onset of the 1.5-5.9 MeV protons was significantly delayed. Similarly, the onset time of the high-energy proton intensity enhancements at L1 was significantly delayed with respect to all significant episodes related to the solar eruptions, even that related to the magnetic connection with the fitted shock (Figures 10l-m). The onset of the  $\sim 65$  keV electron intensity enhancement (estimated at  $\sim 07:20$  UT  $\pm 10$  minutes as measured by Wind/3DP; cf. Figure 10i) implies a time-light shifted release time at  $\sim 07:15$  UT (assuming a scatter-free propagation along the nominal Parker spiral path length of  $L=1.259$  au) that is delayed with respect to the time when the fitted shock established magnetic connection with L1.

## 6. SUMMARY

The intense SEP event on 2021 October 9 was observed by multiple spacecraft at heliocentric distances  $\lesssim 1$  au within a narrow range ( $\lesssim 48^\circ$ ) of heliolongitudes. Despite the small heliolongitudinal separation of these spacecraft, the intensity-time profiles and the anisotropic character of the onset of the event at each spacecraft differed significantly. Considering the spacecraft in order going from east to west:

- 775 : The SEP event at PSP exhibited properties typical of the SEP events originating from western longitudes, and the  
776 onset of the event was extremely anisotropic (Figure 7). The onset of the SEP event occurred during the decay  
777 of the solar wind stream H1 where the magnetic field was radial.
- 778 : The SEP event at STA also exhibited properties typical of western SEP events but the interplanetary shock contribu-  
779 tion was larger than at PSP (Figure 8). The onset also occurred during the decay of solar wind stream H1 and  
780 exhibited anisotropy. However, because of the orientation of the particle instruments on STA, and the magnetic  
781 field fluctuations observed during the onset of the event, the onset appeared to be less anisotropic than at PSP.
- 782 : The SEP event at SolO exhibited properties typical of SEP events generated from heliolongitudes close to the central  
783 meridian with a large contribution to the  $\lesssim 2$  MeV proton intensities resulting from acceleration by the interplan-  
784 etary shock (Figure 9). The onset of the event occurred between two solar wind speed increases at the arrival of  
785 the stream H1 that coincided with a period of steady magnetic field (Figure 9d-e).
- 786 : Although the AR associated with the origin of the SEP event was located at N17E09, the SEP event observed by near-  
787 Earth spacecraft did not show the typical profile of a SEP event generated from central meridian longitudes.  
788 Instead, the intensity-time profiles at L1 were clearly influenced by interplanetary structures such as sector  
789 boundaries and the arrival of the stream H1 just a few hours prior to the CME-driven shock (Figure 10). The  
790 bulk of the low-energy ( $\lesssim 5$  MeV) ions detected near Earth were observed for a period of more than 24 hours  
791 between the compression region preceding H1 and the CME-driven shock.
- 792 : Despite the fact that the nominal magnetic connection of Bepi was close to that of STA and SolO (Figure 1), the  $>1.5$   
793 MeV proton intensities at Bepi (Figure 11) did not reach a peak shortly after the solar eruption as in the case  
794 of SolO and STA (Figures 9 and 8, respectively). In fact, the low-energy proton event observed by the radiation  
795 monitor on Bepi more closely resembled the event observed at L1 than that at STA or SolO. In particular, the  
796 bulk of low-energy particles observed by Bepi were also located between the compressed region preceding H1 and  
797 the CME-driven shock (Figure 11). Evidently, the accumulation of particles between these two magnetic field  
798 enhancements that propagated from Bepi to L1 shaped the intensity-time profiles at both locations (Figure 12).

799 The origin of the SEP event was temporally associated with a long-duration M1.6/2B solar flare, an EUV wave and  
800 a fast CME. Although the extent of the EUV wave on the solar surface was limited by surrounding CHs (Figure 4), the  
801 WL shock at higher altitudes extended over a broad range of longitudes (Figure 5a). In fact, as seen from Earth, the  
802 CME became a halo event about  $\sim 60$  minutes after the onset of parent solar eruption. Despite the limited extent of  
803 the EUV wave, which did not reach Earth’s magnetic footpoint, high-energy particles were observed at L1, including  
804 the 84-98 MeV channel of the Solar and Galactic Proton Sensor (SGPS) of the Space Environment In-Situ Suite  
805 (SEISS)<sup>10</sup> on board the Geostationary Operational Environmental Satellite-16 (GOES/SEISS; Kress et al. 2020). At  
806 SolO the proton intensity enhancement was observed above 98 MeV. At STA, the intensity enhancement in the 60-100  
807 MeV proton channel was more than two orders of magnitude (Figure 8b). However, at PSP only single counts were  
808 observed at the 53-64 MeV energy channel. On the other hand, the electron event was clearly measured at relativistic  
809 energies above  $\gtrsim 2$  MeV at all spacecraft except for the radiation monitor on Bepi. Because of the current lack of  
810 inter-calibration between the particle instruments used here, we have not computed the longitudinal or radial particle  
811 intensity gradients during this event.

812 The estimated solar release times of the first particles observed by PSP and SolO occurred after the time when  
813 the large-scale coronal shock (as inferred from EUV and WL images collected by STA, SDO and SOHO; Figure 5)  
814 established magnetic connection with these spacecraft (Figure 13). Therefore, the release of these particles is consistent  
815 with particle acceleration by a coronal shock. However, the release of protons tends to occur later than that of the  
816 electrons, as has already been observed in prior events and attributed to a delay before a shock is able to accelerate  
817 protons efficiently (e.g., Kouloumvakos et al. 2022). Additionally, the inferred release times of near-relativistic electrons  
818 (black dots in Figure 13) seem to occur earlier than those of the relativistic electrons (red dots in Figure 13). A possible  
819 interpretation for these delayed release of relativistic electrons is that higher energy electrons are accelerated by the  
820 shock whereas the lower energy electrons contain a flare contribution (e.g., Dresing et al. 2022). We should also indicate

<sup>10</sup> data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes16/l2/data/

821 that the near-relativistic electron release times were also delayed with respect to the onset of the metric type III radio  
 822 bursts (see also [Haggerty & Roelof 2002](#)).

