Advances in Research on Radio Emission from the Heliospheric Boundary (Postprint)

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Abstract

Heliospheric boundary radio emission is the most intense radio emission phenomenon in the solar system, with a radiation power of at least 10^{13};W, capable of providing crucial physical information about energetic electron beams and background magnetoplasma structures near the heliospheric boundary. Since its first detection by the Voyager spacecraft in 1983, heliospheric boundary radio emission has attracted extensive and sustained attention from researchers. This emission can be broadly categorized into two types: transient emission, also known as drifting emission, with relatively high frequencies, and persistent emission, also known as non-drifting emission, with relatively low frequencies. Both types typically commence at approximately 2;kHz. Drifting emission exhibits a characteristic drift toward higher frequencies, with a drift rate of approximately 1–3;kHz/yr, a frequency range of 1.8–3.6;kHz, and a relatively short duration of roughly 100–300 d. Non-drifting emission shows no significant frequency drift, with a frequency range of 1.8–2.6;kHz and a relatively long duration of approximately 3 yr. It is currently widely believed that heliospheric boundary radio emission is associated with shock waves. This paper presents the possible source regions, physical mechanisms of radiation generation, and the origins of shock waves related to this emission, discusses outstanding scientific questions, and outlines prospects for future research.

Full Text

Preamble

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Research Progress of the Heliospheric Boundary Radio Emissions

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Abstract

The heliospheric boundary radio emissions represent the strongest radio radiation phenomenon in the solar system, with a radiation power of at least 10^{13} W, providing crucial physical information about high-energy electron beams and background magnetized plasma structures near the heliospheric boundary. Since their first detection by the Voyager spacecraft in 1983, these radio emissions have attracted widespread and sustained attention from researchers. The heliospheric boundary radio emissions can be broadly classified into two types: instantaneous emission, also called drifting emission, with relatively high frequencies, and continuous emission, also called non-drifting emission, with relatively low frequencies. Both types typically start at approximately 2 kHz. The drifting emission exhibits a characteristic drift toward higher frequencies at a rate of about 1–3 kHz/yr, with a frequency range of 1.8–3.6 kHz and a relatively short duration of roughly 100–300 days. The non-drifting emission shows no obvious frequency drift, with a frequency range of 1.8–2.6 kHz and a relatively long duration of about 3 years. It is generally believed that the heliospheric boundary radio emissions are associated with shocks. This paper introduces the possible source regions of the radio emissions, the physical mechanisms of radiation, and the origins of shocks related to the emissions, while also discussing outstanding scientific questions and future research directions.

Key words Sun: heliosphere, Sun: radio radiation, coherent radiation, plasma

Solar system radio phenomena can be categorized into four major types based on their origins: solar radio emissions, planetary radio emissions, interplanetary radio bursts produced by interplanetary electron beams or shocks, and heliospheric boundary radio emissions (also called solar system termination shock radio emissions) originating at the heliospheric boundary. Radio emission phenomena provide rich physical information about plasma structure, state, and activity processes in the source region, holding extremely important scientific research significance. The low-frequency radiation source region at the heliospheric boundary is characterized by low density, large distance, and extensive scope, making low-frequency radio radiation detection almost the primary observational diagnostic tool for the heliospheric boundary layer, apart from in-situ satellite measurements. To date, humanity has launched five spacecraft that have reached the outer heliosphere beyond 10 AU: Pioneers 10 and 11, Voyagers 1 and 2, and New Horizons. Among these, Pioneer 10 flew toward the heliospheric tail region, while the other four spacecraft traveled toward the heliospheric nose region within 40° of the solar equatorial plane. However, only Voyagers 1 and 2 carried dedicated instruments for detecting plasma waves and radio emission signals—the Plasma Wave-Subsystems (PWS) and Planetary Radio Astronomy (PRA) receivers.

Voyagers 1 and 2 were launched on September 5, 1977, and August 20, 1977, respectively, with primary scientific missions to explore the outer planets. They are currently the only human-launched spacecraft that have successfully crossed the heliospheric boundary layer into interstellar space. New Horizons' scientific objective was to investigate Pluto, Charon, and other Kuiper Belt objects, and it is still en route to the heliospheric boundary, expected to reach the heliospheric boundary layer after 2030. The Voyager spacecraft's PWS and PRA receivers, which detect plasma waves and radio emission signals, were placed overlapping and shared two orthogonal, extendable 10 m monopole beryllium-copper alloy tube antennas with a diameter of 0.5 inches to receive electric field information. For radio wave measurements, the antennas were connected as a pair of orthogonal monopoles. For plasma wave measurements, they were connected as an electric dipole with an effective length of approximately 7 m in an expanded V-shaped configuration. The PRA receiver's frequency range was set to two channels: low frequency (1.2 kHz–1.3 MHz) and high frequency (1.2–40.5 MHz).

The heliospheric boundary radio emissions were first observed by Voyagers 1 and 2 at heliocentric radial distances of approximately 13 AU and 17 AU after their encounters with Saturn (9.6 AU), with radiation frequencies concentrated primarily in the 2–3 kHz band. The PRA low-frequency channel interval was 19.2 kHz, so the radio emission signals were recorded by the PWS instrument. The power of heliospheric boundary radio emissions reaches at least 10^{13} W, making it the strongest low-frequency radio radiation phenomenon in the solar system. This unknown new radio emission phenomenon was an "unexpected gain" for the Voyager mission. Some researchers proposed that the radio emissions might originate from the heliopause, and if confirmed, the data would represent the first remote sensing results of the heliopause, providing important physical information about high-energy electron beams and background magnetized plasma structures in the source region. This caused a great sensation in the research field at the time and stimulated researchers' interest and enthusiastic attention.

The heliospheric boundary radio emissions are widely believed to be associated with shocks and can be roughly divided into two components: one component is non-drifting radiation with relatively low frequency (1.8–2.6 kHz) and long duration (approximately 3 years), showing no obvious frequency drift; the other component is drifting radiation with relatively high frequency (1.8–3.6 kHz) and short duration (approximately 100–300 days), whose frequency slowly increases over time at a drift rate of about 1–3 kHz/yr. Currently, only a small amount of measurement data from the Voyager spacecraft is available for heliospheric boundary radio emission signals. Additionally, the failure of some instruments or low measurement precision on the Voyager spacecraft has resulted in extremely limited information about various plasma physics parameters. Many controversies and unresolved mysteries remain regarding the radiation source region, radiation mechanism, and related shock origins of heliospheric boundary radio emissions.

After briefly introducing the heliospheric boundary layer structure (Section 2), this paper provides a relatively detailed description of the low-frequency radio emission observations by the Voyager spacecraft before reaching the heliospheric boundary layer (Section 3) and the detection of radio emissions or local electrostatic waves after crossing the heliospheric boundary layer (Section 4). A brief discussion of related radiation mechanism research is also included. Finally (Section 5), we briefly discuss outstanding scientific questions and future research prospects.

2. Solar Wind Interaction with the Local Interstellar Medium and Boundary Layer Crossings

2.1 The Heliospheric Boundary Interaction Layer

The Local Interstellar Medium (LISM) is a partially ionized medium composed of approximately two-thirds neutral atoms and one-third plasma originating from stars or interstellar space. Plasma cannot cross magnetic field lines to enter the heliosphere, while neutral atoms, unaffected by magnetic fields, can enter the heliosphere. Neutral atoms entering the heliosphere can be ionized by solar wind to form newborn pickup ions or non-thermal ions. The structure and dynamical evolution of the heliosphere depend on the interaction processes between solar wind and LISM. As the Sun moves through the interstellar medium, the outward-flowing solar wind plasma is expected to form a bullet-shaped boundary with its nose pointing toward the direction of interstellar gas flow.

