



Tracking Solar Energetic Electrons from Corona to 1 AU: A Multi-Spacecraft Study of the 28 January 2025 Event

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Received: 15 May 2026 / Accepted: 21 August 2026
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Abstract

We report and analyze a solar energetic electron (SEE) event on January 28, 2025, associated with an extreme ultraviolet (EUV) jet and accompanied by type III and type II radio bursts. Combining multi-viewpoint in situ and remote-sensing observations with modeling, we trace the propagation of energetic electrons from the corona to interplanetary space across time, space, and energy. Potential Field Source Surface (PFSS) reconstruction shows that coronal type III burst sources and the EUV jet ejection direction generally align with open magnetic field lines. Time Difference of Arrival (TDOA) localization indicates that the interplanetary type III burst source lies along the Parker spiral leading to Wind, with electron-beam velocities of $0.06c - 0.17c$. Velocity Dispersion Analysis (VDA) of electrons detected by three spacecraft near 1 AU yields solar release times of 08:03–08:23 UT for Solar TErrestrial RELations Observatory-Ahead (STEREO-A) and 08:07–08:27 UT for Wind, with derived path lengths of 1.2 ± 0.9 AU and 2.6 ± 1.6 AU, respectively. The path length for Wind exceeds the nominal Parker spiral length, suggesting a complex, non-ideal interplanetary magnetic field topology. This study presents a methodology for tracking SEEs from their source to interplanetary observers, providing observational constraints for space weather forecasting models. We also infer that the locally observed SEEs and the electron beams that excite interplanetary type III bursts may not be the same population, based on differences in their release and arrival times.

Keywords Solar physics · Solar electromagnetic emission · Active solar corona · Solar energetic electrons · Radio bursts · Solar coronal radio emission

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1. Introduction

Solar energetic particle (SEP) events involve elevated levels of energetic ions and electrons and are associated with explosive energy-conversion processes in the solar corona. These processes include solar flares, narrow coronal jets, and broad coronal mass ejections (CMEs). The energetic electron component of SEPs is commonly called a solar energetic electron (SEE) event. SEEs have been measured in situ in the interplanetary medium since the 1960s (see, for example, Van Allen and Krimigis 1965; Anderson and Lin 1966). Magnetic fields guide SEPs, so the interplanetary magnetic field structure influences their transport. In Parker's original work (Parker 1958), the magnetic field is assumed to extend radially outward from the Sun as an open field, creating the fundamental spiral structure of the interplanetary magnetic field.

Some ions and electrons are accelerated in the Sun's atmosphere (Kong et al. 2016; Chen et al. 2024), and imaging observations in extreme ultraviolet (EUV) and visible light help locate the coronal plasma dynamics where this acceleration occurs. EUV jets are associated with open magnetic field lines determined by potential magnetic field extrapolations, such as the Potential Field Source Surface (PFSS; Schrijver and De Rosa 2003; van Ballegooyen, Priest, and Mackay 2000) model, suggesting that energetic electrons can escape into interplanetary space via magnetic reconnection with surrounding magnetic fields (Shibata, Yokoyama, and Uchida 1996; Wang et al. 2023). The solar origin of impulsive SEP events has been linked to magnetic reconnection along open field lines, which are typically associated with solar jets (e.g., Mason et al. 2009; Krucker et al. 2011; Reames 2021; Lario et al. 2024). More specifically, energetic electrons in the 55–95 keV range, along with the associated EUV jet, were injected from the flare site toward the spacecraft's magnetic footpoints on the source surface. These electrons propagate along a strongly non-radial and inclined magnetic field beneath the source surface. The inclination angle of the jet trajectory and the respective magnetic field is measured at $63^\circ \pm 11^\circ$ relative to the radial direction (Klassen et al. 2018). More recently, Wang et al. (2026) presented results showing that energetic electrons are concentrated in a compact region just above a mini-flare arcade at the base of the jet spire. Their number density decreases by at least two orders of magnitude in the direction of the jet spire, away from this region.

In addition to EUV jets in the corona, some solar radio bursts are closely correlated with SEEs. The photons generated by SEEs as they propagate along open magnetic field lines can be clearly observed via in situ and solar radio measurements (Mason et al. 2009; Winter, Reiner, and Kaiser 2015). Electron beams traveling along these open field lines have a bulk speed of approximately 0.1–0.5c (Wild 1950; Chen et al. 2013; Reid and Ratcliffe 2014; Feng et al. 2025). These beams interact with the local plasma, generating Langmuir waves (Löring and Reid 2023). These electrostatic waves then decouple, producing radio-wave radiation at the plasma frequency or its second harmonic (Ginzburg and Zhelezniakov 1958; Reid and Ratcliffe 2014). The frequency of this emission is related to the local electron density by the following equation:

$$f_{pe} \text{ (Hz)} \approx 8980 \sqrt{n_e \text{ (cm}^{-3}\text{)}}, \quad (1)$$

where f_{pe} represents the plasma frequency and n_e denotes the electron density.

This radiation appears as distinct features that rapidly drift from high to low frequencies in dynamic spectra and is called a type III radio burst. These bursts are valuable for studying solar coronal properties (Reid and Ratcliffe 2014) and for understanding SEP acceleration

mechanisms (Reiner, Fainberg, and Kaiser 1998). For example, Klein et al. (2008) examined how magnetic fields direct energetic particles through the corona and into interplanetary space, ultimately reaching a spacecraft near Earth. Coronal emission imaging using the Nançay Radioheliograph has identified open flux tubes that guide these electrons, thereby explaining the particles detected at 1 AU. Analysis indicates that type III burst sources are typically found in open flux tubes, as determined by the PFSS model. The researchers concluded that non-radial open flux tubes can transport particles over several tens of degrees in longitude, even during simple impulsive events. However, exceptions exist; for instance, U-bursts, a subtype of type III bursts, follow closed magnetic field lines (Leblanc et al. 1999; Martinez Oliveros et al. 2020).

The spatial relationship between interplanetary type III bursts and the Parker spiral magnetic field is an active area of research. Several techniques have been employed to locate radio burst sources in the interplanetary medium, including goniopolarimetric (direction-finding) methods and the Time Difference of Arrival (TDOA) method. Goniopolarimetry utilizes the directional sensitivity of spacecraft antennas to estimate the arrival direction of radio waves. This information can then be combined with geometric triangulation to locate the source region at heliocentric distances of approximately 0.1–0.5 AU (Martinez Oliveros et al. 2012). However, this method is sensitive to spacecraft antenna properties, which can introduce uncertainties of several degrees in the wavevector direction, especially when the radio source is spatially extended or complex. In contrast, TDOA measures the time differences of radio bursts arriving at three or more spacecraft. It determines radio source trajectories and centroids by generating hyperbolic curves from pairwise time delays and identifying source locations at the intersections of these curves (Weber et al. 1977; Steinberg, Fainberg, and Stone 1984; Krupar et al. 2024). TDOA is particularly effective for tracking the radial propagation of radio sources along Parker spiral field lines, as it provides direct information about trajectories rather than just a single direction for each frequency. In a comparison of these two methods (along with an intensity-fitting technique) for localizing interplanetary type III bursts using data from four spacecraft, Krupar et al. (2024) found that the different approaches yielded consistent results within their respective uncertainties. Each method has its own advantages: goniopolarimetry can provide source directions for individual frequency channels from either a single spacecraft or a pair of spacecraft, whereas TDOA requires at least three spacecraft but directly reconstructs source trajectories.

