Research Progress on Interplanetary Type III Radio Bursts Based on PSP Observations: Postprint

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Abstract

Compared with solar radio bursts, interplanetary radio bursts at lower frequencies are generally believed to originate from interplanetary space far from the low corona. The cutoff of Earth’ s ionosphere prevents ground-based instruments from observing them. The Parker Solar Probe (PSP), launched by the National Aeronautics and Space Administration (NASA), is the closest spacecraft to the Sun to date. Its onboard radio spectrometer can observe radio emissions in the frequency range of 10;kHz–19.17;MHz. PSP is capable of approaching and possibly traversing the source region of interplanetary type III radio bursts, thus offering unprecedented advantages for observing interplanetary radio bursts. This paper briefly introduces the multifaceted research on interplanetary type III radio bursts conducted to date using PSP’ s radio observation data, including research progress on burst occurrence rates, polarization, scattering, cutoff frequencies, possible radiation mechanisms, and related source regions, and discusses future research prospects.

Full Text

Research Progress on Interplanetary Type III Radio Bursts Based on PSP Observations

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Abstract

Compared to solar radio bursts, interplanetary (IP) radio bursts with lower frequencies are generally believed to originate in interplanetary space far from the low corona. The cutoff by Earth' s ionosphere makes ground-based observations impossible. NASA' s Parker Solar Probe (PSP), the closest spacecraft to the Sun to date, carries a radio spectrometer capable of observing radio emissions in the 10 kHz-19.17 MHz range. PSP can approach and potentially traverse the radiation source region of interplanetary type III radio bursts, offering unprecedented advantages for their observation. This paper reviews the multifaceted research conducted to date using PSP' s radio observations of interplanetary type III bursts, covering occurrence rates, polarization, scattering, cutoff frequencies, possible radiation mechanisms, and associated source regions, and discusses future research prospects.

Keywords: Sun: activity, Sun: radio emission, Sun: corona, solar wind

2 Instrument Description

The Parker Solar Probe, initially named Solar Probe Plus, was renamed in May 2017 after Professor Eugene Parker of the University of Chicago, the pioneer of solar wind theory. Launched on August 12, 2018, PSP' s primary scientific objective is to study physical processes in the inner heliosphere and corona using both in situ and remote sensing observations [Figure 1: see original paper]. The FIELDS instrument suite provides electric and magnetic field measurements for this mission.

As shown in [Figure 1: see original paper], FIELDS' electric field sensors consist of four 2-m monopole antennas (V1–V4) mounted on the edge of PSP' s heat shield and a 21-cm dipole antenna (V5) on the tail magnetometer boom. These sensors serve as inputs to FIELDS' main electronic receivers. Radio observations are performed by the Radio Frequency Spectrometer (RFS) [14], which comprises a dual-channel receiver and spectrometer with a bandwidth of 10.5 kHz–19.17 MHz. RFS processes data products through two sub-band receivers: the Low Frequency Receiver (LFR) covering 10.5 kHz–1.7 MHz and the High Frequency Receiver (HFR) covering 1.3–19.17 MHz. RFS can measure auto-spectra from the V1–V4 antenna preamplifiers and one axis of the Search Coil Magnetometer (SCM).

With gravitational assists from Venus, PSP continues to approach the Sun, with perihelion distances decreasing from 35.7 R in the first three orbits to 9.86 R by 2024, where R denotes solar radius. Each PSP orbit is divided into encounter and cruise phases. When PSP' s heliocentric distance is within 0.25 AU (54 R), it operates in encounter mode, with all instruments continuously observing and recording data at high rates. When the heliocentric distance exceeds 0.25 AU, PSP operates in cruise mode, with instruments working intermittently due to power constraints and spacecraft activity, recording data at reduced rates [15]. RFS records radio spectral data with time resolutions of 7 s in encounter mode and 56 s in cruise mode. Available data show that the encounter/cruise mode settings are flexible and not strictly determined by heliocentric distance.

