

Recent Advances in Observational Studies of High-Frequency Electrostatic Waves in the Solar Wind: Postprint

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Abstract

The evolution of solar wind constitutes a significant research topic in space physics, and high-frequency electrostatic waves have garnered extensive attention due to their intimate relationship with the distribution of solar wind particles. The recent Parker Solar Probe (PSP) has observed diverse high-frequency electrostatic fluctuations in the near-Sun solar wind (heliocentric distance $r < 0.3$ AU), offering novel opportunities for investigating wave-particle interactions in the near-Sun solar wind. This paper reviews the current observational status of high-frequency electrostatic waves in the near-Sun solar wind, summarizes the observational characteristics of various wave types—including broadband ion-acoustic waves, electron Bernstein waves of known modes, and electrostatic waves of multiple unknown modes—systematically examines the possible excitation mechanisms or free energy sources for each wave type, and provides prospects for future research directions.

Full Text

Preamble

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Progress in the Observational Research of High-Frequency Electrostatic Waves in the Near-Sun Solar Wind

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Abstract

The evolution of the solar wind is a crucial topic in space physics research. High-frequency electrostatic waves have attracted considerable attention due to their intimate connection with the distribution of solar wind particles. The recently launched Parker Solar Probe (PSP) has observed various high-frequency electrostatic wave modes in the near-Sun solar wind (heliocentric distance $r < 0.3$ AU), providing new opportunities to investigate wave-particle interactions in this region. This review introduces the current observational status of high-frequency electrostatic waves in the near-Sun solar wind, summarizes the observational characteristics of various wave types—including broadband ion-acoustic waves and electron Bernstein waves of known modes, as well as electrostatic waves of unknown modes—and examines the possible excitation mechanisms or free energy sources for each wave type. Finally, we outline prospective research directions for future work.

Keywords: solar wind, plasma, waves

1. Background

High-frequency electrostatic waves can influence the kinetic behavior of charged particles (such as electrons and ions) in the solar wind [1], making their study essential for understanding wave-particle interactions in the solar wind. In this paper, high-frequency electrostatic waves refer to plasma electrostatic waves with frequencies between the lower hybrid frequency (flh) and the electron plasma frequency. Research on high-frequency electrostatic waves in the solar wind can be demarcated by the launch of the Parker Solar Probe in 2018 [2] (Parker Solar Probe, PSP). Before the Parker Solar Probe, limited by satellite orbits, in-situ studies could only investigate high-frequency electrostatic waves in the solar wind at heliocentric distances $r > 0.3$ AU. The Parker Solar Probe can access the near-Sun solar wind ($r < 0.3$ AU), approaching as close as 0.046 AU, and carries electromagnetic field and particle detectors [3,4], enabling in-situ observational studies of high-frequency electrostatic waves in the near-Sun solar wind.

At heliocentric distances $r > 0.3$ AU, two primary types of high-frequency electrostatic waves have been observed in the solar wind: ion-acoustic waves and electron Bernstein waves. Ion-acoustic waves are common electrostatic waves in the solar wind with a long observational history, first studied using Helios satellite observations in 1976 [5], and subsequently observed by multiple satellites in the solar wind [6-10]. Ion-acoustic waves in the solar wind generally exhibit the following characteristics: (1) they are linearly polarized electrostatic waves with electric field perturbations parallel to the background magnetic field [11,12]; (2) they are broadband waves with frequency ranges from 100 Hz to 10 kHz [5, 10]. This phenomenon arises because ion-acoustic waves have short wavelengths (typically 10–50 λ_D , where λ_D denotes the Debye length [7]) and are thus susceptible to Doppler shifting by the solar wind; (3) as heliocentric

distance r increases, the occurrence rate and intensity of ion-acoustic waves decrease, and the peak frequency shifts toward lower frequencies [6, 13]; (4) the intensity and occurrence rate of ion-acoustic waves are latitude-dependent, with both being higher in low-latitude regions (primarily slow solar wind) than in high-latitude regions (fast solar wind) [8]; (5) the intensity and occurrence rate of ion-acoustic waves correlate with various plasma parameters, such as ion beams, proton temperature, electron-to-proton temperature ratio (T_e/T_p), and electron heat flux [6-8, 14]. The excitation of ion-acoustic waves is also related to these plasma parameters, for instance, through the electrostatic electron heat flux instability [15,16], ion-ion acoustic instability [17,18], electron-ion streaming instability [19], electron-electron-ion streaming instability [18, 20-21], among others. Additionally, temperature gradients can also excite ion-acoustic waves [22].