However, even with these well-established localization techniques, research findings on the relationship between interplanetary type III bursts and Parker spirals remain inconsistent. Using TDOA triangulation, some studies have found that type III burst sources align well with Parker spiral field lines (Reiner et al. 2009; Cañizares et al. 2025). For instance, Cañizares et al. (2025), employing five-spacecraft TDOA localization, found that apparent radio sources followed an Archimedean Parker spiral, with an associated solar wind velocity of about 493 km/s, consistent with the speed observed at 1 AU for the relevant longitude connecting to the solar surface at 75° east. Conversely, other studies using different approaches have reported poorer agreement. Nitta et al. (2006), using PFSS magnetic field extrapolation to compare source surface connectivity, found that in only 40% of cases did the modeled open field lines closely connect the photospheric source region to the spacecraft's Parker spiral coordinates. More recently, Deshpande et al. (2025), combining radio density diagnostics with the European Heliospheric Forecasting Information Asset (EUHFORIA) solar wind modeling, found that type III bursts do not always follow the Parker spiral, but instead trace distinct magnetic field lines oriented differently.

SEPs are significant aspects of space weather disturbances (Kouloumvakos et al. 2022, 2024). These energetic particles interact with spaceborne and potentially airborne electronics, contributing to galactic cosmic rays, a radiation source in Earth's atmosphere. As they

pose a serious threat to astronauts outside the magnetosphere's protection, SEPs are a key consideration in space exploration. SEEs emit radio-frequency radiation detectable by radio telescopes. Radio observations can determine the location of the radio source, thereby enabling SEE tracking in interplanetary space. Combined with EUV and optical imaging and in situ observations, this enables a detailed investigation of SEP propagation across time, location, and energy, providing the physical basis for space weather forecasting.

This paper uses radio, EUV, and optical imaging, along with multi-vantage-point in situ and remote observations, to trace energetic electrons between the Sun and Earth. The paper structure is as follows: Section 2 presents observations and methods. Section 3 discusses electron propagation time and energy. Section 4 outlines their interplanetary propagation paths. Section 5 summarizes and discusses the results.

2. Observations and Methods

2.1. Observational Data

The imaging data used in this study were obtained from three primary instruments: the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012), both of which are located on board the Solar Dynamics Observatory (SDO), as well as the Mingantu Spectral Radiograph at the low-frequency band (MUSER-L; Yan et al. 2025).

For solar radio dynamics spectral data, we utilized observations from the Chashan Solar Observatory (CSO; Feng et al. 2018; Chang et al. 2024) at metric wavelengths. Additionally, we incorporated data from several instruments operating over decameter-to-kilometer wavelengths. These include the Radio and Plasma Waves instrument on the Wind spacecraft (Wind/WAVES; Bougeret et al. 1995), the Waves instrument on the Solar Terrestrial RElations Observatory-Ahead (STEREO-A/WAVES; Kaiser et al. 2008), and the Radio and Plasma Waves instrument on Solar Orbiter (Solar Orbiter/RPW; Maksimovic et al. 2020). Moreover, we gathered in situ energetic electron observational data from the Wind 3-D Plasma and Energetic Particle Experiment (Wind/3DP; Lin et al. 1995), the Solar Electron and Proton Telescope (SEPT) on board STEREO-A (STEREO-A SEPT; Müller-Mellin et al. 2008), and the Energetic Particle Detector (EPD) suite aboard Solar Orbiter (Solar Orbiter EPD; Rodríguez-Pacheco et al. 2020).

The AIA captures images of the Sun across ten passbands covering the soft X-ray and EUV regions. This enables researchers to study processes occurring in the Sun's various atmospheric layers, including the chromosphere, transition region, and corona. The AIA has a pixel scale of $0.6''$ per pixel and operates at a cadence of 12 s. HMI observes the Fe I absorption line centered at $6173.3 \text{ \AA}$, using a 4096×4096 CCD detector to image the entire solar disk, providing a spatial resolution of approximately $1.1''$. The HMI offers two main observation cadences: a 45 s cadence for line-of-sight measurements and a 720 s cadence for vector magnetic field assessments, ensuring comprehensive and continuous monitoring of the Sun's photospheric properties. The MUSER-L operates at 30–400 MHz and consists of an extensive array of $100 + 124$ log-periodic dipole antenna elements. The system achieves an excellent frequency resolution of 1–8 MHz and a temporal resolution of 100 ms, enabling the detailed capture of rapid solar radio bursts. With a baseline length of 3000 meters, the radioheliograph provides remarkable spatial resolution ranging from $1.7'$ at 240 MHz to $14'$ at 30 MHz. The MUSER-L has been precisely calibrated using bright celestial radio sources

(including Virgo A and Cygnus A) and artificial transmitters, effectively minimizing spurious sidelobe responses that could produce false source positions. Cross-comparison with observations from other independent radio arrays has also confirmed the accuracy of the source positions derived from MUSER-L images.

The CSO spectrograph operates over 90 to 600 MHz, with a frequency resolution of approximately 76 kHz. In standard operating mode, it provides a temporal resolution of about 10 ms, which can be reduced to 0.2 ms in enhanced mode. The instrument features a 12-meter-diameter mesh parabolic reflector, equipped with a dual linearly polarized log-periodic feed. The Wind/WAVES instrument operates from 20 kHz to 14 MHz and has a time resolution of 60 s. It uses three whip antennas to measure radio and plasma wave phenomena in the solar wind and the magnetosphere. The STEREO/WAVES instrument covers 10 kHz to 16 MHz and has a time resolution of 35 s. This system includes monopole electric antennas and multiple receivers to detect interplanetary radio emissions and plasma waves in situ. The Solar Orbiter/RPW spans a comprehensive frequency range: 0.4 to 16.4 MHz for the high-frequency receiver (HFR), approximately DC to 10 kHz for the low-frequency receiver (LFR), and 0.2 to 200 kHz for the time-domain sampler (TDS). The time resolutions vary: the HFR allows 2 to 22 s (down to 0.07 s in special configurations), the LFR offers 0.25 to 20 s, and the TDS operates at 65.5 to 524 kHz.

The Wind/3DP instrument consists of four electron-specific detector channels that cover an energy range from 3 eV to 1 MeV. For standard measurements, the time resolution is 24 s, while full 4π steradian coverage during each spacecraft spin is achieved at 3 s resolution. The instrument achieves an energy resolution of $\Delta E/E \sim 0.3$, and its angular resolution is $22.5^\circ \times 36^\circ$. The STEREO-A SEPT instrument uses two dual, double-ended magnet/foil telescopes to measure energetic electrons in the 30–80 keV range. This instrument features four energy windows covering 35–5 keV, 65–25 keV, 125–55 keV, and 255–85 keV, with a maximum temporal resolution of 1 min. The Solar Orbiter EPD measures electrons using three complementary instruments: the STEP instrument covers 2–80 keV with 24 energy channels and a maximum time resolution of 1 s; the EPT instrument covers 25–75 keV with 8 energy channels and a maximum time resolution of 1 s (with standard measurements at 30 s and fast measurements at 5 s); and the HET instrument covers 0.3–8 MeV with 4 energy channels, also having a maximum time resolution of 1 s (30 s standard and 5 s fast). Together, these instruments provide comprehensive electron energy coverage from 2 keV to 30 MeV, with four fields of view: sunward, anti-sunward, north, and south for both EPT and HET.

