Advances in Observational and Theoretical Studies of Electromagnetic Ion Cyclotron Waves in the Solar Wind (Postprint)

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Abstract

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Full Text

Preamble

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Advances in Observation and Theory of Electromagnetic Ion Cyclotron Waves in the Solar Wind

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Abstract

Electromagnetic Ion Cyclotron (EMIC) waves in the solar wind have received extensive attention since their discovery. Due to their frequencies being close to the proton cyclotron frequency, EMIC waves can transfer wave energy to ions through cyclotron resonance wave-particle interactions, playing an important role in solar wind particle heating and acceleration phenomena. This paper summarizes the progress of observational and theoretical research on EMIC waves in the solar wind, including a series of results from observational studies of EMIC waves inside and outside magnetic clouds, within magnetic clouds and Interplanetary Coronal Mass Ejection (ICME) sheath regions, as well as research progress on wave excitation mechanisms based on observations. Finally, future breakthrough directions for studying EMIC waves in the solar wind are discussed.

Keywords Sun: solar wind, waves, instabilities

1 Introduction

The solar wind is a high-temperature, high-speed, weakly collisional charged particle flow continuously emanating from the solar atmosphere. Numerous plasma activity phenomena occurring within it—such as Interplanetary Coronal Mass Ejections (ICMEs), shocks, plasma waves, and turbulence—affect variations in interplanetary space weather [1–2]. Solar wind plasma is typically in a highly turbulent and significantly chaotic state, considered a natural carrier of various plasma waves [3–4]. Among these, Electromagnetic Ion Cyclotron (EMIC) waves are a type of electromagnetic disturbance ubiquitous in interplanetary space and represent one of the important physical mechanisms leading to solar wind heating and acceleration phenomena [5–7].

EMIC waves refer to low-frequency plasma waves with frequencies near the proton cyclotron frequency. Their propagation direction relative to the magnetic field can be either parallel or oblique, and they exhibit both left-handed and right-handed polarization states [8]. When the wave propagation direction changes, their polarization characteristics also change accordingly, transitioning from circular polarization (left-handed or right-handed) in the case of parallel propagation to elliptical polarization in the case of oblique propagation. The left-handed EMIC wave branch includes ion cyclotron waves with frequencies close to the proton cyclotron frequency and shear Alfvén waves with frequencies much smaller than the proton cyclotron frequency; therefore, left-handed EMIC waves are also called Alfvén/ion cyclotron waves [9]. Magnetosonic waves with frequencies less than or near the proton cyclotron frequency and whistler waves with frequencies higher than the proton cyclotron frequency but lower than the electron cyclotron frequency both belong to the right-handed EMIC wave branch; thus, right-handed EMIC waves are also called magnetosonic/whistler waves [9]. In the solar wind, the observed non-zero magnetic helicity at ion scales is considered evidence of cyclotron damping of turbulent fluctuations and contributes to dissipation and heating at kinetic scales [10–11]. Ion cyclotron resonance can couple electromagnetic fluctuations with ion cyclotron motion and promote coronal plasma heating through the damping effect of Alfvén waves at ion cyclotron scales [12–14]. Therefore, EMIC waves play a crucial role in revealing the physical mechanisms of solar wind particle heating, acceleration, and wave energy dissipation processes [15–18].

In recent years, with increasing resolution of solar wind in-situ detection satellites, a series of studies on EMIC waves in the solar wind have been conducted. Based on STEREO satellite data, Jian et al. first reported EMIC wave events in the solar wind [19]. Observationally, EMIC waves in the solar wind mainly propagate along the radial magnetic field (i.e., quasi-parallel propagation) and exhibit both left-handed and right-handed polarization states, with the occurrence rate of left-handed EMIC waves being higher than that of right-handed EMIC waves [19–21]. Jian et al. also conducted statistical studies based on MESSENGER and STEREO satellite data, pointing out that EMIC wave events also exist in the inner heliosphere, with wave energy at 0.3 AU being greater than that at 1 AU [20–21]. By comparing the wave characteristics of left-handed and right-handed EMIC waves at different radial distances, Jian et al. found that as the radial distance increases, the frequency of EMIC waves continuously decreases, while the power spectrum of left-handed EMIC waves is always higher than that of right-handed EMIC waves [21].