The interaction between solar wind magnetized plasma and LISM forms the heliospheric boundary interaction layer, which includes the Termination Shock (TS), Heliopause (HP), Outer Bow Shock, and other structures, as shown in Figure 1 [Figure 1: see original paper]. The existence of the HP outer bow shock remains to be further confirmed. The solar wind moves at super-fast magnetosonic speeds, forming a long-standing TS where the solar wind decelerates to subsonic speeds. The TS is the first boundary layer formed by the solar wind-interstellar medium interaction outward from the Sun. The HP is the separating layer where hot, dense plasma inside the heliosphere reaches hydrostatic equilibrium with the local background interstellar gas.

Figure 1 shows not only the boundary layers of solar wind-LISM interaction but also the main plasma regions, such as the inner or outer heliosheath and Very LISM (VLISM) flow. The region between the TS and HP is called the inner heliosheath, where the magnetic field and plasma mainly originate from the Sun. This is a compressed solar wind region that has encountered intense shock impacts and been deflected from the heliospheric nose region back toward the heliospheric tail. The region between the HP and the heliospheric bow shock is called the outer heliosheath. The VLISM lies outside the heliospheric bow shock. Some authors refer to the LISM portion beyond the HP as VLISM, often interchangeably with the outer heliosheath. In this paper, we uniformly use the term LISM for the region outside the HP to avoid ambiguity when no confusion arises. The dashed circle in Figure 1 represents a shock driven by a Global Merged Interaction Region (GMIR). A GMIR is a comprehensive interaction region formed by the interweaving and merging of multiple interacting coronal mass ejections and other fast plasma streams produced by solar activity, featuring overall plasma density and magnetic field disturbances that propagate outward faster than the surrounding solar wind. The dotted region indicates the possible source region of heliospheric boundary radio emissions. The trajectories of Voyagers 1 and 2 are indicated by curved dashed lines, with solid dots on the trajectories marking their respective crossings of the termination shock and heliopause, along with the corresponding times and heliocentric radial distances.

2.2 Crossing the Termination Shock and Heliopause

Voyager 1 and Voyager 2 crossed the TS at 94 AU in December 2004 and at 83.4 AU in August 2007, respectively, and crossed the HP at 121.7 AU on August 25, 2012, and at 119 AU on November 5, 2018, respectively. Voyager 1's Plasma Science (PLS) instrument failed and was shut down in 1980. Figure 2 [Figure 2: see original paper] shows the solar wind radial velocity (V_R), proton density (N), and proton temperature (T) measured by Voyager 2 from 1 AU inside the heliosphere to the LISM. Figure 3 [Figure 3: see original paper] displays the magnetic field strength information measured by Voyagers 1 and 2 during the TS and HP crossings and in the inner heliosheath. As shown in Figure 2, the solar wind radial velocity V_R ranges from approximately 300–850 km/s, tending to stabilize as particle flow interactions intensify. The solar wind proton density N r^{-2}, where r is the heliocentric radial distance, and the proton temperature T 10^4 K.

Observational analysis reveals that Voyager 2's TS crossing during days 242–244 of 2007 differed significantly from Voyager 1's crossing two and a half years earlier, featuring a broad precursor structure extending approximately 0.7 AU upstream of the TS. The solar wind velocity showed a gradual decline within the precursor region, except for two sharp drops closely associated with two magnetic structures in the solar wind (around day 150 and day 200 of 2007). These magnetic structures are believed to be GMIRs or other compression structures related to GMIR shock precursors. Near the TS, the Low Energy Charged Particle (LECP) instrument observed enhancements in proton intensity at lower energy bands of 0.99–2.14 MeV and 2.14–3.5 MeV, indicating the presence of shock acceleration processes.

The solar wind in the inner heliosheath has a radial velocity V_R 100 km/s and a relatively constant density 0.003 cm^{-3}. The solar wind plasma temperature can be shock-heated to as high as 10^6 K, as shown in Figure 2. The inner heliosheath is narrower than expected and exhibits a turbulent state. Newborn pickup ions generate turbulence at larger heliocentric distances and in the inner heliosheath, affecting the properties of the TS and HP. TS high-energy particles and anomalous cosmic rays are the main high-energy charged particles in the inner heliosheath. TS high-energy particles have energies below 10 MeV, primarily formed by newborn particles accelerated through the TS. Anomalous cosmic rays, discovered in the early 1970s as an anomalous enhancement in the cosmic ray energy spectrum near 100 MeV (including H^+, He^+, O^+, N^+, etc.) with intensity increasing with heliocentric distance, are produced by the acceleration of newborn pickup ions within the heliosphere and are therefore also called heliospheric high-energy particles, though their acceleration mechanism remains unknown. Voyagers 1 and 2 crossed the inner heliosheath at northern and southern heliospheric latitudes, respectively. As shown in Figure 3, except when very close to the HP, the magnetic field strength B appears relatively stable in both Voyagers 1 and 2. The reversal of magnetic field direction indicates that the heliospheric current sheet or corotating interaction regions have entered the inner heliosheath with the solar wind. The magnetic field strength is affected by solar activity, with enhanced magnetic fields resulting from GMIRs or MIRs entering the inner heliosheath with the solar wind. These structures are significantly more numerous and prominent in Voyager 1's observations than in Voyager 2's. Both Voyagers 1 and 2 observed relatively strong magnetic fields when crossing the magnetic barrier in the months approaching the HP.

On one side of the HP is hot (10^5–10^6 K) inner heliosheath plasma, while on the other side is colder (10^4 K) partially ionized interstellar gas. The interstellar plasma flow approaches the Sun at 23 km/s. Voyager 1's initial observations at the HP were surprising, as the spacecraft crossed the HP earlier than most models at the time had predicted, and multiple HP crossings were observed. On July 28, 2012, when Voyager 1 was at 121 AU, the first possible encounter with the HP was indicated by sudden decreases in intensity of TS particles and anomalous cosmic rays—two types of high-energy charged particles in the inner heliosheath—observed by LECP and the Cosmic-Ray detector System (CRS), accompanied by increases in Galactic Cosmic Ray (GCR) intensity. GCRs are high-energy particles mainly from supernova remnants in the Milky Way, exhibiting a power-law energy spectrum above GeV and a turnover below GeV due to suppression by heliospheric interactions. Similar boundary crossings occurred five times, with the last one on August 25, 2012, when anomalous cosmic ray levels dropped to nearly undetectable levels. However, the MAGnetometer (MAG) instrument showed enhanced magnetic field strength with unchanged direction. Because the detection of unchanged magnetic field direction from the inner heliosheath to the LISM contradicted all expectations, researchers initially questioned whether the boundary layer crossed by the spacecraft was indeed the HP. Based on pressure balance between hot inner heliosheath plasma and cold interstellar plasma, a significant increase in plasma density at the HP could be expected. This question could have been resolved through plasma density measurements, but unfortunately, Voyager 1's PLS instrument, which could measure plasma density in situ, had failed in 1980. Fortunately, local electron plasma oscillations measured by the PWS instrument can also provide plasma density information. Electron plasma oscillations, or Langmuir waves, occur at the characteristic electron plasma frequency f_{pe} = 8980√(n_e) Hz, where n_e is the electron number density in cm^{-3}. This is discussed in more detail in Section 4.