2.2. PFSS

The PFSS model is an essential technique for modeling the solar coronal magnetic field under the assumption of current-free conditions, expressed as $\nabla \times \mathbf{B} = 0$. This assumption is valid in the region between the solar photosphere and a designated source surface, typically placed at $2.5 R_\odot$. The method determines the magnetic field configuration by using observed photospheric magnetic fields as boundary conditions and enforcing a radial magnetic field at the source surface.

PFSS implementations, such as the one found in *sunkit-magex* (see [The SunPy Community et al. 2020](#)), utilize a numerical approach based on a regular 3D grid in (ϕ, s, ρ) coordinates. Here, $\rho = \ln(r)$, with r representing the radial coordinate in spherical coordinates. This grid structure, combined with finite-difference techniques, enables efficient computation of the coronal magnetic field. It achieves this by solving for a scalar potential Φ , from which the magnetic field is derived using the relation $\mathbf{B} = -\nabla\Phi$. Substituting this

expression into the Maxwell equation $\nabla \cdot \mathbf{B} = 0$ leads to the Laplace equation for the potential: $\nabla^2 \Phi = 0$. This equation is then solved under the boundary conditions defined by the observed photospheric magnetic field and the radial magnetic field at the source surface.

In the implemented code, the PFSS calculation utilizes HMI synoptic magnetogram data (`hmi.synoptic_mr_polfil_720s.2293.Mr_polfil.fits`) as the boundary condition. The model uses 25 radial grid points ($n_\rho = 25$) and a source surface radius of 2.5 solar radii ($r_{ss} = 2.5R_\odot$). A `sunkit_magex.pfss.Input` object is created using the HMI magnetogram, grid parameters, and source surface radius. The code then uses this object to compute the PFSS solution. The code generates 100 seed points in the helioprojective frame to trace magnetic field lines from the photosphere through the corona, offering insights into the structure of the coronal magnetic field.

The field lines are traced using a `tracing.PerformanceTracer` with a maximum of 10,000 steps to ensure complete tracing through the corona. The visualization process involves plotting the traced magnetic field lines over the observed data, with error handling to skip invalid field lines and ensure smooth plotting. Finally, the source surface is visualized as a reference boundary, providing a comprehensive view of the coronal magnetic field configuration.

2.3. TDOA

The TDOA method for triangulating radio-burst positions relies on time delays between signal arrivals at multiple spacecraft to reconstruct the source trajectory. A key assumption is that the radio source emits isotropically, meaning it radiates equally in all directions. This technique is based on the principle of geometric hyperbolae, where each spacecraft pair serves as the foci of a hyperbola. The hyperbola's curvature depends on the signal delay between the two spacecraft. By intersecting hyperbolae from different spacecraft pairs, we can determine the source position, assuming coplanarity (for example, in the ecliptic plane) for simplicity. Deviations from isotropic emission, such as anisotropic radiation patterns due to density inhomogeneities along the magnetic field, could introduce localization uncertainties. However, for interplanetary type III bursts, the emission is generally expected to be broadly directed along the magnetic field. Thus, the geometry provided by three-spacecraft TDOA presents a reasonable first-order approximation of the source location. This approach is enabled by publicly available data, particularly the STEREO radio spectrograms archived as CDF files (Krupar et al. 2022), which enable consistent analysis across spacecraft such as STEREO-A, Solar Orbiter, and Wind.

The workflow for deriving the trajectory of a type III radio burst using TDOA involves four key steps. First, we download radio spectrograph data and slice it to isolate the feature of interest across all spacecraft. Next, we generate position vectors for each spacecraft at the time of interest. Then, we extract features from the spectrograms. This involves identifying the 'rise', 'peak', and 'fall' times for each frequency channel. Specifically, these are defined as follows: 'Rise' time: the first timestamp at which the signal exceeds half of the peak flux. 'Peak' time: the timestamp at which the peak flux occurs. 'Fall' time: the last timestamp before the signal drops below half of the peak flux. The data points in the $(1/f, t)$ format are then fitted with a smooth curve, typically a fourth-degree polynomial in $\log_{10}(1/f)$. The polynomial can be expressed as follows: $t = Ax^4 + Bx^3 + Cx^2 + Dx + E$, where $x = \log_{10}(1/f)$. Here, t represents time (e.g., signal arrival time), f is the frequency of the radio signal, and A, B, C, D, E are the polynomial coefficients derived from the extracted feature data. We then calculate the time delays between spacecraft pairs and use their positions to iteratively solve the hyperbolic equations across frequencies. This process yields the source position as a function of frequency.

2.4. Electron Beam Velocity Estimates

The frequency of plasma emission that results in type III radio bursts, denoted as f_p , is directly proportional to the electron plasma density as shown in Equation 1. For radio emissions at the second harmonic frequency ($f = 2 \times f_{pe}$), the frequency drift rate $\frac{df}{dt}$ can be used to determine the velocity v of the electron beam generating the plasma emission, following this relation:

$$v \approx \frac{\sqrt{n_e}}{8980} \left(\frac{dn_e}{dr} \right)^{-1} \frac{df}{dt}. \quad (2)$$

The drift rate (df/dt) of type III radio bursts was estimated directly from dynamic spectra by computing the ratio between the central frequency and time. The unknown quantity in the above equation is the plasma density, n_e . As the electron density decreases radially in the corona, a density model is required to determine the density at a specific height: $n_e = n_e(r)$. We used the following density model from Kontar et al. (2019) to obtain the velocities of type III bursts in coronal and interplanetary space.

$$n_e(r) = 4.8 \times 10^9 \left(\frac{R_\odot}{r} \right)^{14} + 3 \times 10^8 \left(\frac{R_\odot}{r} \right)^6 + 1.4 \times 10^6 \left(\frac{R_\odot}{r} \right)^{2.3}. \quad (3)$$

3. Propagation Time and Energy

Figure 1 illustrates the X-ray and radio emissions produced by a solar eruption on January 28, 2025. In panel a, we observe a slight increase in solar X-ray radiation around 08:00 UT in the 0.5–4 Å band. Panel b shows the corresponding solar radio bursts, including both type II and type III. The type III bursts occurred between approximately 50 kHz and 300 MHz from about 08:00 to 10:00 UT, while the type II bursts were detected in the frequency range of 50 to 200 MHz during the period from 08:10 to 08:20 UT. Notably, the type III bursts are discontinuous within the 50–150 MHz frequency range. Panel c zooms in on the coronal type III bursts in the 140–320 MHz range during 08:01 to 08:03 UT, revealing that most terminate at around 150 MHz. These type III bursts exhibit a clear frequency drift from higher to lower frequencies, with ten such bursts identified and marked by dotted lines in the panel.