Boardsen et al. used multi-year MESSENGER satellite observations to study in detail the evolution of EMIC wave characteristics with radial distance in the 0.3–0.7 AU range [22]. The results showed that the wave frequency was approximately 0.13 Hz at 0.3 AU and decreased to 0.04 Hz at 0.7 AU; however, the normalized frequency (wave frequency divided by the local proton cyclotron frequency) showed an increasing trend, slowly rising from 0.35 to 0.5. As the radial distance increased, the interplanetary magnetic field also weakened significantly, causing both the wave frequency f_{sw} and the proton cyclotron frequency f_{pc} to shift to lower frequency ranges as the radial distance increased (from 0.3 AU to 1 AU). These characteristics indicate that most EMIC waves are damped during propagation in interplanetary space. When the normalized frequency f_{sw}/f_{pc} approaches 1 (i.e., the wave frequency is close to the proton cyclotron frequency), left-handed EMIC waves can effectively interact with ions through cyclotron resonance, transferring wave energy to ions and thereby heating the solar wind. Recently, Bowen et al. [23] and Bale et al. [24] used the latest observational data from the Parker Solar Probe to study EMIC wave events near the solar atmosphere, and their results showed that the occurrence of EMIC waves is not limited to the radial magnetic field direction. This series of observational studies demonstrates that EMIC waves fill the entire interplanetary space and play an important role in modulating solar wind ion distributions.

Given the importance and ubiquity of EMIC waves in the solar wind, their excitation mechanisms have also received widespread attention. There have generally been two main viewpoints regarding the generation mechanism of EMIC waves in the solar wind: one holds that these waves originate in the solar atmosphere and are residual high-frequency Alfvén waves that propagate through the solar wind to interplanetary space without participating in solar wind heating processes [19, 25–26]; the other holds that these waves may be excited by free energy present in the solar wind through plasma instabilities, such as temperature anisotropy, ion beams, and loss-cone distributions of electrons and ions [27–28]. In the solar wind, the primary mechanism for exciting EMIC waves is ion temperature anisotropy instability [29–34]. In cases where the ion perpendicular temperature is greater than the parallel temperature ($T_{i\perp} > T_{i\parallel}$), the ion temperature anisotropy instability can effectively excite Alfvén/ion cyclotron waves [35–36]; when the ion perpendicular temperature is less than the parallel temperature ($T_{i\perp} < T_{i\parallel}$), the ion temperature anisotropy instability effectively excites magnetosonic/whistler waves [30, 34].

Ion beams in the solar wind can also provide additional free energy to excite parallel-propagating right-handed magnetosonic/whistler waves and obliquely propagating Alfvén/ion cyclotron waves [37–42]. When the plasma exhibits a ring distribution or ring-beam distribution perpendicular to the background magnetic field, Alfvén/ion cyclotron waves can be excited through ion cyclotron instability [43–46]. On the other hand, relatively isotropic and cold ion beams can excite beam instabilities, which can effectively excite magnetosonic/whistler waves and cause them to grow faster [47]. Additionally, research indicates that although a small number of α particles present in the solar wind cannot provide sufficient free energy to excite EMIC waves, their density and drift velocity can significantly affect the occurrence rates of left-handed Alfvén/ion cyclotron waves and right-handed magnetosonic/whistler waves [48–50].

Considering the relative drift velocity between α particles and protons $V_d = V_\alpha - V_p$ (where V_α and V_p represent the flow velocities of α particles and protons, respectively), Podesta et al. analyzed the influence of this parameter on proton temperature anisotropy instability in the solar wind [51]. When the solar wind plasma exhibits proton perpendicular temperature anisotropy ($T_{\perp p} > T_{\parallel p}$) (where $T_{\perp p}$ and $T_{\parallel p}$ represent the proton perpendicular and parallel temperatures, respectively), the maximum growth rate of the ion cyclotron instability occurs in the $+V_d$ direction (i.e., propagating outward away from the Sun). When the solar wind plasma exhibits proton parallel temperature anisotropy ($T_{\perp p} < T_{\parallel p}$), the maximum occurrence rate of the parallel firehose instability occurs in the $-V_d$ direction (i.e., propagating inward toward the Sun). Therefore, the drift velocity of the α beam significantly affects proton beam instability, causing outward-propagating Alfvén/ion cyclotron waves and inward-propagating magnetosonic/whistler waves to be preferentially generated.