3. Heliospheric Boundary Radio Emissions Before Voyager's Heliopause Crossing

3.1 Three Observational Events of Heliospheric Boundary Radio Emissions

Both Voyagers 1 and 2 observed radio emissions at 2–3 kHz in the outer heliosphere using their PWS instruments. The PWS has two signal detection modes: a low-precision 16-channel spectrum analyzer processing electric field waveforms with a frequency range of 10 Hz–56 kHz. This mode can achieve a time resolution of up to 16 s but has very low frequency resolution. The other mode is a high-precision wideband receiver processing voltage waveforms with a frequency range of 50 Hz–10 kHz. This mode features high frequency resolution (typically 1%), a sampling rate of 28,800 s^{-1}, and a sampling time of 48 s, with sampling frequency generally once per week or month. Through Fourier analysis techniques, this can be converted into frequency-time dynamic spectrograms. Three strong heliospheric boundary radio emission events were observed before the spacecraft crossed the HP.

The first radio emission event occurred during Solar Cycle 21 in 1983–1984, observed by the Voyager spacecraft at heliocentric radial distances of approximately 13–17 AU after their encounter with Saturn (9.6 AU). The second radio emission event occurred during Solar Cycle 22 in 1992–1994, with Voyagers 1 and 2 located at heliocentric radial distances of 50.8 AU and 39 AU, respectively. During the 1983–1984 event, although Voyager 1's PLS instrument failed shortly after the Saturn encounter, Voyager 2's PLS data showed that the local solar wind electron plasma frequency (1.3–1.8 kHz) was lower than the 2–3 kHz radiation frequency. The bandwidth of the radiation event was much wider than that of electron plasma oscillations, and the electric field amplitude showed smooth temporal variation rather than sporadic bursts. Even though the two spacecraft were separated by 10 AU in different plasma environments, they simultaneously detected the radiation event with almost identical peak frequencies. Similarly, during the 1992–1994 radio event, Voyager 2's PLS instrument measured a local plasma frequency of 0.4–1.3 kHz, with an average value of

0.7 kHz, which was much lower than both components of the radiation event frequencies. These observational facts demonstrate that the radiation signals in both the 1983–1984 and 1992–1994 events were indeed radio wave signals rather than local plasma oscillation phenomena.

The wideband data have very low time resolution, with spectra generated only once per day, week, or even month. Therefore, the precise start times of radio emission events can only be obtained from the high time-resolution 16-channel spectrum analyzer data of PWS. When Voyager 1 was at approximately 17 AU, its PWS/3.11 kHz frequency channel clearly recorded the 1983–1984 radio emission event from August 30, 1983 (1983/DOY242) to February 21, 1984. Weaker radio emission signals were also visible in the PWS/1.78 kHz channel during several periods of one or two weeks. The high-precision PWS/wideband receiver also recorded four segments of this radio signal. Due to a failure in Voyager 2's flight data system shortly after launch, its PWS spectrum analyzer was not as sensitive as Voyager 1's and did not record this event. However, Voyager 2's high-precision PWS/wideband receiver, unaffected by the flight data system failure, first recorded the 1983–1984 radio emission event on September 14, 1983 (1983/DOY257) at 12.7 AU, with five subsequent recordings of this radio signal. Because Voyager 2 had no wideband data between DOY228 and DOY257, it is entirely possible that, like Voyager 1, the radio signal had been present since August 30, 1983 (1983/DOY242). The detection results from both Voyagers 1 and 2 showed that the strongest electric field spectral density of the 1983–1984 radio emission event was $10^{-14}\ \mathrm{V}^2\cdot\mathrm{m}^{-2}\cdot\mathrm{Hz}^{-1}$, with a bandwidth of 1 kHz. Voyager 1's PWS/1.78 kHz channel data indicated that the 1992–1994 radio emission event initially began on July 6, 1992 (1992/DOY188).

The Voyager waveform observations are shown as frequency-time dynamic spectrograms in Figure 4 [Figure 4: see original paper]. The left upper and lower panels display spectrograms covering the 1983–1984 radio emission events for Voyagers 1 and 2, respectively, where white indicates saturation or spacecraft interference. The right upper and lower panels show spectrograms of the 1992–1994 radio emission events measured by Voyagers 1 and 2 over a one-year period (1992/DOY120–1993/DOY120) in the 1–4 kHz frequency range. Blue represents the weakest wave intensity, while red represents the strongest. The first and second harmonics of the spacecraft power supply appear as horizontal lines at 2.4 kHz and 4.8 kHz, respectively. The narrowband strong bursts at approximately 1.7 kHz in late 1985 and early 1986 in the lower left panel are also caused by spacecraft interference. The actual times when waveform data are available are marked at the top of each panel, with broadband dynamic spectrograms generated roughly monthly (left) or weekly (right). However, during Voyager 2's Uranus observation phase in late 1985 and early 1986, broadband waveform measurements were available almost daily. Interpolation was used to fill gaps between observations to make the spectrograms appear continuous.

The 1983–1984 and 1992–1994 radio emission events are very similar and can be divided into two components: one component is non-drifting radiation with lower frequency (1.8–2.6 kHz) and longer duration (approximately 3 years), showing no obvious frequency drift; the other component is drifting radiation with higher frequency (1.8–3.6 kHz) and shorter duration (approximately 100–300 days), with a frequency drift rate of about 1–3 kHz/yr. Even though Voyagers 1 and 2 were separated by more than 10 AU (for the 1983–1984 event) or 44.6 AU (for the 1992–1994 event), and Voyager 2 had lower sensitivity than Voyager 1, their observations showed almost identical dynamic spectral phenomena, particularly at higher frequencies. This similarity in radio spectra implies that the radiation source is located quite far away—at least greater than 44 AU. As seen in the left panels, for frequencies 3 kHz, the most prominent features in the spectrograms of both Voyagers 1 and 2 began in late 1983, briefly rising to maximum intensity before slowly decaying over the next six months. The start and peak frequencies of the events were both very close to 3 kHz, drifting to 3.5 kHz during the decay phase, with a drift rate on the order of 1 kHz/yr. This drifting structure indicates that the source is moving or that the plasma frequency in the source region is increasing. For frequencies 2 kHz, Voyager 1's results showed that this more stable component was almost continuously visible from the start of the 1983 event to its end in 1984. Although this lower-frequency radiation component also appeared in Voyager 2's data, its slightly lower sensitivity and closer heliocentric radial distance resulted in a higher local plasma frequency, making observation of this low-frequency radiation component more difficult. The right panels show that the 1992–1994 radiation event, except for a significant intensity enhancement by Voyager 1 at approximately 2.7 kHz, also exhibited very similar radio spectra between the two spacecraft. From the maximum radiation intensity of $1.8 \times 10^{-17}\ \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{Hz}^{-1}$ of the 1992–1994 radio event, the radiation power was inferred to be at least 10^{13} W, meaning the radio source is much stronger than any known planetary radio source and may be the strongest radio emission in the solar system.

Comparing the lower-frequency and higher-frequency radio emission components reveals certain correlations along with some different observational characteristics. For example, the left panels show that the low-frequency component appears more frequently, and its bandwidth is narrower than that of the high-frequency component. The correlation is evident in that both components appeared prominently and simultaneously in the 1983–1984 and 1992–1994 events, with peak intensities occurring almost simultaneously in low time-resolution spectrograms. The intensity enhancement at approximately 2.7 kHz during the 1992–1994 radio emission event remains poorly explained, as the frequency ratio of this enhancement to the 2 kHz non-drifting radiation component is only 1.35, indicating it is not a harmonic relationship. If it is considered to originate from two source regions with different plasma densities, there is insufficient detailed information about plasma density distribution to support this view. Although careful analysis of the radio source direction led researchers at the time to believe that this new type of radio emission might originate at or beyond the HP, the characteristics of the radiation source were not well understood.