Figure 2 presents both EUV and radio imaging observations. The EUV image, captured by the AIA and taken in the 171 Å band, shows an EUV jet emerging from the southwestern limb of the Sun, marked by a white circle. Notably, no active regions are visible along AIA's line of sight in this image. Simultaneously, a similar EUV jet, also indicated by a white circle, appears in the STEREO-A 171 Å band image at a comparable location, as illustrated in Figure 2b. This jet closely resembles the one in the AIA image, suggesting they are the same EUV jet. Brightening points on the solar surface associated with this eruption are indicated by an arrow in the panel, highlighting the location of the related active region, which is situated approximately 100'' west of AIA's limb. Since this active region lies on the far side of the Sun relative to AIA's line of sight, no eruption structures are visible within its field of view. Panels c and d display MUSER-L images at 36 MHz and 142 MHz, respectively. These images reveal distinct brightening structures in the Sun's southwestern quadrant, corresponding to the locations of coronal type III radio bursts shown in Figure 1c.

Figure 3 illustrates the radial distances and speeds of the energetic electron beams that are responsible for emitting type III radio bursts in both the corona and interplanetary space. The

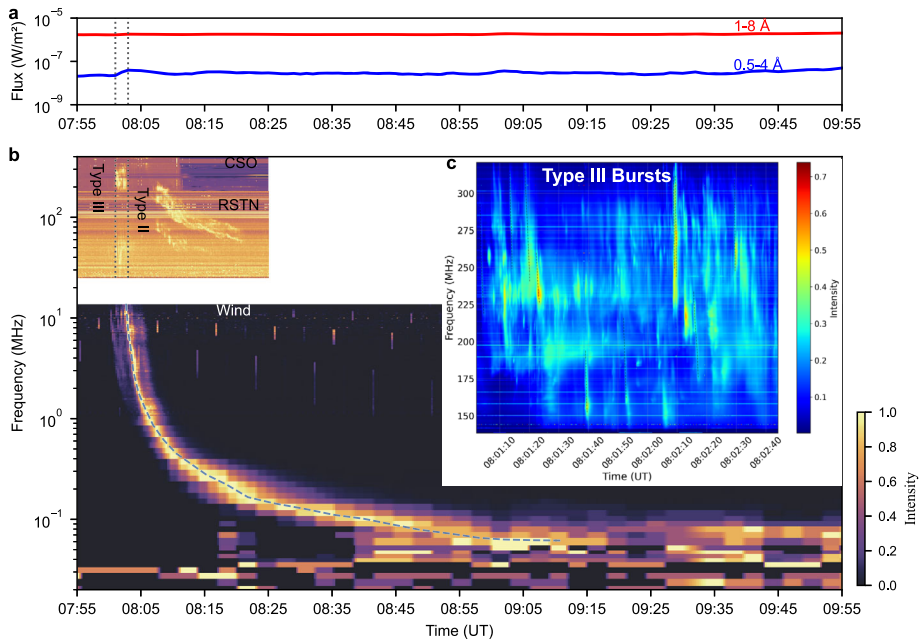


Figure 1 a, Temporal evolution of soft X-ray flux in the 1–8 Å (red) and 0.5–4 Å (blue) bands from 07:55 to 09:55 UT. Two dotted lines indicate the solar eruption between 08:01 and 08:03 UT. b, Solar radio spectrum covering 0.02–300 MHz, including CSO/RSTN data showing type II/III bursts (top) and Wind observations (bottom). Two dotted lines indicate coronal type III bursts observed from 08:01 to 08:03 UT, and a dashed curve represents the frequency drift of the interplanetary type III burst. c, Zoomed-in view of the coronal type III bursts from 08:01 to 08:03 UT, with dotted lines showing their frequency drift. Two color bars indicate the normalized radio-burst intensity.

speeds are estimated using the methodology described in Section 2.4, which relies on the frequency drift rates of the type III radio bursts and the electron density model presented in Equation 3. In the figure, the heliocentric distances traveled by electron beams emitting type III bursts in the 150–320 MHz range are framed by the black rectangular box, while those emitting in the 50 kHz–30 MHz range are shaded. The inset panel zooms in on the speeds within the rectangular box, showing that the electron beam speeds range from 0.07c to 0.42c. For the interplanetary type III bursts, the speeds of the electron beams range between 0.06c and 0.17c, which were calculated from the lower and upper frequency boundaries of the interplanetary type III bursts, respectively. The average speed of 0.11c corresponds to the middle frequency of the interplanetary type III bursts, as indicated by the dashed curve superimposed in Figure 1b.

This eruption produced a SEE event, detected in situ by three spacecraft: STEREO-A, Wind, and Solar Orbiter. The positions of the spacecraft are illustrated in Figure 4. The three curves in the figure – colored blue, black, and red – represent the Parker spirals associated with each spacecraft. The longitude and latitude coordinates of the intersection points of these spirals on the solar source surface at 2.5 $R_{\odot}$ (referred to as footpoints) are as follows: 88.6° and –7.3°, 60.7° and 5.8°, and 34.4° and –0.2°. We also calculated the spirals using a solar wind speed of 400 km/s.

Figure 5 shows how the flux of energetic electrons across various energy channels changes over time, as observed by three spacecraft. The maximum fluxes of energetic elec-