To date, existing research has achieved many important results in the observational identification and excitation mechanisms of EMIC waves, but the research remains in its infancy, with many physical mechanisms and fundamental issues requiring further discussion. For example: (1) Where do EMIC waves in the solar wind originate from, and what is their energy source? (2) Are EMIC waves in the solar wind related to background particle energization phenomena, and can observational evidence of EMIC waves heating background ions be found in the solar wind? (3) Various free energy parameters exist in the solar wind; what is the relationship between their radial evolution and the excitation or absorption of EMIC waves? To answer these questions, we need to conduct a detailed investigation of the progress in both observational and theoretical studies of EMIC waves in the solar wind. In this review, we will provide a detailed introduction to the observational research progress of EMIC waves inside and outside magnetic clouds, within magnetic clouds, and in ICME sheath regions, while also introducing the theoretical research progress of EMIC waves in the solar wind.

2 Dispersion Relation and Polarization Characteristics of EMIC Waves

Based on plasma kinetic theory, Gary [52] studied the basic properties of EMIC waves, including their dispersion relation, polarization characteristics, and magnetic helicity. [Figure 1: see original paper] shows the correlation between the normalized frequency ω_r/Ω_i and normalized damping rate γ/Ω_i of Alfvén/ion cyclotron waves with the normalized wavenumber kc/Ω_i (where ω_r, Ω_i, γ, k, and c represent the wave real frequency, ion cyclotron frequency, growth rate, wavenumber, and speed of light, respectively), with different lines representing different propagation angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° [52]. Other plasma parameters are taken as $m_e/m_i = 1/1836$, $T_e/T_i = 1$, $v_A/c = 10^{-4}$, and $\beta_i = 1$. As shown in [Figure 1: see original paper], the normalized frequency of Alfvén/ion cyclotron waves is less than 1 ($\omega_r/\Omega_i < 1$). Under low-frequency, long-wavelength approximations, the dispersion relation of Alfvén/ion cyclotron waves satisfies the Alfvén wave dispersion relation $\omega_r = k_z v_A$ (where k_z represents the wavenumber in the z-direction), with a relatively small damping rate. At larger wavenumbers, the damping rate of Alfvén/ion cyclotron waves increases. As the propagation angle θ increases, the damping rate decreases. This indicates that in the case of parallel propagation ($\theta = 0^\circ$), cyclotron resonance damping is strongest, resulting in the maximum wave damping rate.

[Figure 2: see original paper] shows the correlation between the reciprocal of Alfvén/ion cyclotron wave polarization $\mathrm{Re}(p^{-1})$ and the normalized wavenumber kc/Ω_i, with different lines representing different propagation angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° [52]. [Figure 3: see original paper] shows the correlation between the magnetic helicity σ of Alfvén/ion cyclotron wave polarization and the normalized wavenumber kc/Ω_i, with different lines representing different propagation angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° [52]. As shown in [Figure 2: see original paper] and [Figure 3: see original paper], in the case of parallel propagation ($\theta = 0^\circ$), Alfvén/ion cyclotron waves exhibit left-handed circular polarization. As the propagation angle θ increases, Alfvén/ion cyclotron waves exhibit left-handed elliptical polarization. When the propagation angle is sufficiently large, Alfvén/ion cyclotron waves transition from left-handed to right-handed polarization, a result similar to that from two-fluid theory [53].

[Figure 4: see original paper] shows the correlation between the normalized frequency ω_r/Ω_i and normalized damping rate γ/Ω_i of magnetosonic/whistler waves with the normalized wavenumber kc/Ω_i, with different lines representing different propagation angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° [52]. As shown in [Figure 4: see original paper], the frequency of magnetosonic/whistler waves can extend from below the proton cyclotron frequency to above it. As the propagation angle θ increases, the damping rate of magnetosonic/whistler waves first increases and then decreases, and when $\theta \gtrsim 60^\circ$, magnetosonic/whistler waves exhibit maximum damping.