Unlike ion-acoustic waves, electron Bernstein waves have been rarely observed in the solar wind at $r > 0.3$ AU, with detections only by the Active Magnetospheric Particle Trace Explorers (AMPTE) and the Wind satellite [23,24]. AMPTE observed electron Bernstein waves during lithium ion releases; these waves propagated quasi-perpendicular to the background magnetic field and exhibited five frequency bands, with the lowest band located at 1.8 times the electron cyclotron frequency (f_{ce}) and frequency differences between bands of 1.1-1.2 f_{ce} [23,24]. These waves did not originate from the solar wind; Baumgärtel et al. [24] suggested that the waves were related to charge non-neutrality caused by lithium ions and electrons from photoionized lithium atoms moving along different trajectories. The electron Bernstein waves detected by Wind were located near interplanetary shocks, exhibited multiple frequency bands at integer or half-integer multiples of f_{ce} , and propagated parallel to the shock normal but with oblique polarization relative to the background magnetic field [25]. Based on observations of waveforms and particle heating, Wilson et al. proposed that these waves might be excited by the electron cyclotron drift instability [25].

The Parker Solar Probe has discovered a greater variety of high-frequency electrostatic waves in the near-Sun solar wind. In addition to the ion-acoustic waves and electron Bernstein waves previously observed by satellites at $r > 0.3$ AU [26-29], it has detected multiple new types of high-frequency electrostatic waves, such as $f \approx 0.7 f_{ce}$ waves, $f < f_{ce}$ multiband electrostatic waves, narrow-band ion-acoustic waves, Type-B waves, Type-C waves, and $f \approx f_{lh}$ broadband electrostatic waves [27-32]. Moreover, the occurrence rates of these waves have increased significantly; for example, the occurrence rate of electron Bernstein waves increases with decreasing heliocentric distance [27].

Research on high-frequency electrostatic waves in the near-Sun solar wind is burgeoning. This paper primarily introduces the observational results of high-frequency electrostatic waves in the near-Sun solar wind from the Parker Solar Probe in recent years. The structure is as follows: Section 2 introduces broadband ion-acoustic waves; Section 3 discusses electron Bernstein waves; Section 4 presents new types of high-frequency electrostatic waves; and the final section,

Section 5, summarizes the entire paper.

2. Broadband Ion-Acoustic Waves

Because the Parker Solar Probe has observed a new mode of narrowband ion-acoustic waves in the near-Sun solar wind, we refer to the ion-acoustic waves previously observed at $r > 0.3$ AU as broadband ion-acoustic waves to distinguish them.

Broadband ion-acoustic waves in the near-Sun solar wind were first reported by Mozer et al. [26]; the wave electric field spectrum is shown in the left panel (a) of Figure 1 [Figure 1: see original paper], and the specific electric field waveform is displayed in the right panel (b) of Figure 1. Broadband ion-acoustic waves are commonly observed in the near-Sun solar wind, and their wave characteristics are similar to those observed at $r > 0.3$ AU, featuring: (1) linearly polarized electrostatic fluctuations with electric field perturbations parallel to the background magnetic field, reaching intensities of 15 mV/m; (2) broadband waves with frequency ranges from several hundred Hz to several tens of kHz; (3) propagation anti-parallel to the background magnetic field. Additionally, Mozer et al. discovered nonlinear broadband ion-acoustic waves in switchback boundary regions and within switchbacks themselves, demonstrating the process of these waves evolving into ion holes—events rarely observed by satellites [33].