3.1 Statistical and Polarization Studies of Type III Bursts Observed in the Inner Heliosphere

Pulupa et al. [15] studied interplanetary type III radio bursts observed during PSP’ s first two encounter phases, E01 (Encounter 01) and E02 (Encounter 02), using data from RFS’ s automatic spectral channel 0 (V1-V2). [Figure 2: see original paper] shows an overview of the power spectral density curves at 4.57 MHz (panels a and d) and HFR/LFR dynamic spectra (panels b, c, e, and f) for the two encounter periods, with color bars indicating decibels (dB) above background. Only a few weak type III bursts and Jovian emissions were observed during E01, while numerous bursts occurred during E02, with the highest burst rate and intensity on April 3-4, 2019. Images from SDO/AIA and STEREO/EUVI reveal activities corresponding to the radio emissions observed during E02, likely originating from NOAA Active Region 12738 at Carrington longitude 300°.

At frequencies of a few hundred kHz, the LFR spectrum primarily contains local spacecraft signals such as shot noise and quasi-thermal noise (QTN) [16]. The QTN feature at 90-150 kHz appears as plasma peaks or plasma lines, enabling RFS to accurately measure fp and derive total electron density. Low-frequency waves, such as those near fg (10-30 kHz) [17] and large-amplitude electrostatic Langmuir waves near fp, are also visible in the LFR spectrum. Similar to Krupar et al.’ s [18] results at 1 AU, PSP spectral analysis shows peak radio intensity at 1 MHz.

PSP’ s large heliocentric distance variation, ranging from perihelion $R_0 = 35.7$ R to more distant 54 R during E01 and E02 as annotated in [Figure 2: see original paper], affects radiation intensity measurements. Consequently, the study applied a distance scaling factor of $(R/R_0)^2$, where R is the heliocentric distance. Individual burst identification in RFS spectra was achieved by locating maxima at a given frequency (4.57 MHz), with a minimum scaled intensity threshold of $I = 10^{-16}\ V^2 \cdot Hz^{-1}$ to exclude noise.

[Figure 3: see original paper] presents statistical results of burst occurrence rates. The three rows represent, from top to bottom: cumulative burst number N exceeding different radially scaled Stokes I intensities, N exceeding different waiting times Δt, and power-law spectral index α at different frequencies. The second row shows λ, the burst occurrence rate for the corresponding period. The three columns represent statistics for three different time intervals: 420, 104, and 107 type III bursts exceeding I . Using Wheatland’ s [19] method, the cumulative distribution curves calculated from intensity distribution functions yield power-law indices of 1.64 ± 0.03, 1.49 ± 0.05, and 1.92 ± 0.09 for the three phases. The index during the type III storm phase (1.92 ± 0.09) agrees with Eastwood et al.’ s [20] index of 2.10 ± 0.05 observed at 5.035 MHz, while the steeper indices during non-storm periods also match Fitzenreiter et al.’ s [21] finding of 1.69. The cumulative waiting time distribution during the type III storm period follows a simple Poisson process model well, while E02’ s distribution shows more structure, corresponding to intervals with distinctly different activity levels. The spectral index also varies more steeply during the storm period (α 1.6–1.9 at 1.8–8 MHz) compared to the encounter phase (α 1.6–1.7 at 1.8–8 MHz). Variations in spectral index with frequency may result from the relative positions of the spacecraft and active regions, as well as refraction and scattering during propagation. Multi-point measurements with directional patterns and studies of large burst intervals will help understand the frequency dependence of spectral index α and its causes.

PSP polarization observations use Stokes I, Q, U, and V components calculated as follows:

$$I = V_{12}V_{12}{}^{*} + V_{34}V_{34}{}^{*}$$
$$Q = V_{12}V_{12}{}^{*} - V_{34}V_{34}{}^{*}$$
$$U = V_{12}V_{34}{}^{*} + V_{34}V_{12}{}^{*}$$
$$iV = V_{12}V_{34}{}^{*} - V_{34}V_{12}{}^{*}$$

where $V_{12}V_{12}{}^{*}$ and $V_{34}V_{34}{}^{*}$ are RFS auto-spectral data from V1-V2 and V3-V4 channels, and $V_{12}V_{34}{}^{*}$ is RFS cross-spectral data. By calculating the ratio V/I from Stokes V and I parameters, Pulupa et al. [15] achieved a simple estimate of relative circular polarization. Linear polarization (Stokes Q and U) cannot be remotely observed due to Faraday rotation. [Figure 4: see original paper] shows several examples of PSP-observed type III burst polarization, displaying Stokes I intensity and V/I ratio representing relative circular polarization. Only a few burst fronts show obvious right-hand circular (RHC) polarization features above 6 MHz (blue regions indicating negative values). Seven similar events with such characteristics were observed during E02, while most other times showed only weak, indistinguishable polarization signals.