[Figure 5: see original paper] shows the correlation between the polarization $\mathrm{Re}(p)$ of magnetosonic/whistler waves and the normalized wavenumber kc/Ω_i, with different lines representing different propagation angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° [52]. [Figure 6: see original paper] shows the correlation between the magnetic helicity σ of magnetosonic/whistler waves and the normalized wavenumber kc/Ω_i, with different lines representing different propagation angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° [52]. As shown in [Figure 5: see original paper] and [Figure 6: see original paper], in the case of parallel propagation ($\theta = 0^\circ$), magnetosonic/whistler waves exhibit right-handed circular polarization. As the propagation angle θ increases, magnetosonic/whistler waves exhibit right-handed elliptical polarization.

Since the solar wind flow velocity is much greater than the local Alfvén speed, there are significant differences in the dispersion relation and polarization characteristics of EMIC waves between the spacecraft reference frame and the plasma reference frame. When converting EMIC wave frequencies from the spacecraft reference frame to the plasma reference frame, the influence of Doppler frequency shift must be removed. Based on two-fluid theory, Zhao et al. studied in detail the effect of solar wind flow velocity on the dispersion and polarization characteristics of EMIC waves and proposed using four parameters—magnetic field polarization, parallel Poynting flux, the ratio of proton velocity to magnetic field perturbation, and the ratio of electron velocity to magnetic field perturbation—to identify the polarization characteristics of EMIC waves in the plasma coordinate system [54]. [Figure 7: see original paper] shows the correlation of wave normalized frequency ω/Ω_i, magnetic field polarization $\mathrm{sign}(\omega)(iB_1/B_2)$ (where i, B_1, and B_2 represent the imaginary unit and magnetic field components in the x- and y-directions, respectively), normalized ratio of proton velocity to magnetic field perturbation $(v_{i\perp}/v_A)/(B_\perp/B_0)$ (where $v_{i\perp}$, $B_\perp$, and B_0 represent the perpendicular proton velocity, perpendicular magnetic field perturbation, and background magnetic field, respectively), ratio of electron velocity to magnetic field perturbation $(v_{e\perp}/v_A)/(B_\perp/B_0)$ (where $v_{e\perp}$ represents the perpendicular electron velocity), and normalized parallel Poynting flux $S_\parallel/(2v_A w_B)$ (where v_A and w_B represent the Alfvén speed and magnetic field energy density, respectively) with the normalized wavenumber $k\rho_i$ (where k and ρ_i represent the wavenumber and ion inertial length, respectively). The left, middle, and right panels correspond to normalized flow velocities $v_0/v_A = 0$, 2, and -2 [54]. Black and red lines in the figure represent propagation parallel and antiparallel to the background magnetic field, respectively. As shown in [Figure 7: see original paper], in the case where the solar wind flow velocity is parallel to the background magnetic field ($v_0/v_A = 2$), the wave characteristics of EMIC waves in the spacecraft reference frame and plasma reference frame change as follows: (1) When the correlation coefficient between perturbation velocity and perturbation magnetic field $CC_{B\perp;V\perp} < 0$ and $S_\parallel/|S_\parallel| = 1$, left-handed EMIC waves in the spacecraft coordinate system correspond to forward-propagating Alfvén/ion cyclotron waves in the plasma coordinate system; (2) When $CC_{B\perp;V\perp} > 0$ and $S_\parallel/|S_\parallel| = 1$, right-handed EMIC waves in the spacecraft coordinate system correspond to backward-propagating Alfvén/ion cyclotron waves in the plasma coordinate system; (3) When $CC_{B\perp;V\perp} < 0$ and $S_\parallel/|S_\parallel| = 1$, right-handed EMIC waves in the spacecraft coordinate system correspond to forward-propagating magnetosonic/whistler waves in the plasma coordinate system; (4) When $CC_{B\perp;V\perp} > 0$ and $S_\parallel/|S_\parallel| = 1$, left-handed EMIC waves in the spacecraft coordinate system correspond to long-wavelength, backward-propagating magnetosonic/whistler waves in the plasma coordinate system; (5) When $CC_{B\perp;V\perp} > 0$ and $S_\parallel/|S_\parallel| = -1$, right-handed EMIC waves in the spacecraft coordinate system correspond to short-wavelength, backward-propagating magnetosonic/whistler waves in the plasma coordinate system.