Mozer et al. discussed the excitation possibilities of two common mechanisms for broadband ion-acoustic waves: the electrostatic electron heat flux instability (or current-driven excitation) and the ion-ion acoustic instability [26]. The excitation threshold of the former is related to the electron-to-ion temperature ratio (T_e/T_i). In typical solar wind environments where $T_e/T_i \approx 1$, the relative velocity between electrons and ions must reach the electron thermal velocity for excitation, a condition difficult to achieve in the solar wind. The latter mechanism is related to relative drifts between different ion components. Mozer et al. analyzed local plasma parameters and found that electron and ion temperatures were nearly identical ($T_e/T_i \approx 1$), indicating that ion-acoustic waves are unlikely to be excited by the electrostatic electron heat flux instability (or current-driven excitation). On the other hand, the ion distribution exhibited clear beam features, and the appearance of ion-acoustic waves correlated with the magnitude of the ion beam. Therefore, Mozer et al. concluded that these broadband ion-acoustic waves were excited by the ion-ion acoustic instability [26].

3. Electron Bernstein Waves

Three types of electron Bernstein waves with different frequency distributions exist in the near-Sun solar wind, with their strongest bands located near f_{ce} , between integer multiples of f_{ce} , and near multiple f_{ce} , respectively. We refer to these as $f \approx f_{ce}$ electron Bernstein waves (Type I electron Bernstein waves), Type II electron Bernstein waves, and Type III electron Bernstein waves.

3.1 Type I: f_{ce} Electron Bernstein Waves

The f_{ce} electron Bernstein waves were first identified by Malaspina et al. [27], with an observational example shown in Figure 2 [Figure 2: see original paper]. The strongest band of f_{ce} electron Bernstein waves is located near 1.0 f_{ce}, as indicated by the red box in Figure 2. These waves exhibit harmonics at higher frequencies, and this frequency distribution differs somewhat from that of electron Bernstein waves in planetary magnetospheres (such as Earth's magnetosphere), which are located between integer multiples of f_{ce}. Based on statistical and case studies of f_{ce} electron Bernstein waves by Malaspina et al. [27] and other researchers [29, 34], the observational properties of these waves can be summarized as follows: (1) they are widely present in the near-Sun solar wind, with occurrence rates and intensities increasing as heliocentric distance r decreases; (2) they tend to occur in quiet radial magnetic fields—when these waves appear, the angle between the magnetic field direction and the solar radial direction is typically less than 25°, mainly within 10°–15°; (3) for some waves, the strongest band and harmonics exhibit good frequency multiple relationships, suggesting that harmonics may be excited through nonlinear wave-wave coupling of the fundamental frequency; (4) they are commonly observed when core electrons have strong sunward drift velocities (in the solar wind frame), as shown in Figure 3 [Figure 3: see original paper], with the number of waves increasing significantly when the core drift velocity is positive. Since the plasma maintains current neutrality, the sunward drift of core electrons is positively correlated with the radial drift of hotter electron components (such as halo and strahl electrons), indicating that f_{ce} electron Bernstein waves may be excited by electron beams.

3.2 Type II Electron Bernstein Waves

Type II electron Bernstein waves were also first reported by Malaspina et al. [28]. Figure 4 [Figure 4: see original paper] shows the electric field power spectrum of a typical Type II electron Bernstein wave, revealing that all frequency bands are greater than f_{ce} and located between integer multiples of f_{ce}, similar to electron Bernstein waves observed in planetary magnetospheres (such as Earth's magnetosphere). In the Type II electron Bernstein waves reported by Malaspina et al. [28], the strongest band was the lowest frequency band, and the waves occurred in quiet radial magnetic fields. Shi et al. [29] discovered Type II electron Bernstein waves with different observational characteristics and environments. In the events studied by Shi et al., the strongest band was located at a harmonic, and the events occurred near the heliospheric current sheet where magnetic field disturbances were strong [29]. Shi et al. [29] found that the observed wave characteristics were consistent with simulation results of electron Bernstein wave excitation and theoretical predictions of instabilities, concluding that the waves were locally excited. They subsequently calculated the resonant energy, finding that these waves could resonate with electrons of 30–3000 eV. In the electron distribution, electrons of 40–150 eV exhibited bidirectional electron

flows both parallel and anti-parallel to the background magnetic field, as well as temperature anisotropy with perpendicular temperature greater than parallel temperature. Therefore, they concluded that the excitation of these waves was related to electron beams or temperature anisotropy [29].