The type III storm in mid-April, lasting approximately one day, was observed by RFS in cruise mode with 56 s time resolution. Its polarization is shown in [Figure 5: see original paper]. Unlike individual activity phases observed in encounter mode, nearly every burst during this storm phase exhibited very clear circular polarization, mostly right-hand circular. The average polarization degree increased from -0.1 at 1 MHz to -0.2 at 5 MHz (time resolution above 5 MHz was insufficient to clearly distinguish individual bursts).

Profile curves of Stokes I (intensity) and V/I (relative circular polarization) for the seven strongly polarized events in encounter mode, extracted along the dashed lines marked in [Figure 4: see original paper], are displayed in [Figure 6: see original paper]. Their intensities are consistent with Krupar et al.’ s [18] observations at 1 AU. Although these are large-amplitude events, many other large-amplitude events showed no obvious circular polarization features, and the small number of events precludes quantitative analysis of intensity-polarization correlations.

These events show significantly higher polarization at 8–12 MHz than below 4 MHz, displaying partial circular polarization consistent with Dulk et al.’ s [22] high-frequency observations. Their circular polarization V/I values agree with the fundamental component in Dulk et al. [22] but are higher than the harmonic component values, suggesting the circular polarization component likely originates from fundamental rather than harmonic radiation. The partial circular polarization may result from either depolarization of 100% O-mode radiation or initial radiation containing both O-mode and X-mode components.

3.2 Solar Wind Density Perturbations Based on PSP Observations of Type III Bursts

Radio waves experience strong scattering in the solar wind, making their apparent source appear larger and offset from the actual source. Since scattering depends on the density turbulence spectrum, detailed analysis of radio wave propagation can provide indirect information about relative density perturbations = δn / n , where δn is the average amplitude of density variations and n is the mean density. Krupar et al. [23] compared decay times of type III bursts observed by STEREO between 125 kHz and 1 MHz with Monte Carlo simulations, proposing that the typical exponential decay profile of type III bursts can be fully explained by scattering of fundamental radiation between the source and observer.

Krupar et al. [24] analyzed 30 type III radio bursts observed by PSP near perihelion during its second orbit (E02 period). They first measured decay times τd at various frequencies between 1–10 MHz, as shown in [Figure 7: see original paper], where “+” symbols represent observed power spectral density values, slanted dashed lines are fits to the decay portion, and vertical dashed lines mark peak time and decay to median time, making τd the time difference between the two vertical lines. [Figure 8: see original paper] shows the statistical relationship between median decay times and frequency for type III bursts observed by PSP and STEREO, with black and gray dots representing STEREO and PSP statistics, respectively. Thin dashed lines indicate 25%–75% error ranges, while the thicker black dashed line shows power-law fits to both datasets. PSP’ s observed power-law index shows significant deviation from STEREO’ s results at 1 MHz. They found the height of 1 MHz burst generation approaches the Alfvén point where solar wind becomes super-Alfvénic, suggesting the spectral index difference may result from different plasma environments on either side of the Alfvén point.

Thejappa et al. [25] developed Monte Carlo simulation code to study scattering and refraction effects on interplanetary radio radiation propagation from isotropic sources. Krupar et al. [24] modified this technique to simulate arrival times tMC of radio radiation at PSP. Simulation results ([Figure 9: see original paper]) show tMC increases with . Comparing Monte Carlo-simulated tMC with PSP-observed τd ([Figure 10: see original paper]) reveals the density perturbation level corresponding to PSP-observed bursts. In Figure 10: see original paper, the black dashed line represents PSP' s observed power-law fit from [Figure 8: see original paper], while colored lines show tMC versus radiation frequency for different values. Figure 10: see original paper displays versus radiation frequency at intersection points between the black dashed line and colored lines in Figure 10: see original paper. Krupar et al. [24] thus predicted relative ranges of 0.22-0.09 at radial distances of 2.5-14 R under effective turbulence scales.