823 The estimated release time of the first protons observed by PSP (black straight line in Figure 13a) is relatively  
 824 delayed with respect to that inferred for SolO (black straight line in Figure 13c), which may result from the fact  
 825 that PSP progressively established magnetic connection with the east flank of the shock (Figure 5c), and therefore  
 826 ions of different energies were injected at different times, breaking one of the assumptions of the VDA method. The  
 827 estimated SRTs for the case of STA are delayed with respect to those of PSP and SolO, which may result from the less  
 828 favorable orientation of the STA instruments for detecting the earliest arriving particles streaming along the magnetic  
 829 field. The arrival of particles near Earth was clearly delayed, not only with respect to the time of the solar eruption,  
 830 but also from the estimated time when the large-scale structure of the coronal shock established magnetic connection  
 831 with L1. The intensity-time profiles at Earth were affected by the arrival of interplanetary structures, in particular  
 832 by the compression region C1 formed in front of the solar wind stream H1 that was able to confine low-energy ( $\lesssim 2$   
 833 MeV) protons and by preceding sector boundaries that produced discontinuities in the intensities of near-relativistic  
 834 electrons (Figure 10a) and high-energy protons (Figure 10k-m). Correlating the particle release times with the evolving  
 835 properties of the coronal shock might help to clarify to what extent the particle properties observed at the spacecraft  
 836 are related to the processes of particle acceleration at the shock. However, estimating the coronal shock properties is  
 837 model-dependent and consistent results regarding the release time of the particles may not always be obtained (e.g.,  
 838 [Lario et al. 2017](#); [Jin et al. 2022](#); [Kouloumvakos et al. 2022](#)). Therefore, we have not included such an analysis in the  
 839 present study.

840 The SIR driven by solar wind stream H1 that was sequentially observed to corotate from PSP to L1 (Figure 2) played  
 841 an essential role in both shaping the intensity-time profile of the SEP event and defining the anisotropic character of  
 842 the onset of the SEP event at each spacecraft. The onset of the SEP event at PSP and STA occurred during the decay  
 843 of solar wind stream H1. Rarefaction regions formed during the decay of solar wind streams are typically characterized  
 844 by a decay in the amplitude of the Alfvénic fluctuations ([Borovsky & Denton 2016](#); [Carnevale et al. 2022](#)), which may  
 845 result in weaker energetic particle scattering than in more typical solar wind, and by sub-Parker fields, which reduce  
 846 the particles' path length from the Sun, providing less opportunity for particles to be scattered. These conditions may  
 847 have contributed to the observation of a highly anisotropic event at PSP. The onset of the SEP event at STA also  
 848 exhibited some anisotropy. However, the configuration of the particle telescopes at STA at that time did not allow for  
 849 a comprehensive pitch angle scan, and hence the anisotropic character was less pronounced than at PSP. The onset of  
 850 the event at SolO was also anisotropic. In this case the orientation of the spacecraft was favorable for detecting the  
 851 first arriving particles propagating along the magnetic field. The onset of the SEP event at SolO also happened to  
 852 occur during the passage of a steady magnetic field region formed between the two steps of the increase in solar wind  
 853 speed associated with the arrival of stream H1. This steady field region acted as a conduit for the anisotropic arrival of  
 854 particles at this spacecraft. In contrast, the arrival of particles at L1 did not show clear evidence of velocity dispersion.  
 855 The data gaps of the SOHO observations did not allow us to assess the anisotropy of the high-energy protons, whereas  
 856 for  $\lesssim 5$  MeV protons, the gradual intensity increase influenced by interplanetary structures showed anomalous flow  
 857 directions, but with a much less anisotropic character than that seen by SolO. Then, as already noted, at both L1  
 858 and at Bepi, the development of the SEP event was strongly influenced by structures associated with the compression  
 859 region ahead of H1 and the interplanetary shock associated with the solar event.

## 860 7. CONCLUSIONS

861 Analysis of the SEP event on 2021 October 9 reveals that spacecraft located within a narrow range of heliolongitudes  
 862 may detect distinct differences in the intensity and anisotropy profiles for the same SEP event, and that these differences  
 863 are closely linked to the solar wind structures present. Therefore, this study demonstrates that considering the  
 864 interplanetary context in which a SEP event develops is essential to understanding the spatial/temporal properties of  
 865 the event, including how large-scale interplanetary structures affect the arrival of particles at different locations. It is  
 866 also noted that good pitch angle coverage, especially for anisotropic events, is necessary in order to properly estimate  
 867 energetic particle release times near the Sun to compare with the different manifestations of the parent solar eruption.  
 868 Furthermore, although the EUV wave generated by the solar eruption was limited in extent, a wide halo CME (at  
 869 least as seen from Earth) was formed that was able to drive an extended shock at high altitudes that magnetically  
 870 connected to each spacecraft and apparently was able to accelerate high energy ( $\gtrsim 50$  MeV) protons.