The third event occurred during Solar Cycle 23 in 2002–2003. This event was relatively weak compared to the first two events in 1983–1984 and 1992–1994, but its spectral characteristics were similar: initial upward drift extending to approximately 3 kHz, with a non-drifting radiation band near 2 kHz. The start time of this radiation event was November 1, 2002, and its relatively weak radiation intensity was correlated with the low activity level of Solar Cycle 23. In addition to these three strong heliospheric boundary radio emission events in 1983–1984, 1992–1994, and 2002–2003, many weaker radio emission events of the same type have sporadically occurred, such as the brief weak drifting events at 3 kHz observed by both Voyagers 1 and 2 in late 1985, particularly evident in Voyager 2's data.

3.2 Solar Cyclic Activity Modulation and Possible Generation Conditions for Heliospheric Boundary Radio Emissions

As shown in the lower panel of Figure 5 [Figure 5: see original paper], the time intervals between these three strong heliospheric boundary radio emission burst events are approximately 9–10 years, roughly consistent with the Sun's 11-year activity cycle, indicating that radio emission burst events are closely related to solar activity. The onboard tape recorder used for high-precision wideband data and the second harmonic of the spacecraft power supply produce strong interference signals below 1 kHz and at 4.8 kHz, respectively, which are not shown in the figure. The first harmonic of the spacecraft power supply at 2.4 kHz appears as a very narrow strong interference signal in the figure. As seen in the upper panel of Figure 5, approximately 400 days before the first two radio emission events in 1983–1984 and 1992–1994, and about 570 days before the relatively weak 2002–2003 event, decreases in galactic cosmic ray count rates/fluxes were observed at Earth—known as Forbush decreases. Forbush decreases are widely believed to result from interplanetary magnetic field disturbances caused by strong interplanetary shocks and solar energetic events that prevent cosmic rays from entering the heliosphere. Combining the time delay of approximately 400–570 days between strong heliospheric boundary radio emissions and Forbush events, Gurnett et al. [33] proposed that radio emissions are generated by the interaction of outward-propagating shocks driven by GMIRs with heliospheric boundary layers (TS or HP), with these GMIR shocks continuing to propagate into the LISM.

Solar transient activity is the main driver of heliospheric boundary radio emissions and electron plasma oscillations. Interplanetary coronal mass ejections and corotating interaction regions are the two main forms of solar transient activity. During solar activity minima, coronal holes accelerate solar wind at high latitudes, making corotating interaction regions very common. When fast solar wind overtakes slow solar wind, corotating interaction regions form, creating forward-reverse shock pairs at their interfaces. During solar activity maxima, more interplanetary coronal mass ejections occur. Solar transient activity takes hundreds of days to propagate from the Sun to the HP, during which countless solar transient activities are generated. Interplanetary coronal mass ejections and corotating interaction regions interact with each other, forming MIRs in the outer heliosphere. Three-dimensional MagnetoHydroDynamics (MHD) numerical simulation results by Kim et al. [38] also show that the merging of corotating interaction regions may play an important role in the formation process of some MIR shocks.

The 1992–1994 radio emission event, which began in July 1992, is believed to have been excited by interplanetary shocks produced during the intense solar activity period at the end of May and beginning of June 1991, near the HP. These shocks generated enormous plasma disturbances, and decreases in cosmic ray intensity were detected at Earth by Pioneers 10 and 11 and Voyagers 1 and 2. Although the spacecraft had not yet reached the HP at that time, using shock velocities of 600–800 km/s observed by Ulysses, Pioneer, and Voyager, estimating the shock propagation time from the Sun to the HP at 1.1 yr, and making some simple assumptions about the thickness of the inner heliosheath and shock propagation speed within it, the HP distance was estimated to be 116–177 AU. This range encompasses the actual HP crossing distances of 120 AU later measured by Voyagers 1 and 2 [32]. The relatively weak 2002–2003 radio emission event is believed to be closely related to the interplanetary shock excited by solar activity in April 2001.

3.3 Possible Radiation Mechanisms and Sources of Heliospheric Boundary Radio Emissions

Gurnett et al. [32] proposed that heliospheric boundary radio emissions are generated by plasma radiation mechanisms. The general process involves shock-accelerated electrons upstream forming electron beams, which excite electron plasma oscillations (or Langmuir waves) at the electron plasma frequency f_{pe}. These Langmuir waves then become freely propagating electromagnetic radiation waves through nonlinear wave-mode conversion processes. This mechanism is similar to that of solar Type II radio bursts [39]. Based on plasma radiation mechanism theory, the frequency of heliospheric boundary radio emissions equals the electron plasma frequency f_{pe} in the radiation source region. By inversely estimating the electron density using n_e = (f_{pe}/8980)^2, it is believed that the radio emission source region may be located in the higher-density LISM region outside the HP, rather than in the lower-density inner heliosheath and TS region. The electron density range in the LISM radio emission source region is approximately 0.04–0.15 cm^{-3}. Remote sensing measurements also indicate that the electron density in the LISM is 0.03–0.1 cm^{-3}, corresponding to an electron plasma frequency of 1.6–2.8 kHz [40–41], which is roughly in the same range as the observed heliospheric boundary radio emission frequencies.

The frequency drift of drifting radiation toward higher frequencies is believed to result from the increase in plasma frequency f_{pe} as shocks propagate into density-increasing ramp regions outside the HP where electron density n_e increases. The density ramp region in the LISM may be caused by plasma “piling up" upstream of the HP [32] or by a "transition region/hydrogen wall" created by plasma-neutral hydrogen interactions [42]. This density-increasing ramp region in the LISM outside the HP is at least the radio emission source region for drifting radiation [32]. Numerical simulation results also show density "piling up" in the LISM outside the HP [43–44]. In contrast, the non-drifting radiation component with significantly constant frequency is believed to be radiation confined within the low-density heliospheric cavity or produced in the LISM outside the HP flanks where little plasma "piling up" occurs [45].

4. Heliospheric Boundary Radio Emission Events or Electron Plasma Oscillations After Voyager's Heliopause Crossing

4.1 Electron Plasma Oscillations or Heliospheric Boundary Radio Emission Events and Shock Models

According to Gurnett et al. [32–33, 45], the region near and outside the HP in the LISM is likely the source region for heliospheric boundary radio emission events. Based on plasma radiation mechanism theory, it is difficult to distinguish whether the observed radiation at the source region consists of electron plasma oscillations (or Langmuir waves) or heliospheric boundary radio emission events. After crossing the HP, Voyagers 1 and 2 observed 8 [46–47] and 2 [46, 48–49] electron plasma oscillations or heliospheric boundary radio emission events, respectively. The eight electron plasma oscillations or heliospheric boundary radio emission events observed by Voyager 1's PWS wideband receiver occurred in October–November 2012, April–May 2013, February–November 2014, September–November 2015, August–October 2016, August 2017, May–June 2018, and May–June 2019. The two electron plasma oscillations or heliospheric boundary radio emission events observed by Voyager 2's PWS spectrum analyzer occurred on January 30, 2019, and June 19, 2020.