Finally, they calculated measured in situ by PSP at 35.7 R radial distance, finding values of 0.07 and 0.06 at perihelia of orbits 1 and 2, respectively. These agree well with previous predictions based on STEREO remote sensing of radio sources at this radial distance (range 0.06-0.07).

3.3 Statistical Study of Cutoff Frequencies of Interplanetary Type III Bursts Observed by PSP

Wu et al. [26] summarized three distinct characteristics of interplanetary type III radio bursts: sudden low-frequency cutoff, relatively low starting frequency, and long duration near the cutoff frequency. Leblanc et al. [27] first performed statistical analysis of low-frequency cutoff frequencies (flo) using Ulysses data in 1995, finding that at four different positions with large ecliptic latitude differences and heliocentric distances of 1.1-4.3 AU, the cutoff frequency distribution of type III bursts remained nearly unchanged, with a peak frequency of 100 kHz, while the local plasma frequency fp distribution varied with spacecraft position.

Dulk et al. [28] conducted similar statistics in 1996 for type III bursts simultaneously observed by WIND and Ulysses, again finding the cutoff frequency distribution peaked near 100 kHz, independent of observation position. They proposed that the cutoff is intrinsic to the radiation mechanism, though radiation directivity and propagation effects may also influence observed cutoff frequencies.

To investigate whether type III bursts observed by PSP in the inner heliosphere still show invariant cutoff frequency distributions, Ma et al. [29] used PSP encounter mode data from the first five orbits (E01-E05) to automatically identify and manually screen type III bursts, obtaining 176 events. [Figure 11: see original paper] shows probability distributions of flo and local fp, with fp mainly distributed at 50-250 kHz, peaking at 100 kHz—significantly higher than Leblanc et al. [27] and Dulk et al. [28]. This aligns with their expectation that local plasma frequency varies with spacecraft position. However, flo mainly distributes at 0.2-1.6 MHz, peaking at 700 kHz—substantially higher than previous cutoff frequency statistics and inconsistent with their finding of position-independent cutoff frequencies. When PSP is very close to the Sun, local fp already exceeds the 100 kHz peak frequency observed for flo beyond 1 AU. While local plasma frequency cutoff may prevent the lower limit of type III burst cutoff frequency from dropping below 100 kHz, it cannot explain the extension of flo' s peak frequency to as high as 700 kHz.

Ma et al. [29] briefly discussed three possible explanations for these differences: (1) Solar activity intensity: Leblanc et al. [27] and Dulk et al. [28] analyzed data from 1990–1995, near solar maximum, while Ma et al. [29] analyzed 2018–2020 data, almost entirely during solar minimum. Solar activity affects magnetic energy release and propagation distance of energetic electron beams that excite radio bursts, influencing observed cutoff frequency distributions. (2) Event selection criteria: Ma et al. [29] included many weak events lasting 2–3 minutes, while Leblanc et al. [27] and Dulk et al. [28] selected only prominent events in 24-hour views. Different selection criteria may cause statistical differences. (3) Radiation attenuation effects: Ma et al. [29] selected only PSP encounter mode events (R $<$ 0.25 AU), while Leblanc et al. [27] and Dulk et al. [28] used 1–4.3 AU data. Radiation attenuation may reduce intensities of many weak bursts below background noise levels at greater distances. Leblanc et al. [30] showed that weak bursts generally have higher cutoff frequencies than strong bursts ([Figure 12: see original paper]), so differences in intensity distributions of identified bursts due to attenuation may affect cutoff frequency distributions.

To further investigate radiation attenuation effects and exclude radiation directivity influences, Ma et al. [31] first compared bursts observed simultaneously by PSP and WIND during the same period. They selected data from January 1, 2019, to July 31, 2020, during low solar activity, and applied identical Canny edge detection image processing methods to both datasets for burst identification and cutoff frequency measurement, followed by manual event screening. As shown in [Figure 13: see original paper], WIND' s results remain similar to Leblanc et al. [27] and Dulk et al. [28], with cutoff frequency flo peaking at 100 kHz, while PSP' s results agree with Ma et al. [29], with cutoff frequency peaking near 700 kHz. This essentially rules out solar activity intensity and event selection criteria as primary causes.