## ACKNOWLEDGMENTS

Solar Orbiter is a space mission of international collaboration between ESA and NASA, operated by ESA. The STEREO SECCHI data are produced by a consortium of RAL (UK), NRL (USA), LMSAL (USA), GSFC (USA), MPS (Germany), CSL (Belgium), IOTA (France), and IAS (France). SOHO is a mission of international cooperation between ESA and NASA. The SDO/AIA data are provided by the Joint Science Operations Center (JSOC) Science Data Processing (SDP). Parker Solar Probe was designed, built, and is now operated by The Johns Hopkins University Applied Physics Laboratory as part of NASA’s LWS program (contract NNN06AA01C). We thank the German Federal Ministry for Economic Affairs and Energy and the German Space Agency (Deutsches Zentrum für Luft- und Raumfahrt, e.V., (DLR)) for their unwavering support of STEP, EPT, and HET under grants numbers 50OT0901, 50OT1202, 50OT1702, and 50OT2002. N.W. acknowledges funding from the Research Foundation – Flanders (FWO – Vlaanderen, fellowship no. 1184319N). This project has received funding from the European Union’s Horizon 2020 research and innovation programs under grant agreement No. 870405 (EUHFORIA 2.0). These results were also obtained in the framework of the ESA project “Heliospheric modelling techniques” (Contract no. 4000133080/20/NL/CRS) and the projects C14/19/089 (C1 project Internal Funds KU Leuven), G.0D07.19N (FWO-Vlaanderen), SIDC Data Exploitation (ESA Prodex-12), and Belpo project B2/191/P1/SWiM. E.P. acknowledges support from NASA’s PSP-GI (grant no. 80NSSC22K0349) and O2R (grant no. 80NSSC20K0285) programs. B.S.-C. acknowledges support through UK-STFC Ernest Rutherford Fellowship ST/V004115/1, and STFC grants ST/W00089X/1, ST/V000209/1. R.G.H acknowledges the financial support by the Spanish MICIU (project PID2019-104863RB-I00/AEI/10.13039/501100011033). R.V. and N.D. acknowledge funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 101004159 (SERPENTINE). N.D. also acknowledges support from the Turku Collegium for Science, Medicine and Technology of the University of Turku, Finland. A.A. acknowledges the support by the Spanish Ministerio de Ciencia e Innovación (MICINN) under grant PID2019-105510GB-C31 and through the “Centre of Excellence María de Maeztu 2020-2023” award to the ICCUB (CEX2019-000918-M). D.L. and I.G.R. acknowledge support from NASA Living With a Star (LWS) programs NNH17ZDA001N-LWS and NNH19ZDA001N-LWS, the Goddard Space Flight Center Internal Scientist Funding Model (competitive work package) program and the Heliophysics Innovation Fund (HIF) program. I.G.R. also acknowledges support from the ACE mission. The data used in this paper can be downloaded from [spdf.gsfc.nasa.gov](http://spdf.gsfc.nasa.gov), [www.srl.caltech.edu/ACE/ASC/](http://www.srl.caltech.edu/ACE/ASC/), [soar.esac.esa.int/soar/](http://soar.esac.esa.int/soar/), [stereo.gsfc.nasa.gov](http://stereo.gsfc.nasa.gov), [gong.nso.edu/data/magmap/](http://gong.nso.edu/data/magmap/), [sdo.gsfc.nasa.gov/data/aiahmi/](http://sdo.gsfc.nasa.gov/data/aiahmi/). See also [doi.org/10.48322/7gr7-1791](https://doi.org/10.48322/7gr7-1791), [doi.org/10.48322/97te-0132](https://doi.org/10.48322/97te-0132), [doi.org/10.48322/wpk2-yq48](https://doi.org/10.48322/wpk2-yq48), and [doi.org/10.48322/c0zj-xf76](https://doi.org/10.48322/c0zj-xf76). BepiColombo data used in Figures 11 and 12 can be downloaded from [doi.org/10.25392/leicester.data.19447259.v1](https://doi.org/10.25392/leicester.data.19447259.v1). We acknowledge all of the science instrument teams for making their data used in this paper available.

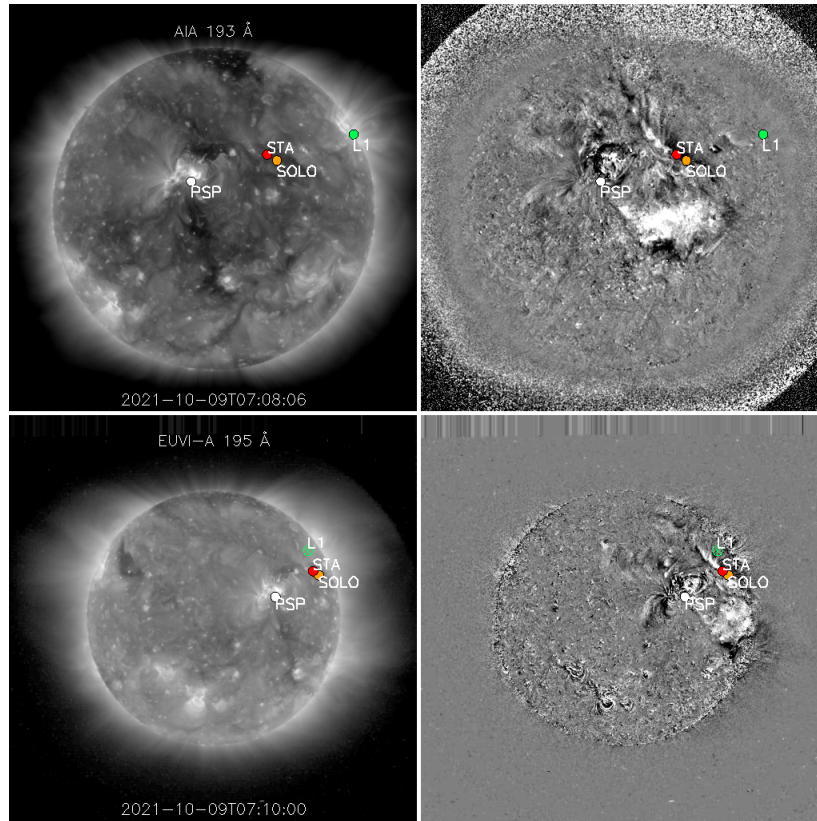
## APPENDIX

## A. EUV AND WL SNAPSHOTS OF THE SOLAR ERUPTION ANIMATIONS

Figures 14 and 15 are snapshots of the animations available in the online version of the journal. They are built from EUV and WL images obtained by SDO/AIA, SOHO/LASCO, STA/SECCHI/EUVI, STA/SECCHI/COR-1, and STA/SECCHI/COR-2 during the solar eruption associated with the origin of the SEP event. The animated version of Figure 14 shows the evolution of the EUV wave together with the magnetic footpoints of the field lines connecting to each spacecraft. The animated version of Figure 15 shows the expansion of the CME as seen in EUV and WL images with the ellipsoid that fits the outermost front of the CME superimposed on the images. The right column of Figure 15 shows the expansion of the fitted shock as it established magnetic connection with the different spacecraft.