3.3 Type III Electron Bernstein Waves

Type III electron Bernstein waves were first discovered and reported by Shi et al. [29]; these waves appear near the heliospheric current sheet where magnetic field disturbances are relatively strong. Figure 5 [Figure 5: see original paper] displays the electric field power spectral density (left panel), averaged power spectral density (middle panel), and parameters for each harmonic such as peak frequency, bandwidth, and amplitude (right panel) for this wave type. It can be seen that the lowest frequency band of Type III electron Bernstein waves is higher than those of the previous two types, located at $3.93 f_{ce}$, with other bands appearing near integer multiples of f_{ce} . The most interesting feature of Type III electron Bernstein waves is their modulation by low-frequency ion-scale waves. Shi et al. [29] found that the electric field spectral intensity of the electron Bernstein waves exhibited periodicity. They performed a coherence analysis between the electric field perturbations of the waves and the magnetic field perturbations of the low-frequency ion-scale waves, discovering a strong correlation between the two (correlation coefficient greater than 0.75), as shown in the bottom panel of Figure 5. This provides direct observational evidence of electron Bernstein wave modulation. Regarding the excitation of these waves, Shi et al. [29] argued that the modulation period of the low-frequency waves ($1/f_{cp}$, where f_{cp} is the proton cyclotron frequency) is much longer than the linear instability timescale ($1/f_{ce}$), suggesting that the waves are more likely excited non-locally. However, they could not rule out the possibility that ion-scale waves modulate the electron distribution to provide free energy for exciting electron Bernstein waves.

4. New Types of High-Frequency Electrostatic Waves

The Parker Solar Probe has observed multiple new types of high-frequency electrostatic waves with unknown modes in the near-Sun solar wind, most of which appear as narrowband wave forms.

4.1 $f \approx 0.7 f_{ce}$ Waves

The $f \approx 0.7 f_{ce}$ waves were first discovered by Malaspina et al. [27], as shown in Figure 2. As the name suggests, the characteristic frequency of these waves is located near $0.7 f_{ce}$ and its harmonics, as indicated by the black box in Figure 2. The $f \approx 0.7 f_{ce}$ waves are often observed simultaneously with $f \approx f_{ce}$ electron Bernstein waves, and both share similar characteristics: the waves primarily occur in quiet radial magnetic fields, their occurrence rates and intensities increase with decreasing heliocentric distance r , and they are most likely excited by electron

beams. In observations, some $f \approx 0.7 f_{ce}$ waves exhibit good frequency multiple relationships between the fundamental frequency and harmonics, suggesting that the harmonics may be generated through nonlinear wave-wave coupling of the $0.7 f_{ce}$ band itself [34]. Additionally, $f \approx 0.7 f_{ce}$ waves can also undergo nonlinear wave-wave coupling with $f \approx f_{ce}$ electron Bernstein waves to excite harmonics [34].

4.2 $f < f_{ce}$ Multiband Electrostatic Waves

The $f < f_{ce}$ multiband electrostatic waves were discovered and reported by Shi et al. [29], as shown in Figure 6 [Figure 6: see original paper]; the wave events occurred near the heliospheric current sheet. Based on the data in Figure 6, Shi et al. [29] identified the following observational characteristics of these waves: (1) they are multiband, narrowband electrostatic waves; (2) the frequency of the strongest band is much lower than f_{ce} , while harmonics can reach or exceed f_{ce} ; (3) the harmonics exhibit good frequency and intensity correlations, implying that the wave harmonics are excited through nonlinear wave-wave interactions. Subsequently, Shi et al. [29] discussed the wave mode and fundamental frequency excitation mechanism. Theoretically, waves in this frequency range could be ion-acoustic waves, ion Bernstein waves, or lower hybrid waves. However, the frequency spacing of ion Bernstein waves does not match observations, and parallel ion-acoustic waves (i.e., broadband ion-acoustic waves) cannot explain electric field perturbations perpendicular to the magnetic field. Therefore, the wave mode is likely oblique ion-acoustic waves or lower hybrid waves. Although the specific mode of these waves remains unknown, the excitation of both oblique ion-acoustic waves and lower hybrid waves is related to particle streams. Theoretical studies indicate that ion-acoustic waves can be excited by the ion-ion acoustic instability, while lower hybrid waves can be excited by the electron heat flux instability, and both sources of free energy can exist near the heliospheric current sheet [29].