To further study radiation attenuation effects, Ma et al. [31] also compared event numbers observed by PSP near perihelion and by WIND when their minimum azimuthal difference Δ was less than 30°. They found PSP and WIND observed 212 and 18 events, respectively, indicating that radiation attenuation prevents WIND at 1 AU from detecting numerous weak bursts. Additionally, [Figure 15: see original paper] shows comparisons of radio dynamic spectra observed by PSP at perihelion and aphelion versus WIND observations when Δ $<$ 30°. PSP at perihelion detects many weak bursts unobservable by WIND, while at aphelion, nearly all events are simultaneously observed. This visually demonstrates radiation attenuation effects: at 1 AU and beyond, many weak bursts with higher cutoff frequencies become undetectable, causing the statistical cutoff frequency distribution to peak near 100 kHz—significantly lower than PSP' s near-Sun observation of 700 kHz.

3.4 An Interplanetary Type IIIb Radio Burst and Its Possible Radiation Mechanism

Type IIIb radio bursts with stripe-like fine structures are a type of burst activity with rapid frequency drift characteristics similar to type III bursts, first discovered and reported by Ellis et al. [32–33] and de la Noë et al. [34]. Chen et al. [35] studied a IIIb-III burst pair observed by LOFAR, shown in [Figure 16: see original paper], where panel (a) displays the dynamic spectrum with arrows marking fundamental (F) and harmonic (H) components, and panels (b) and (c) show enlarged views of harmonic and fundamental components, respectively. Both fundamental and harmonic branches exhibit fine structures, with the fundamental branch consisting of 70 stripes, many of which overlap. Zhang et al. [36] also used LOFAR observations to study the source size and motion of another IIIb-III burst.

The generation mechanism of type IIIb bursts has been discussed by many authors. Based on plasma radiation, density inhomogeneities, density turbulence, and modulation instabilities have been proposed considering solar wind electron density modulation [35, 37–38]. Based on electron cyclotron maser radiation, Wang [39] suggested that IIIb fine structures may result from modulation of electron cyclotron maser instability by spatial structures in density or magnetic field associated with stationary/slow waves. Zhao et al. [40] proposed that Alfvén waves (AW) can modulate electron cyclotron maser emission to produce stripe structures, explaining many IIIb bursts.

Although fine structures in meter-wave bursts have been extensively studied, research on interplanetary low-frequency type IIIb bursts is scarce. Chen et al. [41] investigated the radiation mechanism of a typical interplanetary type IIIb burst reported by Pulupa et al. [15]. As shown in [Figure 17: see original paper], panel (a) shows PSP’s original dynamic spectrum of this IIIb burst, panel (b) shows the denoised spectrum, and panel (c) displays peak intensity at each frequency. This burst consists of 22 stripes with a radiation frequency range of 0.8-19 MHz. Gaussian fitting of power spectral time profiles at each frequency shows durations of 40 s at high frequencies and 80 s at low frequencies, with an average duration of 60 s.

Interplanetary type III bursts require fast electron beams propagating along open magnetic field lines, but the specific excitation mechanism remains uncertain. The mechanism depends on plasma parameters in the source region, specifically the ratio of electron plasma frequency to cyclotron frequency, fpe/fce. Plasma radiation and electron cyclotron maser radiation occur preferentially when fpe/fce > 1 and fpe/fce < 1, respectively. Since this event’ s frequency range far exceeds PSP’ s local plasma and cyclotron frequencies, its source region must be closer to the Sun. Chen et al. [41] used Wu et al.’ s [42] empirical model and PSP in situ data to fit more accurate radial distributions of electron density and magnetic field. [Figure 18: see original paper] shows model curves for 1-10 R with corresponding characteristic frequencies and frequency ratios, where R/Rs is heliocentric distance normalized by solar radius. PSP’ s observed burst frequencies fall in the fpe/fce $<$ 1 range, suggesting electron cyclotron maser radiation plays an important role.