## B. PITCH-ANGLE COVERAGE

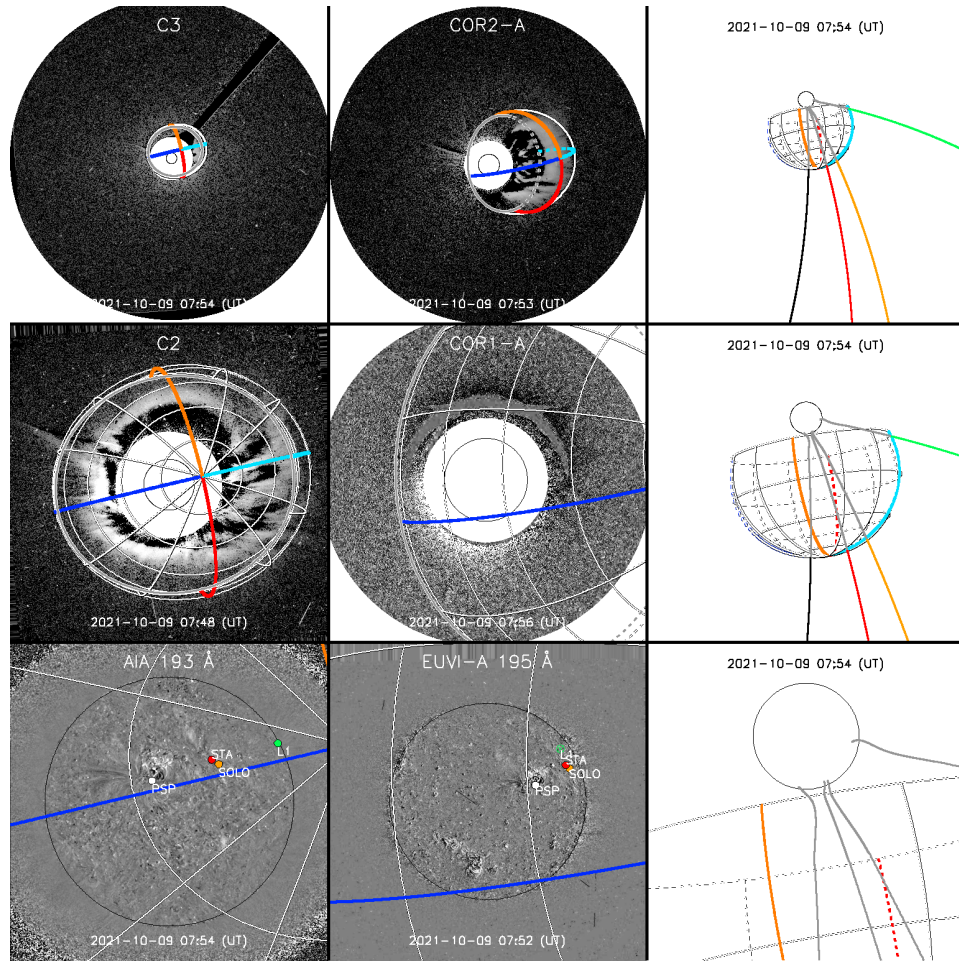
Figure 16 shows the pitch-angle coverage during the onset of the event as provided by the different particle instruments. In particular, the shaded areas in Figure 16(P1) show the pitch angle covered by the 10 apertures of the wedges 7 (pink) and 3 (green) of EPI-Lo using the central axis of each aperture as their look direction. The apertures that are closest to the symmetry axis of EPI-Lo (see Figure 15 in [McComas et al. 2016](#)) scan similar pitch angles and hence that the pink and green shaded areas in Figure 16(P1) are adjacent. The solid lines in Figure 16(P1) are averages of the pitch angles scanned by the 10 apertures in wedge 7 (pink) and in wedge 3 (green). Note that, depending



**Figure 14.** Static representation of the animation showing how the expansion of the EUV wave was limited by surrounding CHs. *Top panels:* Direct image (left) and running-difference image (right) obtained from SDO/AIA 193 Å observations, *Bottom panels:* Direct image (left), and running-difference image (right) obtained from STA/SECCHI/EUVI 195 Å observations. The white, red, orange and green symbols indicate the footpoints of the field lines connecting to PSP, STA, SolO and L1, respectively, assuming nominal Parker spiral field lines down to  $2.5 R_{\odot}$  and then a coronal field configuration obtained from the PFSS model. In the STA/SECCHI/EUVI images, the L1 footpoint is indicated by the open green symbol as it was located behind the west limb. The animated version of this figure runs from 06:20 UT to 07:00 UT on 2021 October 9 and is available in the online journal.

887 on the orientation of the magnetic field, the pitch angle formed by the look direction of the geometric center of a  
 888 wedge (Figure 7m) might differ from both the pitch angle scanned by each individual aperture of the wedge or the  
 889 average of the ten pitch angles scanned by the apertures of the wedge. The solid lines in Figure 16(P2) show the  
 890 pitch angle scanned by the central axis of the sides A (red) and B (blue) of EPI-Hi/LET1, whereas the shaded areas  
 891 indicate the pitch angle covered by the whole apertures of this telescope. The solid lines in Figure 16(P3) show the  
 892 pitch angle scanned by the central axis of the sides A (orange) and B (black) of EPI-Hi/HET, whereas the shaded  
 893 areas indicate the pitch angle covered by the apertures of this telescope. In order to compute these shaded areas, we  
 894 have considered that the FOVs of these apertures are  $45^{\circ}$  half-angle cones. However, obstructions due to spacecraft  
 895 components reduce these field of view (see Figure 18 in [McComas et al. 2016](#)). Note that EPI-Hi telescopes provide  
 896 more angular information than that showed in Figure 16 by using combinations in each one of the stacked detectors  
 897 (see Figures 30 and 35 in [McComas et al. 2016](#)).

898 Figure 16(S1) shows the pitch angle covered by (solid lines) the central axis and by (shaded areas) the  $52^{\circ}$  view cone  
 899 angle of the apertures of the STA/SEPT (see Table 4 in [Müller-Mellin et al. 2008](#)). The shaded areas in Figure 16(S2)  
 900 show the pitch angle covered by the central axes of the eight sectors in the fan pointed  $45^{\circ}$  east of the Sun in the  
 901  $[-R, -T]$  direction (red) and of the eight sectors in the opposite direction in the  $[+R, +T]$  direction (blue), whereas the  
 902 solid lines are averages of the pitch angles in each direction (see Section 4.7 in [Mewaldt et al. 2008](#)). The pitch angle  
 903 covered by the  $55^{\circ}$  view cone angle of the aperture of STA/HET is similar to that of STA/SEPT/SUN shown in  
 904 Figure 16(S1).