Gurnett et al. [46] reported eight strong electron plasma oscillations or radio emission events observed by Voyager 1 after its 2012 HP crossing, shown as epo1–epo8 in Figure 6 [Figure 6: see original paper] (b), although epo8 occurred during a period of severely degraded telemetry performance and missing data. Some researchers collectively refer to them as "plasma wave emission" or "emission"; for convenience, this paper uses No.1–8 to represent their collective designation. The straight line at 2.4 kHz is interference from the spacecraft power supply. The relatively broad intensity enhancements, particularly from late 2018 to mid-2019, are caused by a large amount of telemetry error due to the very small signal-to-noise ratio on Voyager's connection to the Deep Space Network. These oscillations or radio events measured by the PWS wideband receiver and spectrum analyzer appear as narrow bandwidths (0.2–0.4 kHz) in frequency-time spectra, with durations ranging from days to a year and featuring drift toward higher frequencies [50]. Although researchers believe electron plasma oscillations are likely driven by electron beams propagating outward along magnetic field lines connected to shock fronts [51], Voyager 1's charged particle detectors cannot confirm the existence of these electron beams because the PLS instrument [52] that could detect such beams failed in 1980, while the LECP instrument [53] with an energy range $>$ 28 keV is insufficient to detect such low-energy beams. The shocks that excite electron plasma oscillations are related to solar eruptive activity and are excited when shocks cross the HP and propagate into the LISM [14, 51, 54]. A very weak line of plasma thermal noise at the electron plasma frequency detected after 2015 is labeled f_{pe}.

CRS observations from the Electron Telescope (TET), which can detect electrons $>$ 3 MeV, show that almost all (No.1, No.2, No.3, No.4, No.6) oscillation or radio events were preceded by high-energy relativistic electron bursts of 5–100 MeV. In addition to the CRS/TET that detects electrons, the CRS/HET1 (High Energy Telescope 1, HET 1) instrument that can detect multiple particle types and the LECP detector both indicate the occurrence of high-energy relativistic electron bursts in the $>$ 211 MeV galactic cosmic ray energy range. High-energy relativistic electron bursts are interpreted as being produced by the remote reflection (and acceleration) of cosmic ray electrons when shocks interact with magnetic fields [51]. Gurnett et al. [51] first estimated the energy of electron beams exciting electron plasma oscillations to be approximately 20–100 eV, with an average value of 50 eV. This energy is lower than that of electron beams exciting electron plasma oscillations upstream of Earth's bow shock but comparable to the energy of electron beams exciting solar Type II radio bursts (100–150 eV) [56]. Gurnett et al. [51] proposed a shock foreshock model to describe the interaction of shocks of solar origin with interstellar plasma.

Similar to the Earth's bow shock case, electron plasma oscillations are excited by electrons accelerated at the shock and escaping into the shock foreshock, with escaping upstream electrons having a bump-on-tail velocity distribution. Electron plasma oscillations and heliospheric boundary radio emissions are believed to be produced by electron beam plasma instabilities, typically associated with electron foreshock regions related to solar transient activity propagating through the LISM, as shown in Figure 7 [Figure 7: see original paper]. Figure 7(a) shows the Earth's bow shock configuration, while Figure 7(b) shows the interplanetary shock propagating in interstellar medium. For Earth's bow shock, the shock is generally considered stationary, with solar wind approaching the shock at uniform velocity from the Sun's direction. For interplanetary shocks propagating in interstellar medium, the shock propagates outward from the Sun through the HP into interstellar plasma and can only be considered stationary as a first approximation. Despite the enormous spatial scale difference of more than ten thousand times, the shock front is curved and away from the incident plasma flow, with essentially the same local geometry. Interplanetary shocks propagating in interstellar medium also have some unexpected effects not present in Earth's bow shock case [14].

Electron plasma oscillations produced by electron beams are typically observed upstream of interplanetary shocks and after solar energetic electron events. As shown in Figure 7(b), electron plasma oscillations are generated by electron beams moving outward along magnetic field lines connected to the shock front, i.e., the electron beams are located in the electron foreshock region. Electron plasma oscillation intensity is strongest near the leading edge of the electron foreshock region shown by the black shaded area. Cosmic ray intensity perturbations caused by cosmic ray-shock interactions are located in the cosmic ray foreshock. Because cosmic rays are faster than electrons moving outward from the shock, the leading edge of the cosmic ray foreshock is located ahead of the electron foreshock but still behind the tangent field line. Observationally, Richardson et al. [57] also showed, through studies of observation time intervals by Voyagers 1 and 2, that events observed by Voyager 1 in the LISM may be driven by MIRs observed by Voyager 2.

In Figure 6(a), sh1 and sh2 identify two shocks, while pf1 and pf2 identify two pressure fronts. As seen from the actual observations in Figure 6(a), not all electron plasma oscillations or heliospheric boundary radio emission events correspond to shocks (or compression waves) observed by MAG [47]. Among these eight oscillation or radio events, No.1 and No.3 can be directly associated with shocks, corresponding to shocks sh1 and sh2 in Figure 6(a), respectively, while No.5 is related to pressure front pf1. The remaining oscillation or radio events without detected shocks are believed to be excited by shocks far from the spacecraft, so the spacecraft did not detect magnetic field strength jumps [51]. Electron plasma oscillations, considered to be driven by upstream electrons from shocks, can be regarded as precursors of interplanetary shocks originating from the Sun and propagating outward. For example, quasi-perpendicular shocks sh1 and sh2 both had corresponding electron plasma oscillations No.1 and No.3 before arrival, with oscillations terminating when the shocks arrived [14, 45]. Conversely, observing strong electron plasma oscillations upstream of magnetic field jumps would strongly support that the magnetic field jump is a shock. pf1 (2016/DOY346) and pf2 (2020/DOY147) were not accompanied by strong electron plasma oscillations or enhancements in high-energy particle intensity, indicating that although their magnetic field and density compression ratios were relatively large (magnetic field jumps of 1.19 and 1.33, density jumps of 1.12 and 1.36, respectively), pf1 and pf2 events were not entropy-increasing shocks with steep layers but rather pressure fronts [47]. Voyager 1 took 35 days and 8 days to cross them, respectively. Burlaga et al. [47] provided detailed proof from the perspectives of incremental standard deviation, incremental kurtosis, and intermittency that pf2 was not a shock but a magnetic field or MHD pressure front associated with compression waves. Each magnetic field jump exhibited a "jump-ramp" structure, with the magnetic field rapidly jumping to a maximum value and then relatively slowly decreasing.

Figure 6(a) shows that the basic characteristics of the LISM observed during 2012/DOY238–2020/DOY292 consist of four magnetic field jump-ramp structures—shocks sh1 and sh2, pressure fronts pf1 and pf2—and relatively long quiet intervals between these structures, with small-scale waves and turbulence present within these structures.

4.2 Heliospheric Boundary Radio Emission Events Observed by Voyager 1

Researchers have analyzed that among Voyager 1's heliospheric boundary radio emission events after its 2012 HP crossing, No.3, No.4, and No.5 had heliospheric boundary radio emission occurrences. No.1 is considered to be electron plasma oscillations occurring near 2.2 kHz, corresponding to an electron density of 0.06 cm^{-3}, drifting slowly toward higher frequencies at 2 Hz/day. This event was near shock sh1 on 2012/DOY335. This shock sh1, with a magnetic field jump of $\mathrm{B}_2/\mathrm{B}_1 = 1.43$, took 5.4 days to cross Voyager 1, about 10^4 times larger than expected for a shock at 1 AU. Mostafavi et al. [58–59] theoretically showed that shocks in the relatively dense LISM should be collisional shocks, with magnetic resistivity and viscosity causing collisional shocks in the LISM to be much wider than collisionless shocks in interplanetary medium. Similar to No.3, No.1 showed V-shaped depressions in galactic cosmic ray proton intensity perpendicular to the magnetic field [14], but unlike No.3, no radio emission signal was detected upstream of the shock, possibly because these electron plasma oscillations were relatively too weak to be detected by PWS's 16-channel spectrum analyzer and wideband receiver.