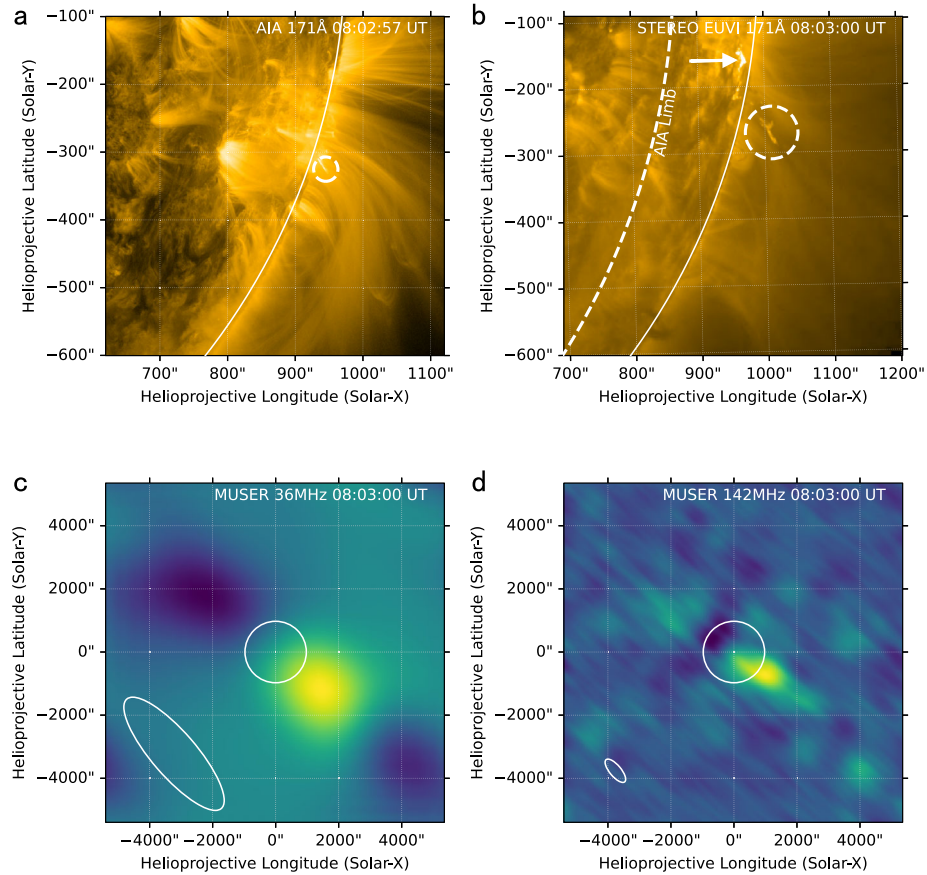


Figure 2 a, AIA 171 Å image taken at 08:02:57 UT, with a circle marking the EUV jet position. b, STEREO-A 171 Å image captured at 08:03:00 UT, showing the same jet (circle), the active region (arrow), and the AIA limb (dashed curve). c, MUSER-L radio imaging at 36 MHz (08:03:00 UT), with a circle marking the solar limb and an ellipse indicating the MUSER-L beam size. d, MUSER-L radio imaging at 142 MHz (08:03:00 UT).

trons are largely consistent among the spacecraft and peak around 10:20 UT. This timing corresponds with the “peak start” indicated in Figure 3, nearly coinciding with the arrival of the slowest energetic electron beams at approximately 1 AU, which excite the interplanetary type III burst.

To evaluate the onset of SEEs detected by each spacecraft, we performed a velocity dispersion analysis (VDA; see, e.g., Krucker et al. 1999; Kollhoff et al. 2021; Wang et al. 2023). This analysis assumes particles with varying energies are injected simultaneously, and that cross-field diffusion is negligible. From the particle onset times at different energy levels, we can calculate both the effective path length and the common solar injection time. A crucial aspect of this analysis is accurately determining the spacecraft’s arrival time, which depends on reliable methods for detecting event onset. One traditional approach is the $n\sigma$ threshold method, where an event onset is marked when the electron flux exceeds the background mean by a specified number of standard deviations (specifically, 3σ in this paper). The background is established from a quiet pre-event period, and the first instance when the

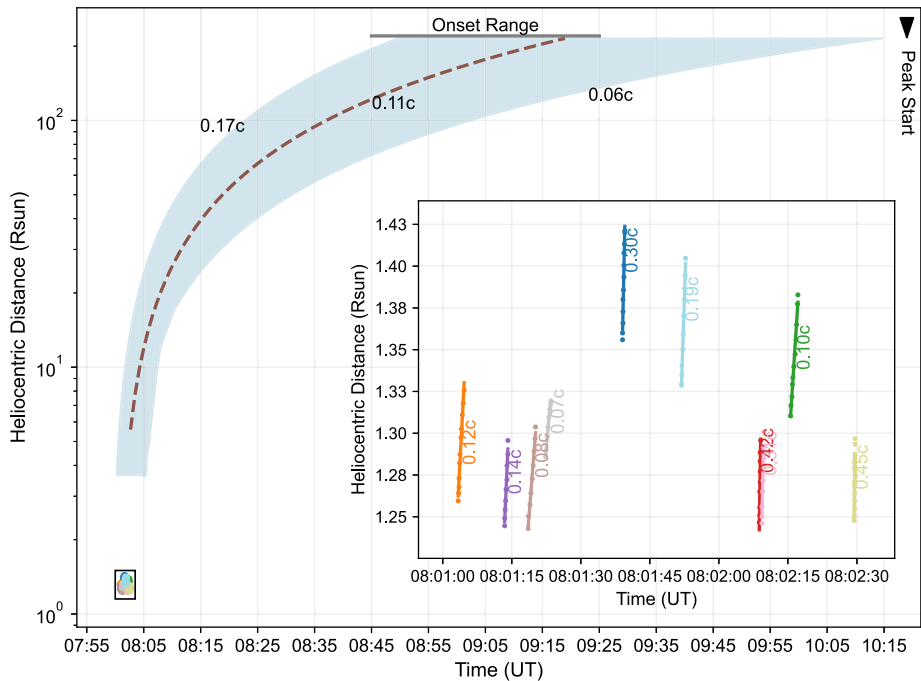


Figure 3 Radial distances and speeds of the energetic electron beams producing type III radio bursts: the main panel shows the interplanetary type III burst observed by Wind, and the inset panel displays results from the coronal type III bursts (dashed lines in Figure 1c). The farthest distance measured is 215 $R_{\odot}$. The term “Peak Start” refers to the maximum flux of the SEE event.

flux significantly exceeds this threshold indicates the observational start time $t_{\text{onset}}(E)$. This method provides a consistent, statistically grounded approach to identifying the onset and can be applied systematically across energy channels. Figure 6a illustrates the determined onsets at different spacecraft. In the figure, STEREO-A detected the SEE event first, followed by Wind and Solar Orbiter. Specifically, STEREO-A first detected the events between 08:25 and 08:35 UT, while Wind observed them between 08:45 and 09:25 UT. Notably, energetic electrons in higher-energy channels generally reach the spacecraft before those in lower-energy channels. The onset of Wind is also highlighted in Figure 3 by a thick horizontal line, showing that this earlier onset occurs before the arrival of the energetic electron beam that excites the interplanetary type III burst at 1 AU, and it only partially coincides with the arrival moment of the electron beam.

To determine the release time and path length of particles exhibiting velocity dispersion, the following function is often applied:

$$t_{\text{onset}}(E) = t_0 + 8.33 \frac{\min}{\text{AU}} \cdot \frac{L_0}{\beta(E)}. \quad (4)$$

The observed onset time of SEE, denoted as $t_{\text{onset}}(E)$ and measured in minutes, corresponds to particles with a specific kinetic energy E . The variable $\beta(E) = v(E)/c$ represents the velocity of these particles, where $v(E)$ is the particle velocity and c is the speed of light. The parameters t_0 (in minutes) and L_0 (AU) indicate the initial release time and the travel distance derived from this function, respectively. By plotting $\beta(E)$ on the x-axis and