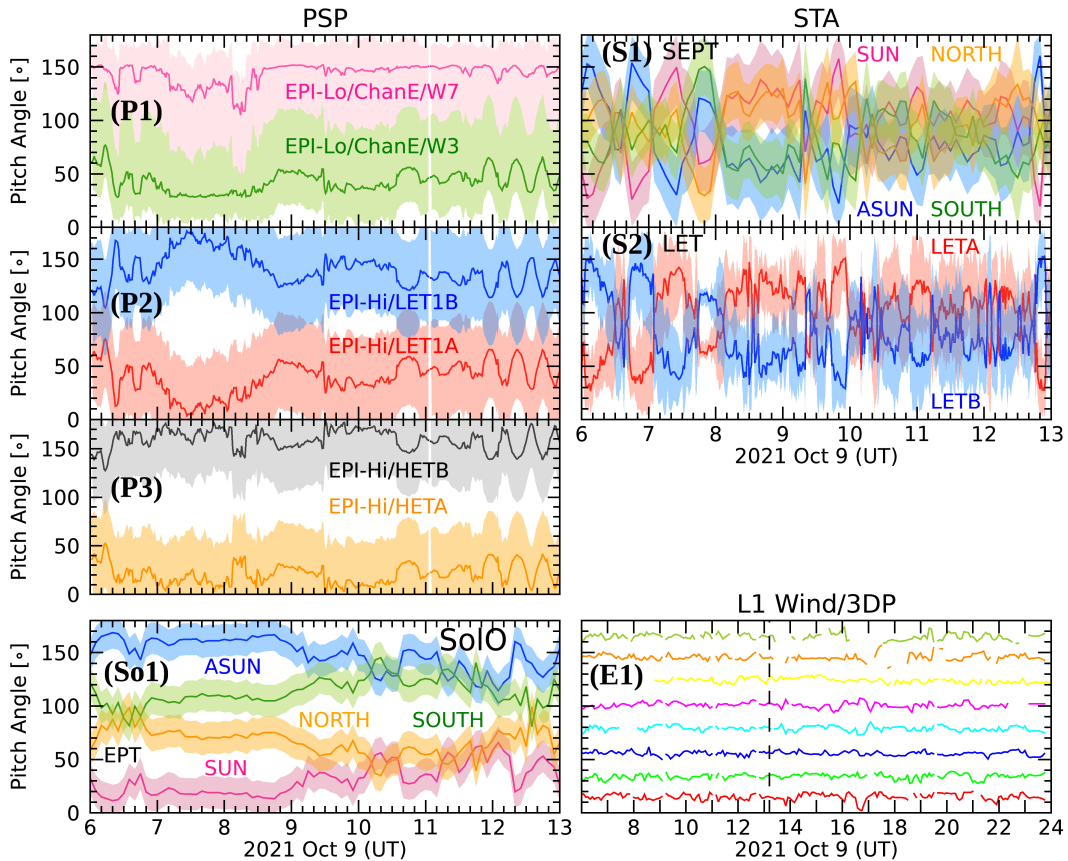
**Figure 15.** Static representation of the animation showing the evolution of the 3D ellipsoid fitting the outermost front of the CME as seen in EUV and WL images from SDO, SOHO and STA. *Left column:* Running-difference images of, from bottom to top, SDO/AIA 193 Å, SOHO/LASCO/C2, and SOHO/LASCO/C3. *Middle column:* Running-difference images of, from bottom to top, STA/SECCHI/EUVI 195 Å, STA/SECCHI/COR-1 and STA/SECCHI/COR-2. Superimposed on the images is the fitted ellipsoid indicated by the grid of white lines, with the red, orange, blue and cyan lines indicating the different quadrants of the reconstructed 3D shock front. *Right Column:* projection of the ellipsoid in the ecliptic plane as seen from the north ecliptic pole. The black, red, orange and green lines indicate the magnetic field lines connecting to PSP, STA, SolO and L1, respectively, computed assuming Parker field lines above  $2.5 R_{\odot}$  and the results from the PFSS model below  $2.5 R_{\odot}$  (gray is used for the portion of the field lines inside the modeled ellipsoid). The large black circle indicates the solar surface. The white, red, orange and green symbols in the two bottom left panels indicate the footpoints of the field lines connecting to PSP, STA, SolO and L1, respectively. The animated version of this figure runs from  $\sim 06:30$  UT to  $08:42$  UT on 2021 October 9 and is available in the online journal.

Figure 16(So1) shows the pitch angle covered by the central axis (solid lines) and the  $30^{\circ}$  FOV (shaded areas) of the four SolO/EPT apertures. The pitch angle covered by the  $43^{\circ}$  FOV of the SolO/HET apertures is similar to those displayed in Figure 16(So1) as shown in Figure 4 of Rodríguez-Pacheco et al. (2020).

Figure 16(E1) shows the pitch-angle directions used to bin the Wind/3DP intensities shown in Figures 10(i-k) and 12(b). The dashed vertical line in Figure 16(E1) indicates the passage of the sector boundary SB1 as in Figure 10.

## REFERENCES

- Acuña, M. H., Curtis, D., Scheifele, J. L., et al. 2008, *SSRv*, 912  
136, 203, doi: [10.1007/s11214-007-9259-2](https://doi.org/10.1007/s11214-007-9259-2)
- Arge, C. N., Henney, C. J., Koller, J., et al. 2010, in American Institute of Physics Conference Series, Vol. 1216, Twelfth International Solar Wind Conference, ed. M. Maksimovic, K. Issautier, N. Meyer-Vernet, M. Moncuquet, & F. Pantellini, 343–346, doi: [10.1063/1.3395870](https://doi.org/10.1063/1.3395870)



**Figure 16.** Pitch angles covered by (P1) the wedges 3 and 7 of EPI-Lo, (P2) the two apertures of the double-ended EPI-Hi/LET1 telescope, and (P3) the two apertures of the double-ended EPI-Hi/HET telescope, (S01) the four apertures of SolO/EPT, (S1) the four apertures of STA/SEPT, and (S2) the 16 sectors of STA/LET separated into two fans (LET-A and LET-B). The panel (E1) shows the pitch-angle directions used to bin the Wind/3DP intensities plotted in Figures 10(i-k) and 12(b).