No.2 began suddenly on 2013/DOY99 at a frequency near 2.6 kHz, corresponding to an electron density of 0.08 cm^{-3}, drifting slowly toward higher frequencies at 2.6 Hz/day. Based on comparison with Earth's bow shock case, this sudden onset is interpreted as the leading edge of the electron foreshock. PWS/3.11 kHz channel detected No.2 from April 9 to May 22, 2013, lasting nearly one and a half months. Similar to No.1, no radio emission propagating outward from the electron foreshock region was observed for No.2, only sideband characteristics of electron plasma oscillations produced by processes such as three-wave parametric decay [45]. Gurnett et al. [14] suggested that the electron plasma oscillations might not have been strong enough to produce effective radio emission. CRS and LECP instrument results both indicated that a relativistic high-energy cosmic ray electron burst occurred before No.2 (2013/DOY80–2013/DOY94). Observations from the CRS/HET1 instrument, which can detect multiple particle types, and the LECP detector in the > 211 MeV galactic cosmic ray energy range both showed that energetic proton intensity exhibited a clear broad V-shaped depression during the time interval 2012/DOY350–2013/DOY225, with scattering angles near 90° (LECP sectors S1–S5). Gurnett et al. [14] considered both the relativistic high-energy cosmic ray electron burst and the V-shaped depression in galactic cosmic ray proton intensity as precursor effects remotely associated with shocks propagating outward from the Sun. These phenomena, similar to those directly associated with shocks like No.3, provide strong supporting evidence for this view.

The frequency variations of these two electron plasma oscillation events, No.1 and No.2, indicate a steady increase in electron plasma density. The region between No.1 and No.2 is a density-increasing "density ramp" region with a density gradient of approximately 19% per AU, similar to the density gradient inferred from the drifting component of the 2–3 kHz heliospheric boundary radio emissions observed before Voyager's HP crossing. Gurnett et al. [45] compared the 1992–1994 2–3 kHz radio emission event with these two electron plasma oscillations No.1–2, as shown in Figure 8 [Figure 8: see original paper]. In Figure 8(A), drifting radiation is represented by inclined white dashed lines, with frequency increasing by 1.5 kHz over 231 days. In Figure 8(B), the time of GCR intensity increase (August 25) is aligned with the initial time of the radio emission event in Figure 8(A). For comparison, the time scale of the spectrogram was rescaled so that the white dashed lines representing density ramps have the same slope in both the radio emission event and electron plasma oscillations. As seen in Figure 8, when the density ramp in Figure 8(B) is pushed forward in time to when GCR intensity increased, the corresponding plasma frequency is 1.9 kHz, almost identical to the frequency at which the radio emission in Figure 8(A) began. To estimate shock velocity, the density ramp in Figure 8(B) was extrapolated to the point where the plasma frequency increased by 1.5 kHz to reach 3.4 kHz, the same frequency increase as in Figure 8(A). The results show that 542 days are required from the time of GCR intensity increase to this point, corresponding to a radial distance change of 5.3 AU based on Voyager's flight speed of 3.58 AU/yr at that time. In comparison with Figure 8(A), in a density ramp with the same radial density gradient, an interplanetary shock would take 231 days to cross this comparable radial distance of 5.3 AU, yielding a shock propagation speed of 5.3 AU/231 days, corresponding to 40 km/s. This shock propagation speed is reasonable and credible, roughly matching the speed of interplanetary disturbances propagating into nearby interstellar medium obtained through plasma simulations by Zank et al. [42] and Washimi et al. [60]. Through this analysis, Gurnett et al. [45] concluded that the density gradients of both the No.1–2 electron plasma oscillations and the 1992–1994 heliospheric boundary radio emission event are caused by the same basic density structure upstream of the HP, and that the increase in GCR intensity on August 25, 2012, marked Voyager 1's crossing of the HP into interstellar medium.

Liu et al. [61] combined STEREO wide-angle imaging observations, in-situ measurements, and MHD propagation characteristics of solar wind disturbances to first attempt establishing a method for calculating the propagation time of solar transient activity to the LISM. Using data from the Wind spacecraft near Earth and based on a one-dimensional MHD numerical model, the authors proposed that the heliospheric boundary radio emission event in April–May 2013 (see Figure 6(b)) was excited by an interplanetary coronal mass ejection near Earth in March 2012 propagating to the LISM. In March 2012, NOAA AR (National Oceanic and Atmospheric Administration Active Region) 11429, one of the most active regions of Solar Cycle 24, exhibited exceptional activity, producing a series of strong coronal mass ejection events as it rotated from east to west, with numerous shocks and interplanetary coronal mass ejections observed near Earth. MHD numerical simulations showing their outward propagation velocities at different heliocentric radial distances indicate that solar transient activities interacted with each other, forming a large MIR with a shock front in the outer heliosphere. The predicted arrival time of the shock and MIR at 120 AU was April 22, 2013, consistent with the timing of No.2 in April–May 2013. Liu et al.'s [61] work included pickup ion effects and, without considering the great uncertainties of shock crossing the TS into the inner heliosheath and crossing the HP into the LISM, determined the shock speed in the inner heliosheath by analogy with interplanetary shocks passing Earth's bow shock and magnetosheath. Subsequent three-dimensional MHD and multi-fluid simulation studies have deeply considered the transition scenarios of the TS, inner heliosheath, and HP [38, 62–63].

No.3 contains both electron plasma oscillations and radio emission events [14]. As shown in Figure 9 [Figure 9: see original paper], Fourier transforms of Voyager 1's PWS high-precision wideband receiver waveform data reveal that very weak narrowband radio emission was first observed on February 17, 2014 (2014/DOY48) at approximately 2.7 kHz (see Figure 9(a)). Approximately three months later, on May 13, 2014 (2014/DOY133), strong electron plasma oscillations were observed. This sudden enhancement was clearly shown in Voyager 1's PWS low-precision 16-channel spectrum analyzer at the 3.11 kHz frequency channel (see Figure 9(b)). About another three months later, on August 25, 2014 (2014/DOY237), a shock was detected, with increases in magnetic field (see Figure 9(c)) and density inferred from the low-frequency cutoff of the radiation spectrum (see Figure 9(a)). The shock corresponding to No.3 was a quasi-perpendicular shock sh2 observed in the LISM with nearly identical magnetic field jump $B_2/B_1 = 1.13$ and density jump $N_2/N_1 = 1.11$ and no change in magnetic field direction (see Figure 6(a), where av represents average). Shock sh2 was weaker than sh1, taking Voyager 1 3.3 days to cross. Fraternale et al. [64] also showed that sh2 is associated with strong intermittency in the magnetic field and electron plasma oscillations, with this strong, local intermittency possibly being a signal of the shock.

Through comparison with Earth's bow shock observations, Gurnett et al. [14] considered the sudden enhancement on 2014/DOY133 to correspond to the leading edge of the electron foreshock. The weak narrowband radio emission before the electron plasma oscillations shows strong similarity to observations at Earth. At Earth, narrowband radio emissions are typically observed at the electron plasma oscillation frequency f_{pe} or 2f_{pe}, or both, upstream of shocks and are believed to be generated by nonlinear mode conversion of electron plasma oscillations in the shock foreshock region [65–66]. Solar Type II radio bursts are often considered to occur in the corona or upstream of interplanetary shocks in the solar wind, excited by the same mode conversion process. Therefore, Gurnett et al. [14] concluded by analogy that the weak narrowband emission from 2014/DOY48 to 2014/DOY133 is electromagnetic wave radio emission, generated by nonlinear mode conversion of strong electron plasma oscillations near the leading edge of the shock foreshock at or near f_{pe}. Figure 9(a) shows that during the time interval from the start of strong electron plasma oscillations to the arrival of the shock (2014/DOY133–2014/DOY237), the low-frequency cutoff shows a slight parabolic decrease, i.e., the cutoff frequency decreased from

2.70 kHz at DOY133 to a minimum of about 2.55 kHz near DOY170, then to about 2.65 kHz before the shock arrival at DOY237. The simultaneous decrease in low-frequency cutoff and increase in radiation intensity during this period imply that the radio emission was confined within. Figure 9(b) shows that the strong intensity variation characteristic of electron plasma oscillations disappears near the shock, replaced by smoother intensity variation typical of radio emission phenomena.