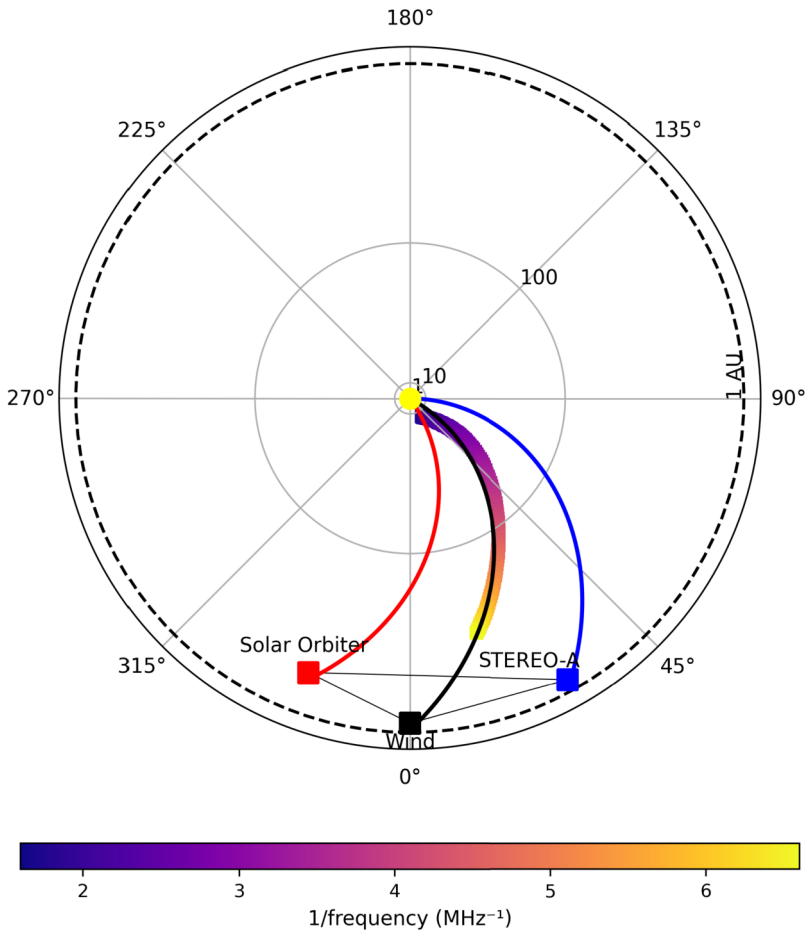


Figure 4 Three curves show Parker spirals connecting to the three spacecraft. Colored circles overlaid on the black curve represent source locations of interplanetary type III bursts determined using TDOA methods. The color bar indicates the frequency range of the interplanetary type III bursts used for these source locations.

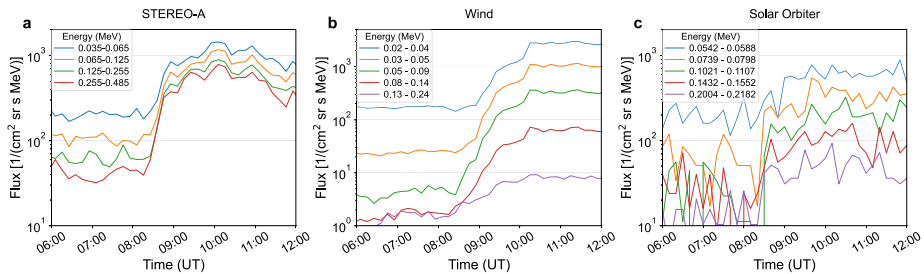


Figure 5 Energetic electron fluxes at different energy channels versus time detected by STEREO-A (a), Wind (b), and Solar Orbiter (c).

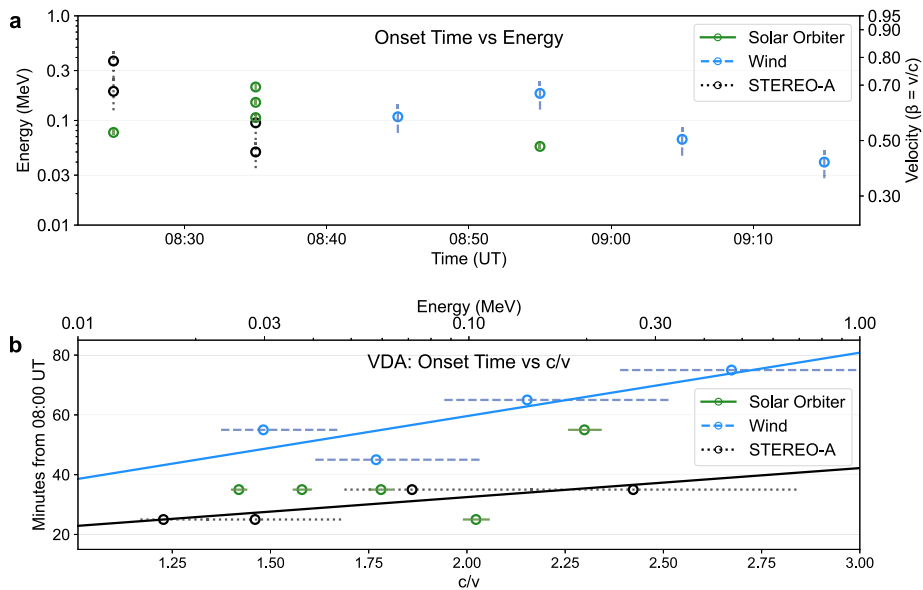


Figure 6 a, Onset time versus energy range determined from STEREO-A, Wind, and Solar Orbiter observations. Error bars indicate channel bins for different energy levels. b, Onset time versus energy range ($\beta = v/c$), with blue and black lines showing linear relationships from VDA analysis of Wind and STEREO-A data, respectively.

the observed t_{onset} on the y-axis, we can use orthogonal distance regression to fit a linear model to the data, as illustrated in Figure 6b. The energy uncertainty arises from the widths of the energy bins used by the three instruments, while the time uncertainty comes from 10-min intervals in the particle flux data. Using this methodology, we determined both the initial release times and the particles' travel paths. For the SEE detected by the STEREO-A spacecraft, the initial release times ranged from 08:03 to 08:23 UT, and the travel path was 1.2 ± 0.9 AU. In comparison, the times detected by the Wind spacecraft extended from 08:07 to 08:27 UT, with a travel path of 2.6 ± 1.6 AU. The release times indicate that the SEEs occurred after the end of the coronal type III burst at meter wavelengths, although they are partially consistent with the timing of the coronal type II burst.

Furthermore, the travel path of 1.2 ± 0.9 AU is close to the ideal length, consistent with Wang et al. (2023). However, the path length of 2.6 ± 1.6 AU suggests that the actual magnetic field path is longer than that of the ideal Parker spiral, consistent with findings from Badman et al. (2022). Recently, Wimmer-Schweingruber et al. (2023) reached a similar conclusion, noting that the inferred interplanetary magnetic field along which the solar energetic particles traveled was approximately three times the nominal length of the Parker spiral.

4. Propagation Paths

STEREO-A and Solar Orbiter detected the interplanetary type III radio burst almost simultaneously with Wind (Figures 1 and 7). Specifically, the interplanetary type III burst at ~ 1 MHz started at approximately 08:05 UT in the Wind/WAVES data, while the corresponding start times in the STEREO-A/WAVES and Solar Orbiter/RPW data are consistent

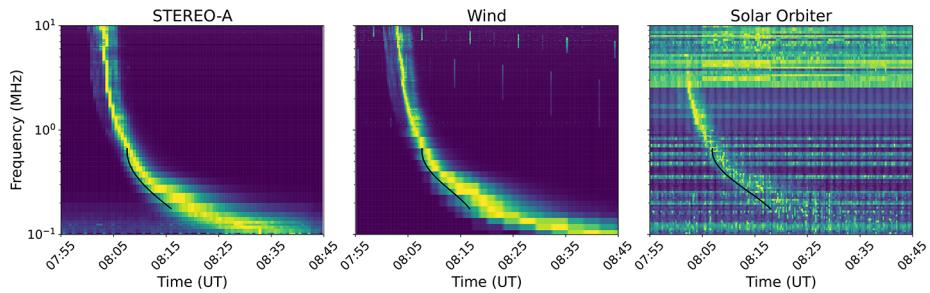


Figure 7 Radio spectra observed by STEREO-A, Wind, and Solar Orbiter, with an overlaid black curve showing the fitted equation $t = Ax^4 + Bx^3 + Cx^2 + Dx + E$, where $x = \log_{10}(1/f)$. The fitting data covers the frequency range from 1/6.6 MHz to 1/1.6 MHz.