- 918 Arge, C. N., Luhmann, J. G., Odstrcil, D., Schrijver, C. J., 939  
 919 & Li, Y. 2004, *Journal of Atmospheric and* 940  
 920 *Solar-Terrestrial Physics*, 66, 1295, 941  
 921 doi: [10.1016/j.jastp.2004.03.018](https://doi.org/10.1016/j.jastp.2004.03.018) 942  
 922 Bale, S. D., Goetz, K., Harvey, P. R., et al. 2016, *SSRv*, 943  
 923 204, 49, doi: [10.1007/s11214-016-0244-5](https://doi.org/10.1007/s11214-016-0244-5) 944  
 924 Barouch, E., & Burlaga, L. F. 1976, *JGR*, 81, 2103, 945  
 925 doi: [10.1029/JA081i013p02103](https://doi.org/10.1029/JA081i013p02103) 946  
 926 Beeck, J., Mason, G. M., Hamilton, D. C., et al. 1987, *ApJ*, 947  
 927 322, 1052, doi: [10.1086/165800](https://doi.org/10.1086/165800) 948  
 928 Benkhoff, J., Murakami, G., Baumjohann, W., et al. 2021, 949  
 929 *SSRv*, 217, 90, doi: [10.1007/s11214-021-00861-4](https://doi.org/10.1007/s11214-021-00861-4) 950  
 930 Bieber, J. W., Dröge, W., Evenson, P. A., et al. 2002, *ApJ*, 951  
 931 567, 622, doi: [10.1086/338246](https://doi.org/10.1086/338246) 952  
 932 Borovsky, J. E., & Denton, M. H. 2016, *Journal of* 953  
 933 *Geophysical Research (Space Physics)*, 121, 6107, 954  
 934 doi: [10.1002/2016JA022863](https://doi.org/10.1002/2016JA022863) 955  
 935 Brueckner, G. E., Howard, R. A., Koomen, M. J., et al. 956  
 936 1995, *SoPh*, 162, 357, doi: [10.1007/BF00733434](https://doi.org/10.1007/BF00733434) 957  
 937 Cane, H. V., Reames, D. V., & von Rosenvinge, T. T. 1988, 958  
 938 *JGR*, 93, 9555, doi: [10.1029/JA093iA09p09555](https://doi.org/10.1029/JA093iA09p09555) 959  
 Cane, H. V., Richardson, I. G., & Wibberenz, G. 1997,  
*JGR*, 102, 7075, doi: [10.1029/97JA00149](https://doi.org/10.1029/97JA00149)  
 Carnevale, G., Bruno, R., Marino, R., Pietropaolo, E., &  
 Raines, J. M. 2022, *A&A*, 661, A64,  
 doi: [10.1051/0004-6361/202040006](https://doi.org/10.1051/0004-6361/202040006)  
 Case, A. W., Kasper, J. C., Stevens, M. L., et al. 2020,  
*ApJS*, 246, 43, doi: [10.3847/1538-4365/ab5a7b](https://doi.org/10.3847/1538-4365/ab5a7b)  
 Domingo, V., Fleck, B., & Poland, A. I. 1995, *SoPh*, 162, 1,  
 doi: [10.1007/BF00733425](https://doi.org/10.1007/BF00733425)  
 Dresing, N., Kouloumvakos, A., Vainio, R., & Rouillard, A.  
 2022, *ApJL*, 925, L21, doi: [10.3847/2041-8213/ac4ca7](https://doi.org/10.3847/2041-8213/ac4ca7)  
 Fox, N. J., Velli, M. C., Bale, S. D., et al. 2016, *SSRv*, 204,  
 7, doi: [10.1007/s11214-015-0211-6](https://doi.org/10.1007/s11214-015-0211-6)  
 Galvin, A. B., Kistler, L. M., Popecki, M. A., et al. 2008,  
*SSRv*, 136, 437, doi: [10.1007/s11214-007-9296-x](https://doi.org/10.1007/s11214-007-9296-x)  
 Gold, R. E., Krimigis, S. M., Hawkins, S. E., I., et al. 1998,  
*SSRv*, 86, 541, doi: [10.1023/A:1005088115759](https://doi.org/10.1023/A:1005088115759)  
 Haggerty, D. K., & Roelof, E. C. 2002, *ApJ*, 579, 841,  
 doi: [10.1086/342870](https://doi.org/10.1086/342870)