Figures 9(d)–(f) show observations from CRS/TET, the CRS/HET1 instrument that can detect multiple particle types, and the LECP detector in the > 211 MeV galactic cosmic ray energy range. Relativistic high-energy cosmic ray electron bursts occurred before the start of the electron plasma oscillation event (2014/DOY133). During 2014/DOY133–2014/DOY237, V-shaped depressions in energetic proton intensity were also observed, limited to protons with scattering angles near 90° (LECP sectors S1–S5). The relativistic high-energy cosmic ray electron bursts correspond to the cosmic ray foreshock region, while the V-shaped depressions in energetic proton intensity correspond to the electron foreshock region (see Figure 7(b)).

Ocker et al. [50] considered No.4 to be radio emission, but the article did not provide further specific identification discussion. Figure 10 [Figure 10: see original paper] (a) shows a very faint line marked as f_{pe} near 3 kHz, i.e., the plasma thermal noise line. Figure 10(b) highlights the weak plasma thermal noise line in black, showing it has a constant narrow bandwidth of about 0.04 kHz and lasts for nearly 3 years, equivalent to the spacecraft traveling about 10 AU. The observed electron plasma oscillations can vary in intensity by more than an order of magnitude within days, while the weak plasma thermal noise line shows no obvious frequency dispersion or monotonic frequency drift. The narrow bandwidth, low amplitude, and multi-year duration of the plasma thermal noise line indicate it is different from electron plasma oscillations generated by shocks [50]. After No.5, two lines appear: one broader and stronger at 3 kHz, and another thinner and weaker near 2.9 kHz. Burlaga et al. [47] suggested that the broader, stronger line at 3 kHz might be radio emission generated 245 days earlier at No.5, with the radio emission propagating into a lower-density region until the plasma frequency increased to 3 kHz in early 2017. The lower-frequency line is the weak plasma thermal noise line at f_{pe}.

4.3 Electron Plasma Oscillations or Heliospheric Boundary Radio Emission Events Observed by Voyager 2

Voyager 2's high-precision wideband acquisition mode failed as early as 2006. After crossing the HP in 2018, the spacecraft observed two electron plasma oscillations or heliospheric boundary radio emission events through its low-precision 16-channel spectrum analyzer. The first was electron plasma oscillations detected on January 30, 2019, at 119.7 AU in the 1.78 kHz channel [46]. The second was a weak radio emission event followed by strong electron plasma oscillations detected on June 19, 2020, at 124.2 AU in the 3.11 kHz channel

[48–49]. The 48-second averaged magnetic field strength shows a magnetic field jump $B_2/B_1 = 1.1$ on 2020/DOY182. Electric field measurements on Voyager 2's PWS/3.11 kHz channel showed little peak fluctuation during days 173–175, and this signal is considered radio emission. A very obvious spike in electric field measurements before the magnetic field jump indicates electric field disturbances associated with electron plasma oscillations. Although Voyager 2 observed three magnetic field jumps after crossing the HP, the first two observed in 2019 were pressure fronts. Based on the understanding that electron plasma oscillations are driven by energized electrons in electron foreshocks near shocks, the 2020/DOY182 observation strongly proves that this magnetic field jump is a shock. Electron plasma oscillations reached maximum amplitude on DOY178, after which the amplitude decreased and became continuous weak radio emission until DOY193. The amplitude enhancement on DOY182–183 implies the transition from local electron plasma oscillations to radio emission, which corresponds well with the magnetic field jump, but the oscillating level of peak wave amplitude after DOY182 makes it difficult for researchers to determine whether the activity is caused by electron plasma oscillations or radio waves [49].

4.4 Plasma Number Density and Possible Source Regions

Electron number density n_e is one of the important parameters for the generation mechanism of radio emission phenomena. In proton-dominated heliospheric and interstellar plasma, proton and electron number densities are considered almost identical. As shown in Figure 11 [Figure 11: see original paper], combining PWS data from Voyagers 1 and 2 and PLS data from Voyager 2, plasma number density information from upstream of the TS to the outer heliosphere within 146 AU and in the LISM has been obtained through inversion or in-situ detection [48], with black and red corresponding to Voyager 1 and 2 detection results, respectively.

Voyager 1's PLS instrument failed in 1980 and cannot directly measure proton number density in situ. Since electron plasma oscillations occur at the characteristic electron plasma frequency (f_{pe} = 8980√(n_e) Hz), electron number density can be inferred from electron plasma oscillations detected by the PWS instrument, with priority given to using high-precision wideband receiver waveform data. However, near the TS crossing, Voyager 1's PWS wideband receiver did not collect data, only low-precision 16-channel spectrum analyzer data were available. On February 11, 2004, when Voyager 1 was at 91 AU, electron plasma oscillations were first observed by the PWS/0.311 kHz channel spectrum analyzer upstream of the TS, occurring roughly five times over nearly one year. The last of these five events was recorded on December 15, 2004, at 94.1 AU by both PWS/0.178 kHz and PWS/0.311 kHz channels [67]. Therefore, electron number densities for Voyager 1 near the TS crossing in Figure 11 are inferred from electron plasma oscillations observed by the PWS spectrum analyzer, marked as black dots with error bars. After Voyager 1 entered the LISM, PWS wideband receiver data were used to infer electron number density from No.1–8 electron plasma oscillations measured after the spacecraft crossed the HP, shown as black dots.

The proton number density information measured by Voyager 2's PLS instrument is shown as red dots. Voyager 2's high-precision wideband voltage waveform acquisition mode failed as early as 2006, so electron density can only be obtained by inverting electron plasma oscillation events from its 16-channel spectrum analyzer electric field waveform acquisition mode, marked as red dots with error bars. Although Voyager 2's PLS instrument can continue to collect data, in the LISM, due to relatively low plasma temperature and different plasma inflow directions, the PLS instrument cannot provide good momentum constraints on the plasma distribution function. Therefore, Voyager 2 still uses electron plasma oscillations to infer electron number density information after entering the LISM.

As early as the 1970s, Crandall [68] proposed that interstellar plasma could be perturbed by interacting with the nearby heliosheath, forming density gradients near the interaction region. Although Voyagers 1 and 2 flew at different heliospheric latitudes and were in different solar activity periods at the same heliocentric distance, the results show surprisingly similar heliocentric radial density variations, with density increasing significantly with heliocentric radial distance. Voyager 1's detection shows that, except for the electron number density inferred from the No.8 event, interstellar electron number density has an initial increase near the HP, after which density increases slowly as the spacecraft moves away from the solar system into the LISM. The electron number density inferred from No.1 is n_e 0.055 cm^{-3}, consistent with the plasma number density expected in the LISM at that time based on ground-based remote sensing measurements [69]. From No.1 to No.2, electron number density increased from approximately 0.06 cm^{-3} to 0.08 cm^{-3}, with this region being the density-increasing "density ramp" region. As shown previously in Figure 8, the steady increase in electron plasma frequency f_{pe} and electron number density n_e in this region is consistent with the electron density ramp inferred from the 2–3 kHz radio emissions observed before Voyager's HP crossing [45]. This steep density gradient region is now called the heliospheric boundary layer.