with this time, making the three detections effectively simultaneous on the timescale of the burst's evolution (which spans tens of minutes). We determined the source locations using the TDOA method, focusing on the 'rise' times within the 1/6.6–1/1.6 MHz range. The fitted quartic curves (solid black lines) and identified source locations (colored circles) are shown in Figure 4. The sources lie 20–50 $R_{\odot}$ from the Sun and align with the Parker spiral toward the Wind, consistent with previous findings that interplanetary type III burst sources follow Parker spiral lines (Cañizares et al. 2025; Reiner 2026). We note that the Parker Solar Probe (PSP) is not shown in Figure 4. On 2025-01-28, PSP was at a heliocentric distance of ~ 0.75 AU on the opposite side of the Sun from the Earth-Sun line, and PSP/FIELDS data for this date are not yet publicly available, so no PSP observations can be used to assess this event.

The sources of the metric (coronal) type III bursts were accurately located using MUSER-L imaging data. We selected images captured at frequencies of 36, 65, 121, and 142 MHz during the peak emission of the type III burst, specifically between 08:01 and 08:03 UT. From these images, we identified the locations with the maximum brightness temperature, represented by blue symbols in Figure 8a. It is evident that the source locations of the type III bursts move away from the solar surface as the bursts drift from higher to lower frequencies. The angular resolution of MUSER-L at these frequencies ranges from $\sim 3.5'$ at 142 MHz to $\sim 14'$ at 30 MHz, and the measured source sizes (deconvolved from the beam) are on the order of $2' - 5'$ across the observed frequency channels, providing a positional uncertainty of approximately $\pm 2' - 7'$ depending on frequency. Figure 8 also displays the open magnetic field in the corona, represented by the red lines, as modeled by the PFSS. We selected the magnetic field lines that were closest to the coronal type III burst sources, adhering to criteria that required them to be within 10° of the source locations and to deviate by no more than 10° from the burst's propagation direction. Our observations show that these selected magnetic field lines broadly match the locations of the type III sources, and their orientation generally aligns with the burst's propagation direction. Additionally, the "Jet" label in the figure indicates the position of the EUV jet, highlighting that the jet's ejection direction generally aligns with the magnetic field lines, particularly the field line on the far right, as well as with the direction of coronal type III burst propagation.

Figure 2 shows the same EUV jets as captured in images from both the Wind and STEREO-A observations. The two spacecraft view the jet from different angles, allowing us to determine its three-dimensional (3D) position using the tie-pointing method introduced in Thompson and Reginald (2008) and Nisticò (2023). These 3D positions, along with the PFSS magnetic field lines and the footpoints connecting the three spacecraft, are illustrated

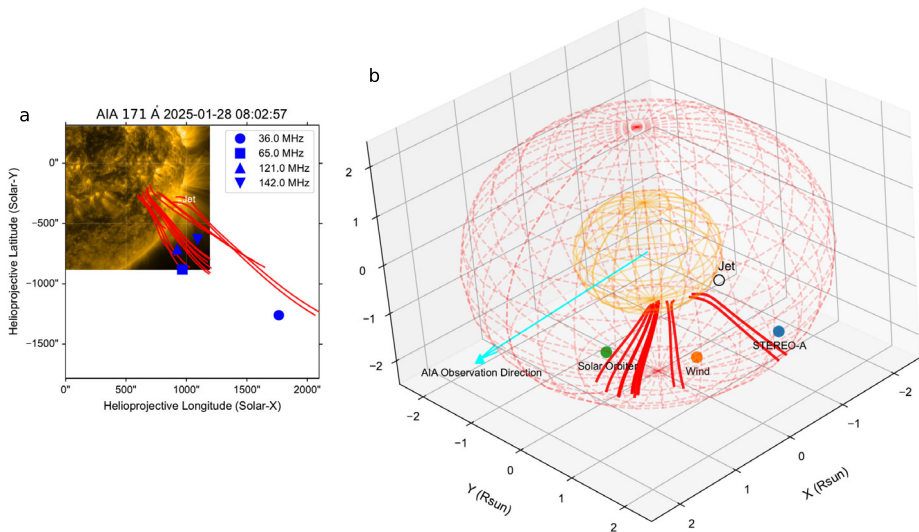


Figure 8 a, PFSS-extrapolated open magnetic field lines and peak brightness temperature positions from MUSER-L at different frequencies, overlaid on an AIA 171 Å image, with “Jet” indicating the ejecting EUV jet location. b, Footpoints of the Parker spiral connecting to STEREO-A, Wind, and Solar Orbiter, shown in 3D on the source surface. The inner yellow meshed shell represents the Sun, and the outer red meshed shell is at $2.5 R_{\odot}$. Red lines show PFSS-extrapolated magnetic field lines, and the label “Jet” indicates the EUV jet position.

in Figure 8b. This figure reveals that the distribution of the three footpoints is generally consistent with the magnetic field lines in the longitudinal direction. Furthermore, the EUV jet is situated closer to the magnetic field lines on the far right, near the STEREO-A footpoint. As discussed further in Section 5, this proximity explains why STEREO-A was the first to detect the SEE at around 1 AU, directly linking the observed arrival timing to the magnetic connectivity inferred from the EUV jet’s location.

5. Summary and Conclusions

This study presents a multi-instrument observational report of a SEE event that occurred on January 28, 2025. Rather than performing a dedicated theoretical analysis, our primary goal is to synthesize the available multi-spacecraft and multi-wavelength observations to provide a comprehensive observational characterization of the event, tracing the journey of energetic electrons from their acceleration and release in the solar corona to their propagation through interplanetary space, spanning various dimensions of time, location, and energy. The main conclusions are as follows:

1. **3D Tracing of Energetic Electron Beams:** We successfully linked the propagation of energetic electron beams from their coronal origin- identified through type III radio bursts – to their detection in interplanetary space. Reconstructions using the PFSS model confirmed that the sources of metric-type III bursts are located on open magnetic field lines and that the ejection direction of the EUV jet generally aligns with the orientation of these open magnetic field lines. For the interplanetary phase, TDOA triangulation using data from Wind, STEREO-A, and Solar Orbiter localized the source of the interplanetary type III burst along the Parker spiral connecting to the Wind spacecraft.

2. **Timeline and Dynamics of Energetic Electrons:** The event timeline indicates that coronal type III bursts occurred between 08:01 and 08:03 UT, marking the initial acceleration and escape of energetic electron beams from the corona. Following this, three spacecraft – STEREO-A, Wind, and Solar Orbiter – sequentially detected energetic electrons with energies ranging from tens of keV to several MeV, peaking around 10:20 UTC. VDA suggests that the solar release times (approximately 08:03 to 08:27 UT) were slightly delayed compared to the end of the coronal type III bursts but coincided with the period of the coronal type II burst. This sequence of events indicates that the observed energetic electrons may be linked to a shock-acceleration process (which produces the type II burst; see Feng et al. 2012 and Feng and Zucca 2025) or to a more complex injection mechanism.