- Henney, C. J., Toussaint, W. A., White, S. M., & Arge, C. N. 2012, *Space Weather*, 10, S02011, doi: [10.1029/2011SW000748](https://doi.org/10.1029/2011SW000748)
- Heras, A. M., Sanahuja, B., Lario, D., et al. 1995, *ApJ*, 445, 497, doi: [10.1086/175714](https://doi.org/10.1086/175714)
- Heras, A. M., Sanahuja, B., Sanderson, T. R., Marsden, R. G., & Wenzel, K. P. 1994, *JGR*, 99, 43, doi: [10.1029/93JA02826](https://doi.org/10.1029/93JA02826)
- Heyner, D., Auster, H. U., Fornaçon, K. H., et al. 2021, *SSRv*, 217, 52, doi: [10.1007/s11214-021-00822-x](https://doi.org/10.1007/s11214-021-00822-x)
- Hickmann, K. S., Godinez, H. C., Henney, C. J., & Arge, C. N. 2015, *SoPh*, 290, 1105, doi: [10.1007/s11207-015-0666-3](https://doi.org/10.1007/s11207-015-0666-3)
- Hill, M. E., Mitchell, D. G., Andrews, G. B., et al. 2017, *Journal of Geophysical Research (Space Physics)*, 122, 1513, doi: [10.1002/2016JA022614](https://doi.org/10.1002/2016JA022614)
- Horbury, T. S., O'Brien, H., Carrasco Blazquez, I., et al. 2020, *A&A*, 642, A9, doi: [10.1051/0004-6361/201937257](https://doi.org/10.1051/0004-6361/201937257)
- Howard, R. A., Moses, J. D., Vourlidas, A., et al. 2008, *SSRv*, 136, 67, doi: [10.1007/s11214-008-9341-4](https://doi.org/10.1007/s11214-008-9341-4)
- Huovelin, J., Vainio, R., Kilpua, E., et al. 2020, *SSRv*, 216, 94, doi: [10.1007/s11214-020-00717-3](https://doi.org/10.1007/s11214-020-00717-3)
- Isavnin, A., Vourlidas, A., & Kilpua, E. K. J. 2014, *SoPh*, 289, 2141, doi: [10.1007/s11207-013-0468-4](https://doi.org/10.1007/s11207-013-0468-4)
- Janvier, M., Winslow, R. M., Good, S., et al. 2019, *Journal of Geophysical Research (Space Physics)*, 124, 812, doi: [10.1029/2018JA025949](https://doi.org/10.1029/2018JA025949)
- Jin, M., Nitta, N. V., & Cohen, C. M. S. 2022, *Space Weather*, 20, e02894, doi: [10.1029/2021SW002894](https://doi.org/10.1029/2021SW002894)
- Jokipii, J. R. 1971, *Reviews of Geophysics and Space Physics*, 9, 27, doi: [10.1029/RG009i001p00027](https://doi.org/10.1029/RG009i001p00027)
- Kaiser, M. L., Kucera, T. A., Davila, J. M., et al. 2008, *SSRv*, 136, 5, doi: [10.1007/s11214-007-9277-0](https://doi.org/10.1007/s11214-007-9277-0)
- Kasper, J. C., Abiad, R., Austin, G., et al. 2016, *SSRv*, 204, 131, doi: [10.1007/s11214-015-0206-3](https://doi.org/10.1007/s11214-015-0206-3)
- Kilpua, E., Koskinen, H. E. J., & Pulkkinen, T. I. 2017, *Living Reviews in Solar Physics*, 14, 5, doi: [10.1007/s41116-017-0009-6](https://doi.org/10.1007/s41116-017-0009-6)
- Klein, K.-L., & Dalla, S. 2017, *SSRv*, 212, 1107, doi: [10.1007/s11214-017-0382-4](https://doi.org/10.1007/s11214-017-0382-4)
- Kouloumvakos, A., Kown, R., Rodriguez-Garcia, L., et al. 2022, *A&A*, doi: [10.1051/0004-6361/202142515](https://doi.org/10.1051/0004-6361/202142515)
- Kress, B. T., Rodriguez, J. V., & Onsager, T. G. 2020, in *The GOES-R Series*, ed. S. J. Goodman, T. J. Schmit, J. Daniels, & R. J. Redmon (Elsevier), 243–250, doi: <https://doi.org/10.1016/B978-0-12-814327-8.00020-2>
- Kwon, R.-Y., & Vourlidas, A. 2017, *ApJ*, 836, 246, doi: [10.3847/1538-4357/aa5b92](https://doi.org/10.3847/1538-4357/aa5b92)
- Kwon, R.-Y., Zhang, J., & Olmedo, O. 2014, *ApJ*, 794, 148, doi: [10.1088/0004-637X/794/2/148](https://doi.org/10.1088/0004-637X/794/2/148)
- Lario, D., Decker, R. B., Malandraki, O. E., & Lanzerotti, L. J. 2008, *Journal of Geophysical Research (Space Physics)*, 113, A03105, doi: [10.1029/2007JA012721](https://doi.org/10.1029/2007JA012721)
- Lario, D., Ho, G. C., Roelof, E. C., Decker, R. B., & Anderson, B. J. 2013, in *American Institute of Physics Conference Series*, Vol. 1539, *Solar Wind 13*, ed. G. P. Zank, J. Borovsky, R. Bruno, J. Cirtain, S. Cranmer, H. Elliott, J. Giacalone, W. Gonzalez, G. Li, E. Marsch, E. Moebius, N. Pogorelov, J. Spann, & O. Verkhoglyadova, 215–218, doi: [10.1063/1.4811026](https://doi.org/10.1063/1.4811026)
- Lario, D., Kwon, R. Y., Riley, P., & Raouafi, N. E. 2017, *ApJ*, 847, 103, doi: [10.3847/1538-4357/aa89e3](https://doi.org/10.3847/1538-4357/aa89e3)
- Lario, D., & Roelof, E. C. 2010, in *American Institute of Physics Conference Series*, Vol. 1216, *Twelfth International Solar Wind Conference*, ed. M. Maksimovic, K. Issautier, N. Meyer-Vernet, M. Moncuquet, & F. Pantellini, 639–642, doi: [10.1063/1.3395947](https://doi.org/10.1063/1.3395947)
- Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, *SoPh*, 275, 17, doi: [10.1007/s11207-011-9776-8](https://doi.org/10.1007/s11207-011-9776-8)
- Lin, R. P., Anderson, K. A., Ashford, S., et al. 1995, *SSRv*, 71, 125, doi: [10.1007/BF00751328](https://doi.org/10.1007/BF00751328)
- Luhmann, J. G., Curtis, D. W., Schroeder, P., et al. 2008, *SSRv*, 136, 117, doi: [10.1007/s11214-007-9170-x](https://doi.org/10.1007/s11214-007-9170-x)
- Luhmann, J. G., Mays, M. L., Odstrcil, D., et al. 2017, *Space Weather*, 15, 934, doi: [10.1002/2017SW001617](https://doi.org/10.1002/2017SW001617)
- Marubashi, K., & Lepping, R. P. 2007, *Annales Geophysicae*, 25, 2453, doi: [10.5194/angeo-25-2453-2007](https://doi.org/10.5194/angeo-25-2453-2007)
- McComas, D. J., Bame, S. J., Barker, P., et al. 1998, *SSRv*, 86, 563, doi: [10.1023/A:1005040232597](https://doi.org/10.1023/A:1005040232597)
- McComas, D. J., Alexander, N., Angold, N., et al. 2016, *SSRv*, 204, 187, doi: [10.1007/s11214-014-0059-1](https://doi.org/10.1007/s11214-014-0059-1)
- Mewaldt, R. A., Cohen, C. M. S., Cook, W. R., et al. 2008, *SSRv*, 136, 285, doi: [10.1007/s11214-007-9288-x](https://doi.org/10.1007/s11214-007-9288-x)
- Meyer, P., Parker, E. N., & Simpson, J. A. 1956, *Physical Review*, 104, 768, doi: [10.1103/PhysRev.104.768](https://doi.org/10.1103/PhysRev.104.768)
- Mitchell, J. G., De Nolfo, G. A., Hill, M. E., et al. 2021, *ApJ*, 919, 119, doi: [10.3847/1538-4357/ac110e](https://doi.org/10.3847/1538-4357/ac110e)
- Müller, D., St. Cyr, O. C., Zouganelis, I., et al. 2020, *A&A*, 642, A1, doi: [10.1051/0004-6361/202038467](https://doi.org/10.1051/0004-6361/202038467)
- Müller-Mellin, R., Kunow, H., Fleißner, V., et al. 1995, *SoPh*, 162, 483, doi: [10.1007/BF00733437](https://doi.org/10.1007/BF00733437)
- Müller-Mellin, R., Böttcher, S., Falenski, J., et al. 2008, *SSRv*, 136, 363, doi: [10.1007/s11214-007-9204-4](https://doi.org/10.1007/s11214-007-9204-4)
- Mulligan, T., Russell, C. T., Anderson, B. J., et al. 1999, *JGR*, 104, 28217, doi: [10.1029/1999JA900215](https://doi.org/10.1029/1999JA900215)
- Nolte, J. T., & Roelof, E. C. 1973, *SoPh*, 33, 241, doi: [10.1007/BF00152395](https://doi.org/10.1007/BF00152395)
- Owen, C. J., Bruno, R., Livi, S., et al. 2020, *A&A*, 642, A16, doi: [10.1051/0004-6361/201937259](https://doi.org/10.1051/0004-6361/201937259)