In the case where the solar wind flow velocity is antiparallel to the background magnetic field ($v_0/v_A = -2$), the wave characteristics of EMIC waves in the spacecraft reference frame and plasma reference frame change as follows: (1) When $CC_{B\perp;V\perp} < 0$ and $S_\parallel/|S_\parallel| = -1$, right-handed EMIC waves in the spacecraft coordinate system correspond to forward-propagating Alfvén/ion cyclotron waves in the plasma coordinate system; (2) When $CC_{B\perp;V\perp} > 0$ and $S_\parallel/|S_\parallel| = -1$, left-handed EMIC waves in the spacecraft coordinate system correspond to backward-propagating Alfvén/ion cyclotron waves in the plasma coordinate system; (3) When $CC_{B\perp;V\perp} < 0$ and $S_\parallel/|S_\parallel| = -1$, left-handed EMIC waves in the spacecraft coordinate system correspond to long-wavelength, forward-propagating magnetosonic/whistler waves in the plasma coordinate system; (4) When $CC_{B\perp;V\perp} < 0$ and $S_\parallel/|S_\parallel| = 1$, right-handed EMIC waves in the spacecraft coordinate system correspond to short-wavelength, backward-propagating magnetosonic/whistler waves in the plasma coordinate system.

3.1 Observational Characteristics of EMIC Waves Inside and Outside IMCs

Interplanetary Magnetic Clouds (IMCs) interact with the surrounding solar wind and planetary magnetospheres [55–56]. However, plasma waves associated with IMCs have received relatively little attention [57–58]. Based on STEREO satellite observations from 2007–2013, Zhao et al. conducted a statistical analysis of 7807 EMIC wave events inside and around 120 IMCs [59]. Using Hamming window functions and bandpass filter methods, Zhao et al. developed an automatic wave detection program [59]. According to this program, 24% of the waves occurred inside IMCs, while 76% occurred in the plasma environment surrounding IMCs. Through comparative analysis of the influence of background plasma parameters on wave occurrence rates, it was found that EMIC waves have higher occurrence rates in high-temperature, low-density, and high-speed plasma environments.

The plasma β value is typically an important parameter in magnetized plasma theoretical research. Magnetic clouds and their surrounding regions have a wide range of β values, providing an excellent opportunity to study the influence of β on EMIC wave characteristics. [Figure 8: see original paper] describes the influence of background plasma β parameters on wave characteristics for left-handed and right-handed EMIC waves [59]. Notably, there is a positive correlation between wave frequency, frequency bandwidth, and total power with the β value. The correlation coefficient is higher for left-handed EMIC waves, with the power-law spectral fitting correlation coefficient always greater than that for right-handed EMIC waves. From the perspective of the power-law spectral fitting exponent, the exponent for left-handed EMIC waves is always greater than that for right-handed EMIC waves.

3.2 Observational Characteristics of EMIC Waves in ICME/IMC Sheath Regions

Interplanetary Coronal Mass Ejections (ICMEs) are the interplanetary counterparts of coronal mass ejections, with IMCs being a subset of ICMEs. When ICMEs/IMCs interact with the background solar wind, their leading edge continuously compresses the background solar wind, forming shock structures to some extent. Between the shock and the ICME/IMC main body, there exists a high-temperature, high-density, and high-β plasma region called the ICME/IMC sheath region. Unlike the plasma environment inside ICMEs/IMCs, the plasma turbulence in ICME/IMC sheath regions is often more intense, with various plasma waves participating. Zhao et al.'s research also indicates that EMIC waves have relatively high occurrence rates around IMCs [59]. However, there are relatively few studies on the identification and statistical analysis of EMIC waves in ICME/IMC sheath regions.