Considering the ubiquity of Alfvén waves in the corona and solar wind [6, 43-45], Chen et al. [41] introduced two monochromatic waves to describe Alfvén wave perturbations and used Chen et al.’ s [45] O1-mode growth rate formula for electron cyclotron maser radiation with a crescent-shaped electron velocity distribution. The calculated growth rates are shown in [Figure 19: see original paper], where panel (a) displays maximum growth rates at different frequencies, producing stripe-like structures with periodic intensity variations, and panel (b) shows a dynamic spectrum calculated using typical electron beam motion parameters. This result matches PSP’ s observed interplanetary type IIIb burst ([Figure 17: see original paper]) well.

3.5.1 Periodic Activity in Active Regions Associated with PSP-Observed Type III Bursts

Periodic activity across multiple wavelengths in the corona, with periods of 5 minutes comparable to solar p-modes, has been frequently reported, suggesting coupling between the solar photosphere and corona. Cattell et al. [46] first reported periodic type III bursts observed by PSP ([Figure 20: see original paper]). They analyzed a periodic type III burst on April 12, 2019, using joint observations from SDO’ s extreme ultraviolet, white-light, and magnetic field images, along with NuSTAR solar flare X-ray observations. Multiple periodicity assessment methods were used for verification.

The results show that 5-minute periodicity in extreme ultraviolet bands in several active region areas correlates well with repetition rates of type III bursts observed by PSP and WIND. Decreasing 211 Å and 171 Å light curves show periodic profiles, with 171 Å peaks sometimes lagging 211 Å peaks, suggesting pulsed events cause heating and subsequent cooling in the low corona. NuSTAR X-ray observations reveal at least one microflare during the type III burst period, though not one-to-one correspondence with individual bursts. This study provides evidence for periodic non-thermal electron acceleration during periods without flares observed in X-ray and EUV data, suggesting the acceleration must be associated with small periodic events (possibly nanoflares).

3.5.2 Source Active Region of the Type III Storm Observed by PSP During E02

As mentioned in Section 3.1, Pulupa et al. [15] observed a type III storm during PSP’ s E02 period composed of numerous small type III bursts, suggesting it was excited by energetic electrons accelerated by the large Active Region 12738 present at that time. However, Harra et al. [47] analyzed the smaller Active Region 12737 in detail and concluded these type III storms were more likely generated by electron beams accelerated in this region.

[Figure 21: see original paper] shows an overview of this storm, which began on March 31, 2019, and lasted until April 6. GOES soft X-ray curves show no flare signatures during this period. The peak frequency of bursts gradually decreased over time, suggesting decreasing density or expansion of the burst source region. [Figure 22: see original paper] shows SDO/AIA 193 Å images of Active Region 12737 evolving over time, indicating clear expansion during the storm period.

Harra et al. [47] also used different linear force-free field (LFFF) models to calculate coronal magnetic field distributions and construct global coronal structure maps. As shown in [Figure 23: see original paper], magnetic fields at the active region' s edge observed by EIS became significantly more open from April 1 to April 4. [Figure 24: see original paper] shows EIS observations of Fe II 195.119 Å intensity, Doppler velocity, and non-thermal particle velocity evolution, clearly showing the blue-shifted region on the active region' s eastern side expanding significantly, with more high-speed non-thermal particles. This aligns with AIA imaging and extrapolated magnetic field structures, indicating plasma can accelerate and escape into the solar wind through this outflow region.

First ionization potential (FIP) bias levels can reflect solar energetic particle (SEP) activity [48], and the outflow region' s FIP bias showed clear enhancement during this period, peaking on April 4. This suggests SEP activity also intensified. Harra et al. [47] explored outflow region dynamics but found no turbulence at the observational time resolution, possibly due to insufficient temporal resolution.

Despite no obvious flares, Active Region 12737' s evolution temporally coincides well with PSP' s observed type III storm, indicating it is the source of electron beams causing the radio storm, most likely originating from strongly blue-shifted plasma regions at the active region' s edge.

3.5.3 Solar Radio Bursts from a Far-Side Active Region Detected by PSP

Stanislavsky et al. [49] studied several solar radio bursts from a limb active region on the Sun' s far side, observed by PSP on June 5, 2020. Newly emerged Active Region NOAA 12765 on June 3 evolved a dipolar sunspot on June 5, reaching a size of 130 MH (millionths of the visible solar hemisphere). They argued this sized active region could produce high-density electron beams and excite U-bursts accompanied by type III bursts. [Figure 25: see original paper] shows the positions of this active region relative to PSP, STEREO A, and Earth-direction WIND observations, with the active region located on the Sun' s far side from PSP' s perspective.