4.3 Narrowband Ion-Acoustic Waves

Narrowband ion-acoustic waves, also known as triggered ion-acoustic waves, are a new type of wave discovered in the near-Sun solar wind, first reported by Mozer et al. [30], with wave characteristics shown in Figure 7 [Figure 7: see original paper]. The left panel of Figure 7 presents a long-duration (≈ 12 h) narrowband ion-acoustic wave event, where distinct narrowband electrostatic fluctuations can be seen with frequencies of order 100 Hz, much lower than the local ion plasma frequency $f_{pi} \approx 9$ kHz. The right panel of Figure 7 shows the electric field waveform of narrowband ion-acoustic waves, which exhibit shock-like wave packets with a period of 1.5 s, identical to the period of local low-frequency magnetic field perturbations.

Mozer et al. [30] proposed that the nature of these waves is obliquely propagating ion-acoustic waves, based on the following reasons: (1) local ions exhibited clear ion beams, and with $Te/Ti \approx 5$, the plasma environment was favorable

for ion-acoustic wave excitation; (2) the wave phase velocity was approximately 100 km/s, close to the local ion acoustic speed of 120 km/s; (3) there was a certain angle between the magnetic and electric fields in the satellite X-Y plane, indicating that the waves did not propagate parallel to the background magnetic field.

Regarding the excitation mechanism, Mozer et al. [30] examined ion distribution functions in different velocity planes in the instrument coordinate system, as shown in Figure 8 [Figure 8: see original paper]. Figure 8 reveals that the local ion beam was substantial, creating a bump in the tail of the distribution function. Fitting results for this ion distribution indicated that local ion parameters were at the threshold of the ion-ion acoustic instability predicted by theory, leading Mozer et al. [30] to conclude that these waves were excited by the ion-ion acoustic instability.

Subsequently, Mozer et al. [31] conducted a statistical study of narrowband ion-acoustic waves, finding that these waves generally exhibit the following characteristics: (1) they commonly occur at 15–30 solar radii; (2) their frequency range is approximately 100–1000 Hz; (3) low-frequency electric field structures of a few Hz appear in the background electric field, with narrowband ion-acoustic waves periodically emerging locked to a certain phase of the electric field structure; (4) the periodic waves and electric field structures can persist for long durations, even approaching 1 day; (5) plasma number density exhibits perturbations at the same frequencies as the narrowband ion-acoustic waves and electric field structures; (6) no wave signals matching the frequencies of narrowband ion-acoustic waves and electric field structures were observed in the magnetic field; (7) the electric field and density perturbations of narrowband ion-acoustic waves are pure sinusoids, with very narrow bandwidths. Furthermore, Mozer et al. [31] found that narrowband ion-acoustic waves are associated with core electron heating—when narrowband ion-acoustic waves appear, core electrons are heated to twice the minimum temperature in theoretical models.

Generally, instabilities provided by ion beams can excite quasi-monochromatic ion-acoustic waves in the linear stage. After excitation, ion-acoustic waves trap ions and electrons, entering a nonlinear development stage and eventually evolving into the broadband waves observed previously [26, 30, 33]. Mozer et al. suggested that the narrowband form of these waves was due to low-frequency magnetic field fluctuations providing stable plasma parameters for locally exciting quasi-monochromatic ion-acoustic waves [30]. However, their subsequent statistical study found no correlation between narrowband ion-acoustic waves and magnetic field perturbations [31]. Consequently, the mode of narrowband ion-acoustic waves remains questionable. Although Mozer et al. [30] proposed that the wave mode is oblique ion-acoustic waves, we categorize them as narrowband electrostatic waves of unknown mode.