In the plasma reference frame, the polarization characteristics of EMIC waves do not depend on the wave propagation direction [9–10, 27], where the maximum perturbation direction of left-handed EMIC waves is almost perpendicular to the B_0–k plane formed by the wave vector k and background magnetic field, while the maximum perturbation direction of right-handed EMIC waves is almost parallel to the B_0–k plane. In the spacecraft reference frame, the polarization state of EMIC waves depends on the direction of wave propagation k relative to the background solar wind flow velocity [19, 27]. Due to the influence of the solar wind Doppler effect, the observed polarization characteristics of EMIC waves can be the same as or opposite to the polarization state in the plasma reference frame, depending on whether the wave propagates outward away from the Sun or inward toward the Sun.

Using STEREO satellite observational data, Li et al. statistically analyzed the spatial distribution and wave characteristics of EMIC waves in IMC sheath regions, as shown in [Figure 9: see original paper] [60]. In terms of time occupancy, the duration of EMIC waves in IMC sheath regions accounts for 9.2% of the total analysis time, which is significantly higher than the 0.9% duration in the solar wind [21]. These waves exhibit both left-handed and right-handed polarization states in the spacecraft reference frame, with the occurrence rate of left-handed polarized waves being higher than that of right-handed polarized waves. Considering the influence of the Doppler effect, Li et al. further analyzed the wave characteristics of EMIC waves in the plasma reference frame [60], with results showing that wave events propagating toward the Sun (inward-propagating EMIC waves) account for more than half of the total events. Additionally, the occurrence rate of outward-propagating left-handed waves is higher than that of inward-propagating left-handed waves, while the occurrence rate of outward-propagating right-handed waves is lower than that of inward-propagating right-handed waves.

Unlike the background solar wind environment, kinetic-scale shocks or plasma instabilities in ICME/IMC sheath regions may provide free energy for EMIC wave excitation. Using magnetic field and plasma data from the WIND satellite, Li et al. conducted a statistical study on the spatial distribution characteristics of EMIC waves in 62 ICME sheath regions associated with quasi-perpendicular shocks, analyzing the spatial distribution characteristics of EMIC waves in both the spacecraft and plasma reference frames and the influence of shock parameters on the occurrence rates of these waves [61]. Statistical results indicate that EMIC wave events frequently occur in sheath regions with low Mach number M_f and low upstream plasma thermal-to-magnetic pressure ratio β_1. In ICME sheath regions with low-M_f shocks, left-handed EMIC waves may be excited near the shock front and then transported to downstream regions, i.e., the front part of the ICME sheath region near the shock structure. Therefore, left-handed EMIC waves typically exist in downstream regions of quasi-perpendicular shocks with low Mach numbers and low β_1. On the other hand, in downstream regions of quasi-perpendicular shocks, α particles exhibit beam-like distributions, and left-handed EMIC waves are excited in shock cases with medium and low Mach numbers, thereby scattering α particles into shell-like distributions.

[Figure 10: see original paper] and [Figure 11: see original paper] respectively show the distribution characteristics of EMIC wave events in ICME sheath regions in the $\beta_{p\parallel} - T_{p\perp}/T_{p\parallel}$ and $\beta_{\alpha\parallel} - T_{\alpha\perp}/T_{\alpha\parallel}$ planes, where the color scale represents the spatial position of the wave event in the sheath region (0 indicates the position of the leading shock, and 1 indicates the leading edge of the ICME). Blue, red, black, and magenta solid lines represent the theoretical thresholds for proton (in [Figure 10: see original paper]) or α particle (in [Figure 11: see original paper]) cyclotron instability, parallel firehose instability, mirror instability, and oblique firehose instability, respectively.

As shown in [Figure 10: see original paper] and [Figure 11: see original paper], most EMIC waves are distributed within the thresholds of ion cyclotron instability and firehose instability, especially for right-handed polarized EMIC waves. From Figure 10: see original paper, it can be seen that in the middle region of the ICME sheath, a small number of outward-propagating left-handed EMIC waves are distributed between the theoretical thresholds of proton cyclotron instability and mirror instability. This indicates that proton temperature anisotropy instability exists in the middle region of the ICME sheath, which can provide free energy to excite outward-propagating left-handed EMIC waves. From Figure 11: see original paper, it can be seen that outward-propagating left-handed EMIC waves near the shock are likely ion cyclotron waves, which may be excited by α particle temperature anisotropy instability downstream of the shock. Additionally, when the distribution of EMIC waves exceeds the instability threshold, local plasma conditions can effectively excite EMIC fluctuations, and wave excitation and wave-particle interactions in turn suppress ion temperature anisotropy $T_{i\perp}/T_{i\|}$, keeping it below the instability threshold.