They used the Giant Ukrainian Radio Telescope (GURT) array for ground-based observations, with frequency range 8–80 MHz, time resolution 100 ms, and frequency resolution 38.147 kHz. GURT observed four burst groups between 09:33 and 09:38 UT on June 5. Figure 26: see original paper and (b) show dynamic spectra from GURT and PSP, respectively. The first three groups are weak type III bursts, while the fourth group contains stronger U- and J-bursts accompanied by type III bursts. Corresponding PSP-observed bursts occurred several minutes earlier than GURT observations, but PSP' s relatively low time and frequency resolution prevented resolving more details within each burst group.

Stanislavsky et al. [49] proposed that U+J+III bursts likely originated near high-density plasma loops in Active Region AR 12765 and developed an improved coronal density model based on this assumption. Figure 27: see original paper and (b) schematically show radio radiation propagation effects for spherically symmetric and active-region-enhanced coronal density models, respectively. They argued that if coronal density were spherically symmetric, type III bursts from this active region would be shielded by nearby high-density plasma and unobservable by PSP on the far side. However, if coronal density varies with angle—higher near active regions—the observed burst source would be at relatively higher altitude, allowing radio radiation to propagate through low-density plasma in quiet Sun regions and be observed by far-side PSP.

4 Summary and Discussion

Interplanetary type III bursts have lower radiation frequencies and are believed to be excited by electron beams in interplanetary space. PSP' s close proximity to the Sun offers the potential to approach the radiation source region of interplanetary bursts. Since its launch in August 2018, PSP has discovered many new phenomena and characteristics of interplanetary type III bursts through low-frequency radio observations. This paper briefly reviews research on interplanetary type III bursts using PSP data.

Observations from the first two encounter modes found few bursts during E01 but numerous bursts during E02. Type III bursts near perihelion during the second orbit showed distinctly different characteristics in occurrence rate and spectral index compared to the mid-April storm. Their circular polarization also differed significantly. Partial circular polarization may result from either depolarization of 100% O-mode radiation or initial radiation containing both O-mode and X-mode components. Interplanetary type III burst propagation is affected by solar wind plasma scattering, with decay times fully explainable by fundamental radiation scattering between source and observer. PSP' s density perturbation results agree with previous STEREO predictions. Type III burst cutoff frequencies may be determined by intrinsic radiation mechanism properties, with radiation attenuation enabling observation of more weak bursts with higher cutoff frequencies at smaller heliocentric distances. This is likely the main reason for PSP' s observed cutoff frequencies differing from those at greater distances. Type IIIb bursts have stripe-like fine structures that may provide more detailed information for understanding radiation mechanisms. Based on electron cyclotron maser radiation, ubiquitous Alfvén waves in the solar wind can modulate growth rates to produce stripe structures, well explaining PSP' s observed interplanetary type IIIb bursts. Studies of periodic activity in active regions associated with PSP' s E02-observed periodic bursts reveal evidence of non-thermal electron acceleration during flare-free periods, likely originating from small periodic events. Comparison of EIS Doppler shift and non-thermal particle velocity distributions with linear force-free extrapolation models suggests the source active region for the E02 storm was NOAA AR 12737, not the larger AR 12738. PSP' s detection of type III bursts from a far-side active region, with simultaneous ground-based GURT observations of U+J+III bursts, suggests that non-spherically symmetric solar wind electron density distribution may be the main reason enabling PSP to observe far-side active region type III bursts.

Beyond the studies mentioned above, other researchers have used PSP radio observations to investigate energetic particle events [50–51], interplanetary coronal mass ejections [52], and quasi-thermal noise spectra [53–54] observed in RFS bands, which are not detailed here.

Although PSP has not yet reached 10 solar radii, its early observations have provided unprecedented rich information. The importance of close proximity observations is self-evident, and multi-location, multi-wavelength joint observations have also played crucial roles. In the future, as PSP approaches the Sun closer to interplanetary type III burst source regions, more detailed information about radiation generation processes will gradually be revealed.

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