After the initial rapid increase, electron number density only increased slightly, reaching approximately 0.09–0.11 cm^{-3} during No.3. The black dashed line in Figure 11 shows that plasma density increased by about 50 times from 0.002 cm^{-3} at the TS to 0.1 cm^{-3} at the HP. This significant density increase results from pressure balance between hot heliospheric plasma and cold interstellar plasma. After crossing the HP, Voyager 1 measured electron plasma oscillation frequencies increasing roughly from 2.1 kHz to 3.2 kHz, inferring that electron number density increased from approximately 0.055 cm^{-3} to 0.13 cm^{-3} over a span of about 20 AU. Although limited in resolution compared to Voyager 1's PWS high-precision wideband receiver, Voyager 2's PWS spectrum analyzer measurements clearly show a steep increase in LISM density immediately after the HP crossing (i.e., a density ramp with increasing density), with a density gradient consistent with Voyager 1's higher spectral resolution measurements from eight years earlier. Because the heliospheric latitude difference between Voyagers 1 and 2 is 67° and the longitude difference is 43°, this indicates that the density gradient is a large-scale feature of the LISM in any direction in the heliospheric nose region.

The electron number density obtained by inverting the weak plasma thermal noise line at the electron plasma frequency f_{pe} observed by Voyager 1 after 2015 [5, 47] agrees well with that obtained from electron plasma oscillations (see Figure 6(c)). This weak plasma thermal noise line allows continuous determination of interstellar plasma density even when shocks are not generating electron plasma oscillations. Thermal or superthermal processes can produce this weak, narrowband plasma thermal noise line. In the LISM, thermal density perturbations with wavelengths greater than the Debye length (20 m) can cause electrostatic oscillations at the electron plasma frequency f_{pe}, and superthermal electrons from inside the heliosphere or near the HP may increase the intensity of these electrostatic oscillations [70–71].

5. Summary and Outlook

The heliospheric region beyond 10 AU heliocentric distance is often called the outer heliosphere. To date, humanity has launched five spacecraft that have reached the outer heliosphere: Pioneers 10 and 11, Voyagers 1 and 2, and New Horizons. Pioneer 10 flew toward the heliospheric tail region, while the other four spacecraft traveled toward the heliospheric nose region within 40° of the solar equatorial plane. Pioneer 10, launched in 1972, lost contact at 80 AU in 2003, and Pioneer 11, launched in 1973, had insufficient power for all instruments at 40 AU in 1995; therefore, neither entered the heliospheric boundary layer. The Voyager spacecraft are the first and currently the only spacecraft launched from Earth that have successfully reached the heliospheric boundary layer and entered the LISM, providing humanity with rich and surprising observational results for regions including the TS, heliosheath, HP, and LISM. The Voyager instruments will be gradually shut down after mid-2020 to extend the spacecraft's lifetime to at least 2030. New Horizons has obtained the most important and detailed pickup ion measurements in the distant heliosphere to date and is expected to cross the TS into the heliosheath after 2030, currently still en route to the solar system boundary.

The Voyager spacecraft have captured a wealth of peculiar information about the TS, heliosheath, HP, and LISM, making many important scientific discoveries. Capturing the 2–3 kHz heliospheric boundary radio emission signal, the strongest low-frequency radio emission in the solar system, is undoubtedly one of Voyager's major achievements. Heliospheric boundary radio emissions can be roughly divided into two components: drifting radiation with relatively high frequency, featuring frequency drift toward higher frequencies at a rate of 1–3 kHz/yr, a frequency range of 1.8–3.6 kHz, and a relatively short duration of roughly 100–300 days; and non-drifting radiation with relatively low frequency, showing no obvious frequency drift, a frequency range of 1.8–2.6 kHz, and a relatively long duration of about 3 years. If the view that this radio emission originates near the HP is confirmed, the obtained data would represent the first remote sensing results of the HP, providing rich physical information about plasma structure, state, and activity processes in the radiation source region.

The scientific objective of the radio wave detection payload PRA carried by the Voyager spacecraft was to detect outer planet magnetospheres. The PRA was configured with low-frequency (1.2 kHz–1.3 MHz) and high-frequency (1.2–40.5 MHz) channels, with channel intervals of 19.2 kHz and 307.2 kHz, respectively. Therefore, the heliospheric boundary radio emissions concentrated in the 2–3 kHz band were an "unexpected gain" recorded by the plasma wave detection payload PWS that shares antennas with PRA, rather than being recorded by a dedicated radio detection instrument. Currently, only a small amount of measurement data from the Voyager spacecraft is available for heliospheric boundary radio emission signals, leaving many controversies. For example, regarding the radiation source region of heliospheric boundary radio emissions, there are different views placing it at or outside the HP, in the heliosheath region, or at the TS. Regarding the generating shocks, there are different views on whether they originate from the Sun or from interstellar medium. Furthermore, the failure of some instruments (Voyager 1's PLS instrument failed in 1980; Voyager 2's high-precision PWS wideband receiver was shut down in 2006 due to malfunction), low magnetic field measurement precision, and the lack of detection equipment providing lower-energy electron beam information have resulted in extremely limited plasma physics parameter information such as electron number density, magnetic field, and electron beam flows that play important roles in radio emission research. Due to these objective observational limitations, important scientific questions about heliospheric boundary radio emissions—including the radiation source region, shock origin, radiation mechanism, excitation mechanisms of the two different drifting and non-drifting radiation components, and the identification of electron plasma oscillations and radio emission events in the LISM—are difficult to answer convincingly with sufficient evidence.

The electron cyclotron maser radiation mechanism, based on plasma linear instability excitation for direct amplification of radiation electromagnetic waves, has a simple physical picture and high radiation efficiency. As this radiation mechanism theory continues to develop, its application has expanded extensively from Earth's auroral kilometric radiation and solar system planetary radio emission phenomena to solar radio burst phenomena, extrasolar planetary radio emission phenomena, and radio burst phenomena from other stars such as flare stars, M-type dwarfs, T Tauri stars, and pulsars, and even to more distant time-varying radio emission phenomena from extragalactic active objects [72]. Under the current situation of low magnetic field measurement precision and uncertain magnetic field direction determination, although the plasma radiation mechanism is more discussed, the electron cyclotron maser radiation mechanism should not be excluded and deserves our further attention and exploration.

Research on heliospheric boundary radio emissions is currently still in the preliminary exploration stage, yet the physical information provided by radio emissions is extremely important, making in-depth detection research significantly valuable and meaningful. Developing dedicated radio detectors with higher precision and sensitivity for this heliospheric boundary radio emission phenomenon will undoubtedly provide more important physical information about heliospheric boundary radio emissions, helping researchers deeply understand, clarify scientific questions, and even revolutionize existing knowledge. In addition to radio emission-related issues, while the Voyager spacecraft have made many important scientific discoveries, they have also left many unsolved mysteries for humanity, such as failing to confirm the long-standing theoretical speculation that anomalous cosmic ray components of 10–150 MeV are related to the TS, and discovering a new type of high-energy particles (10 keV to MeV) highly correlated with the TS. With the rapid development of cutting-edge space science technology, it is necessary for humanity to launch more spacecraft capable of reaching the solar system boundary, carrying various advanced detection equipment including high-precision, high-sensitivity radio detectors, to find answers to many fascinating and unresolved major scientific questions about the solar system boundary environment.

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