3. **Propagation Path Lengths and Magnetic Field Geometry:** A key finding reveals a significant difference in the propagation path lengths derived for the SEEs observed by different spacecraft. The path length for STEREO-A is approximately 1.2 ± 0.9 AU, which is close to the nominal Sun-Earth distance. In contrast, the path length for Wind is considerably longer at 2.6 ± 1.6 AU, exceeding the ideal Parker spiral length of about 1.15 AU for a solar wind speed of 400 km/s at 1 AU. This discrepancy suggests significant scattering or a non-Parker-spiral magnetic-field topology along that specific magnetic field line. The factor of 2.2 difference between the measured path length (2.6 AU) and the nominal Parker spiral length (1.15 AU) cannot be explained by simple magnetic field expansion alone. This observation aligns with recent studies (e.g., Badman et al. 2022; Wimmer-Schweingruber et al. 2023), indicating that the interplanetary magnetic field is not a simple, smooth Archimedean spiral. Instead, it likely exhibits significant meandering, folding, or interactions with perturbed background fields, resulting in particle propagation paths much longer than the nominal magnetic connection length. This finding provides constraints on models of particle propagation and magnetic field topology in the heliosphere. Importantly, the shorter Parker spiral connecting the EUV jet to STEREO-A (1.2 ± 0.9 AU) and the spatial proximity of the EUV jet's magnetic footpoint to STEREO-A provide a consistent explanation for why STEREO-A detected the SEE first, followed by Wind and Solar Orbiter.

This study shows that a synergistic approach combining radio imaging (MUSER-L), radio spectral analysis (TDOA), coronal magnetic field reconstruction (PFSS), and multi-point in situ particle measurements (VDA) can track the physical process of solar energetic electrons from their source to interplanetary observers.

5.1. Discussion and Implications

The observations reported here raise several questions about the relationship between the different electron populations detected. We consider these implications in light of the multi-spacecraft and multi-wavelength evidence.

SEE vs. Interplanetary Type III Burst Electrons: An important implication of this study is that the locally observed SEEs and the energetic electron beams that excite interplanetary type III bursts may not be the same electron population. Four lines of evidence support this inference. First, the release times of the SEEs (08:03–08:27 UT) occur after the end of the coronal type III bursts at meter wavelengths, although they partially overlap with the coronal type II burst period. Second, the SEEs arrive before the interplanetary type III burst electrons at 1 AU, and their temporal profiles only partially coincide. Third, the electron beams that excite interplanetary type III bursts travel at $0.06c$ – $0.17c$ (average $0.11c$), whereas the SEE electrons exhibit velocity dispersion over a broader energy range. Finally, the earlier onset of the SEEs suggests that a fraction of the SEE population may be accelerated through a different process – possibly shock acceleration associated with the type II burst – rather than the primary type III burst mechanism.

Candidate Physical Mechanisms: We consider two mechanisms that could explain the observational findings. (1) Cross-field transport and magnetic meandering: Turbulent field fluctuations and large-scale current-sheet corrugation could cause electrons to undergo a random walk, increasing effective travel distance – an effect more pronounced for field lines farther from the nominal Parker spiral, such as the one connecting to Wind. (2) Extended acceleration region: Ongoing reconnection in a current sheet trailing the EUV jet or stochastic acceleration by compressive turbulence could produce the partially overlapping but non-identical release times at the two spacecraft. Future studies incorporating dynamic coronal or MHD heliospheric models would help distinguish among these scenarios.

STEREO-A vs. Wind Onset Delay and Path Length: The onset delay between STEREO-A and Wind (approximately 10–50 min, depending on energy channel) is qualitatively consistent with the different path lengths derived from VDA: a shorter path of ~ 1.2 AU for STEREO-A versus a longer path of ~ 2.6 AU for Wind. The EUV jet's magnetic footpoint lies closer to the STEREO-A Parker spiral footpoint than to the Wind footpoint (Figure 8b), providing a consistent geometric explanation. However, the factor of ~ 2.2 difference between the measured path length for Wind (2.6 AU) and the nominal Parker spiral length (1.15 AU) cannot be explained by simple field-line geometry alone, suggesting significant magnetic meandering or cross-field transport (e.g., Laitinen et al. 2016). In contrast, the interplanetary type III burst onset shows no resolvable delay between spacecraft, because radio emission propagates at the speed of light regardless of the magnetic path.

Type II and Type III Burst Origins: We note that SOHO/LASCO C2 observations reveal a CME associated with this event (speed ~ 344 km/s, first seen at 08:24 UT; see the [LASCO C2 animation](#)). The type III bursts likely originate from magnetic reconnection associated with the EUV jet, whereas the type II burst is produced by a shock wave driven by this CME. In the metric wavelength range (observed by CSO), the two burst types are clearly separated in time and frequency, indicating distinct acceleration processes that may nevertheless share a common magnetic eruption origin.

Limitations: The observation geometry affects the reliability of our conclusions in several ways. The eruption originated on the far side of the Sun as viewed from Earth (AIA), which reduces the accuracy of source-position determination and PFSS connectivity assessment in that region. Furthermore, the PFSS model used in this study assumes a current-free coronal magnetic field, which becomes increasingly unreliable near the photosphere, where electric currents, magnetic shear, and flux rope formation are present. PFSS does not capture non-potential effects and may affect the inferred magnetic connectivity, particularly for higher-frequency type III burst sources near the low corona. More sophisticated models (e.g., nonlinear force-free field or MHD models) would better represent the field in these regions but are beyond the scope of the present observational study.

In summary, this study presents an integrated case linking solar surface phenomena (such as jets and radio sources) to in situ detectors (specifically, energetic electrons at 1 AU). This highlights the capability to trace and source solar energetic electron events, providing an important methodological framework and observational evidence for understanding the complete chain of particle acceleration and transport in solar eruptive events. It also aims to improve the accuracy of SEP event forecasts in space weather.

Acknowledgements The authors thank the CSO, RSTN, SDO, Solar Orbiter, STEREO, Wind, and GOES teams for providing their data. The authors acknowledge the use of data from the Chinese Meridian Project. We acknowledge the use of spectral image of Meter Decameter Radio Heliograph from the Chinese Meridian Project (DOI). The data can be accessed via <https://dcstatus.meridianproject.ac.cn/>. We thank the staff of the Chinese Meridian Project (<https://cstr.cn/31122.02.MSP>) for their technical support and assistance in data collection and analysis.

Author Contributions SW wrote the main manuscript, which was then reviewed and edited by XH, NB, and SY. All authors participated in the review of the manuscript.

Funding Information This research was jointly supported by the National Key R & D Program of China (grant No. 2025YFF0510701), the National Natural Science Foundation of China (grant No. 42474224, 12673064), the Beijing Natural Science Foundation (1242035), the Specialized Research Fund for State Key Laboratory of Solar Activity and Space Weather, and the Climbing Program of NSSC (E6PD3001).

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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