4.4 Type-B and Type-C Waves

Malaspina et al. [28] found three wave types appearing simultaneously near f_{ce} , with electric field power spectral density, degree of polarization, and ellipticity shown in Figure 9 [Figure 9: see original paper]. In Figure 9, the waves with frequencies higher than f_{ce} are electron Bernstein waves (i.e., Type II electron Bernstein waves discussed in Section 3), which Malaspina et al. designated as Type-A waves [28]. Additionally, Figure 9 shows two new wave types with frequencies below f_{ce} , which Malaspina et al. designated as Type-B and Type-C waves [28]. Both Type-B and Type-C waves are narrowband waves with the following characteristics [28]: (1) both are susceptible to Doppler effects, exhibiting variable frequencies in the spacecraft frame and displaying mirror-symmetric features; (2) in the plasma frame, Type-B wave frequencies are close to $1.0 f_{ce}$, while Type-C wave frequencies are approximately $0.5 f_{ce}$; (3) comparing frequencies in the spacecraft frame and plasma frame, the wave vector of Type-B waves has a component directed toward the Sun, while the wave vector of Type-C waves has a component directed away from the Sun; (4) Type-B waves are right-hand polarized, while Type-C waves are left-hand polarized; (5) both propagate obliquely to the background magnetic field, with Type-B waves forming an angle of approximately 70° with the background magnetic field and Type-C waves forming an angle of approximately 85° ; (6) both generally occur in quiet radial magnetic fields. It should be noted that Type-B and Type-C waves do not always appear simultaneously—for example, Shi et al. subsequently reported events with only Type-B waves present [29]—but when they do appear together, the mirror-symmetric frequency feature is observed [28]. In the events reported by Shi et al., Type-B waves exhibited a new feature of harmonic presence [29]. Furthermore, Malaspina et al. [28] noted that due to the low time resolution (0.87 s) of the spacecraft spectrograms, Type-B and Type-C waves appear in the same frequency bands as f_{ce} electron Bernstein waves and $0.7 f_{ce}$ waves, respectively, making them difficult to distinguish.

Currently, theory cannot provide possible wave modes for Type-B and Type-C waves. Malaspina et al. [28] analyzed potential free energy sources and excitation mechanisms for both wave types. They calculated the resonant energies of Type-B and Type-C waves, finding that both resonate with low-energy (0.00007 – 23.0 eV) core electron components, possibly related to anomalous electron cyclotron resonance and locally excited. However, limited by the inability of instruments to detect reliable low-energy electron distributions, instability studies are difficult. Malaspina et al. [28] subsequently constructed excitation models for the waves and discussed various possible excitation mechanisms, such as electron cyclotron drift instability, nonlinear wave-wave interactions, electromagnetic wave decay, and loss-cone instability. However, none could excite waves corresponding to observations, or the observed parameters did not meet the requirements for instability onset. The excitation mechanisms of Type-B and Type-C waves remain unknown.

4.5 f flh Broadband Electrostatic Waves

Zhao et al. [32] first reported broadband electrostatic waves with frequencies near the lower hybrid frequency flh. Figure 10 [Figure 10: see original paper] shows the electric field spectra (panels II and III) and electric field waveforms (panel IV) of these waves in four different time periods. Based on the frequency characteristics, we designate these waves as f flh broadband electrostatic waves. Zhao et al. [32] analyzed a long-duration f flh broadband electrostatic wave event detected during Parker Solar Probe's eighth orbit, finding that f flh broadband electrostatic waves exhibit the following features: (1) wave energy is primarily concentrated at 0.3-2 flh, with wave bandwidths of 1-6 flh; (2) wave amplitudes are 0.1-50 mV/m; (3) electric field solitary structures accompany the waves, with electric field amplitudes reaching 500 mV/m (see Figure 10(d-VI)); (4) the waves propagate obliquely to the background magnetic field; (5) the waves show some correlation with β_p (the ratio of proton thermal pressure to magnetic pressure), primarily occurring at $\beta_p \approx 0.03-3$; (6) the appearance of the waves is independent of whether the magnetic field is radial and independent of the angle between the magnetic field and solar wind. It should be noted that Malaspina et al. [35] also reported waves near flh, but the waves in their events were electromagnetic waves with magnetic field perturbations, fundamentally different from these electrostatic waves.