- 1057 Owens, M. J. 2016, *ApJ*, 818, 197, 1089  
 1058 doi: [10.3847/0004-637X/818/2/197](https://doi.org/10.3847/0004-637X/818/2/197) 1090
- 1059 Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 1091  
 1060 2012, *SoPh*, 275, 3, doi: [10.1007/s11207-011-9841-3](https://doi.org/10.1007/s11207-011-9841-3) 1092
- 1061 Pinto, M., , Sanchez-Cano, B., et al. 2022, *SSRv* 1093
- 1062 Pomoell, J., & Poedts, S. 2018, *Journal of Space Weather* 1094  
 1063 *and Space Climate*, 8, A35, doi: [10.1051/swsc/2018020](https://doi.org/10.1051/swsc/2018020) 1095
- 1064 Richardson, I. G. 2018, *Living Reviews in Solar Physics*, 15, 1096  
 1065 1, doi: [10.1007/s41116-017-0011-z](https://doi.org/10.1007/s41116-017-0011-z) 1097
- 1066 Richardson, I. G., & Cane, H. V. 1996, *JGR*, 101, 27521, 1098  
 1067 doi: [10.1029/96JA02643](https://doi.org/10.1029/96JA02643) 1099
- 1068 Rodríguez-Pacheco, J., Wimmer-Schweingruber, R. F., 1100  
 1069 Mason, G. M., et al. 2020, *A&A*, 642, A7, 1101  
 1070 doi: [10.1051/0004-6361/201935287](https://doi.org/10.1051/0004-6361/201935287) 1102
- 1071 Roelof, E. C. 1969, in *Lectures in High-Energy* 1103  
 1072 *Astrophysics*, ed. H. Ögelman & J. R. Wayland, 111 1104
- 1073 Schatten, K. H. 1971, *Cosmic Electrodynamics*, 2, 232 1105
- 1074 Schatten, K. H., Wilcox, J. M., & Ness, N. F. 1969, *SoPh*, 1106  
 1075 6, 442, doi: [10.1007/BF00146478](https://doi.org/10.1007/BF00146478) 1107
- 1076 Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, *SoPh*, 1108  
 1077 275, 207, doi: [10.1007/s11207-011-9834-2](https://doi.org/10.1007/s11207-011-9834-2) 1109
- 1078 Smart, D. F., & Shea, M. A. 1985, *JGR*, 90, 183, 1110  
 1079 doi: [10.1029/JA090iA01p00183](https://doi.org/10.1029/JA090iA01p00183) 1111
- 1080 Smith, C. W., L'Heureux, J., Ness, N. F., et al. 1998, *SSRv*, 113 1112  
 1081 86, 613, doi: [10.1023/A:1005092216668](https://doi.org/10.1023/A:1005092216668) 1114
- 1082 Stone, E. C., Frandsen, A. M., Mewaldt, R. A., et al. 1998, 1115  
 1083 *SSRv*, 86, 1, doi: [10.1023/A:1005082526237](https://doi.org/10.1023/A:1005082526237) 1116
- 1084 Temmer, M., Holzknecht, L., Dumbović, M., et al. 2021, 1117  
 1085 *Journal of Geophysical Research (Space Physics)*, 126, 1118  
 1086 e28380, doi: [10.1029/2020JA028380](https://doi.org/10.1029/2020JA028380) 1119
- 1087 Torsti, J., Laitinen, T., Vainio, R., et al. 1997, *SoPh*, 175, 1120  
 1088 771, doi: [10.1023/A:1004944222260](https://doi.org/10.1023/A:1004944222260) 1121
- 1089 Torsti, J., Valtonen, E., Lumme, M., et al. 1995, *SoPh*, 162, 1122  
 1090 505, doi: [10.1007/BF00733438](https://doi.org/10.1007/BF00733438) 1123
- 1091 Vainio, R., Valtonen, E., Heber, B., et al. 2013, *Journal of* 1124  
 1092 *Space Weather and Space Climate*, 3, A12, 1125  
 1093 doi: [10.1051/swsc/2013030](https://doi.org/10.1051/swsc/2013030) 1126
- 1094 von Roseninge, T. T., Reames, D. V., Baker, R., et al. 1127  
 1095 2008, *SSRv*, 136, 391, doi: [10.1007/s11214-007-9300-5](https://doi.org/10.1007/s11214-007-9300-5) 1128
- 1096 Wallace, S., Arge, C. N., Pattichis, M., Hock-Mysliwiec, 1129  
 1097 R. A., & Henney, C. J. 2019, *SoPh*, 294, 19, 1130  
 1098 doi: [10.1007/s11207-019-1402-1](https://doi.org/10.1007/s11207-019-1402-1) 1131
- 1099 Wiedenbeck, M. E., Angold, N. G., Birdwell, B., et al. 2017, 1132  
 1100 in *International Cosmic Ray Conference*, Vol. 301, 35th 1133  
 1101 *International Cosmic Ray Conference (ICRC2017)*, 16 1134
- 1102 Wijzen, N., Aran, A., Sanahuja, B., Pomoell, J., & Poedts, 1135  
 1103 S. 2020, *A&A*, 634, A82, 1136  
 1104 doi: [10.1051/0004-6361/201937026](https://doi.org/10.1051/0004-6361/201937026) 1137
- 1105 Wilson, Lynn B., I., Brosius, A. L., Gopalswamy, N., et al. 1138  
 1106 2021, *Reviews of Geophysics*, 59, e2020RG000714, 1139  
 1107 doi: [10.1029/2020RG000714](https://doi.org/10.1029/2020RG000714) 1140
- 1108 Wimmer-Schweingruber, R. F., Janitzek, N. P., Pacheco, 1141  
 1109 D., et al. 2021, *A&A*, 656, A22, 1142  
 1110 doi: [10.1051/0004-6361/202140940](https://doi.org/10.1051/0004-6361/202140940) 1143
- 1111 Winslow, R. M., Scolini, C., Lugaz, N., & Galvin, A. B. 1144  
 1112 2021, *ApJ*, 916, 40, doi: [10.3847/1538-4357/ac0439](https://doi.org/10.3847/1538-4357/ac0439) 1145
- 1113 Wraase, S., Heber, B., Böttcher, S., et al. 2018, *A&A*, 611, 1146  
 1114 A100, doi: [10.1051/0004-6361/201732063](https://doi.org/10.1051/0004-6361/201732063) 1147
- 1115 Wuelser, J.-P., Lemen, J. R., Tarbell, T. D., et al. 2004, in 1148  
 1116 *Society of Photo-Optical Instrumentation Engineers* 1149  
 1117 *(SPIE) Conference Series*, Vol. 5171, *Telescopes and* 1150  
 1118 *Instrumentation for Solar Astrophysics*, ed. S. Fineschi & 1151  
 1119 M. A. Gummin, 111–122, doi: [10.1117/12.506877](https://doi.org/10.1117/12.506877) 1152
- 1120 Zurbuchen, T. H., & Richardson, I. G. 2006, *SSRv*, 123, 31, 1153  
 1121 doi: [10.1007/s11214-006-9010-4](https://doi.org/10.1007/s11214-006-9010-4) 1154