Zhao et al. [32] subsequently conducted a detailed discussion of the wave mode for f flh broadband electrostatic waves. Theoretically, there are three types of obliquely propagating electrostatic (or quasi-electrostatic) waves with frequencies below fce: lower hybrid waves, oblique ion-acoustic waves, and ion Bernstein waves. They argued that the wave mode is most likely lower hybrid waves for the following reasons: (1) theoretical two-component (ion and electron) plasma models approximating the near-Sun solar wind environment indicate that frequencies of oblique ion-acoustic waves and ion Bernstein waves are difficult to reach the observed frequencies, while lower hybrid wave frequencies match observations more closely; (2) theoretical instability studies show that instabilities related to lower hybrid waves can excite waves more consistent with observations; (3) lower hybrid waves have been observed in Earth's magnetosheath as broadband electrostatic waves near flh, similar to the characteristics of these events. However, due to instrument limitations on the Parker Solar Probe and possible differences between theoretical models and actual observations, Zhao et al. did not completely rule out the possibilities of oblique ion-acoustic waves and ion Bernstein waves [32]. Finally, because f flh broadband electrostatic waves are relatively common in the near-Sun solar wind, Zhao et al. [32] suggested that these waves can cause pitch-angle scattering of strahl electrons, playing a role in regulating electron heat flux.

5. Summary

The Parker Solar Probe has enabled in-situ observational studies of high-frequency electrostatic waves in the near-Sun solar wind at $r < 0.3$ AU, opening

a new chapter in high-frequency electrostatic wave research.

This review has introduced the research findings on high-frequency electrostatic waves observed by the Parker Solar Probe in the near-Sun solar wind. Two types of high-frequency electrostatic waves previously known to exist in the solar wind at $r > 0.3$ AU (broadband ion-acoustic waves and electron Bernstein waves) have been discovered and reported in the near-Sun solar wind. Ion-acoustic waves exhibit similar behavior across different solar wind regions, while electron Bernstein waves show significantly increased occurrence rates and richer characteristic frequencies in the near-Sun solar wind. In addition to these two known wave types, multiple new waves with unknown modes have been discovered, such as $f \approx 0.7 f_{ce}$ waves, $f < f_{ce}$ multiband electrostatic waves, narrowband ion-acoustic waves, Type-B waves, Type-C waves, and $f \approx f_{lh}$ broadband electrostatic waves. Research on these new waves has primarily focused on wave identification and statistical characteristics, followed by discussions of wave nature and excitation mechanisms. Studies on wave applications are relatively scarce, with only narrowband ion-acoustic waves found to heat core electrons in the near-Sun solar wind.

Based on current observational research, the prospects for high-frequency electrostatic wave studies are broad. The Parker Solar Probe has observed various new phenomena of high-frequency electrostatic waves that await deeper investigation and explanation. The nature of new waves remains unclear, and theoretical research urgently needs improvement. Excitation mechanisms are often limited to parameter statistics or empirical analysis, and qualitative or quantitative instability analyses could be performed. Wave applications, particularly how they interact with particles, should also receive attention. Furthermore, recent studies have found that some electrostatic waves observed by the Parker Solar Probe may be caused by spacecraft wake effects [36], meaning that the waves may not necessarily originate from the solar wind. The source of the waves is also a new issue requiring careful consideration.

High-frequency electrostatic waves play roles in regulating electron heat flux and heating solar wind particles, serving as a probe for understanding wave-particle interactions in the solar wind [37]. We believe that as the Parker Solar Probe continues its approach toward the Sun and theoretical research advances, we will observe richer high-frequency electrostatic waves of known or unknown modes, resolve issues regarding wave nature and excitation mechanisms, understand the influence of waves on particle dynamics in the near-Sun solar wind, evaluate the role of high-frequency electrostatic waves in the evolution of the near-Sun solar wind, and contribute to solving challenging problems such as solar wind acceleration.

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