As shown in Figure 10: see original paper, (d) and Figure 11: see original paper, (d), the distribution of right-handed EMIC waves is below the theoretical threshold of parallel firehose instability, indicating that parallel firehose instability cannot effectively excite right-handed EMIC waves in ICME sheath regions. On the other hand, 47.3% of EMIC wave events have high α particle abundance, i.e., a high ratio of α particle density to proton density N_α/N_p, which may provide a possible source of free energy for exciting right-handed EMIC waves [61]. α particles may play an important role in the formation, propagation, and absorption processes of EMIC waves [35, 48]. Due to the velocity difference between protons and α particles $V_d = V_\alpha - V_p$, parallel firehose instability may effectively excite inward-propagating right-handed EMIC waves [51].

3.3 Influence of Background Plasma Parameters on EMIC Wave Occurrence Rates

The solar wind is a highly complex magnetized plasma system where some parameters are interrelated. In-depth study of these relationships plays an important role in revealing related heating processes and physical mechanisms. Zhao et al. scanned solar wind data from the STEREO satellite during 2007–2013 and conducted a series of statistical analyses on EMIC waves [62]. [Figure 12: see original paper] shows the temporal variation of EMIC wave occurrence rates in the solar wind, where the red solid line represents left-handed EMIC waves and the blue solid line represents right-handed EMIC waves [62]. As shown in [Figure 12: see original paper], the occurrence rate of left-handed EMIC waves is significantly higher than that of right-handed EMIC waves during most time periods, consistent with previous research conclusions that left-handed EMIC waves have higher occurrence rates in the solar wind. It can also be seen from [Figure 12: see original paper] that the occurrence rate of left-handed EMIC waves varies greatly with time, ranging from 0.5% to 2.5%. The occurrence rate of right-handed EMIC waves changes little over time. Additionally, the minimum occurrence rate of left-handed EMIC waves is comparable to that of right-handed EMIC waves. To further understand the physical mechanisms underlying [Figure 12: see original paper], Zhao et al. studied the correlation between background plasma characteristics and EMIC wave occurrence rates [62]. The results indicate that high temperature, low density, and high speed are the preferred plasma conditions for the existence or generation of left-handed EMIC waves in the solar wind.

Numerous studies have shown that high-speed flows have higher temperatures, lower densities, and greater velocities than low-speed flows [63–64]. Additionally, in high-speed flows, α particles typically move faster than protons, making it easy to form a drift velocity of α particles relative to protons in interplanetary space [65–66]. The left panel of [Figure 13: see original paper] is a scatter plot of the monthly occurrence rate of left-handed EMIC waves versus the α-proton drift velocity (V_d) [62]. As shown in the left panel of [Figure 13: see original paper], the correlation coefficient between the occurrence rate of left-handed waves and the drift velocity of α particles is 0.71, indicating a strong positive correlation between the two. The right panel of [Figure 13: see original paper] shows the scatter distribution between the occurrence rate of right-handed EMIC waves and the drift velocity of α particles [62]. Compared with left-handed EMIC waves, the occurrence rate of right-handed EMIC waves has a very weak correlation with the drift velocity of α particles, with a correlation coefficient of 0.19.

3.4 Statistical Analysis of EMIC Wave Excitation Mechanisms in the Solar Wind

Although EMIC waves are ubiquitous in the solar wind, their generation mechanism remains an unresolved issue. Based on 15 years of accumulated WIND satellite data, Zhao et al. analyzed the probability density distribution of proton temperature anisotropy and the ratio of parallel proton thermal pressure to magnetic pressure $\beta_{p\parallel}$ in solar wind where wave events exist [48]. Unlike the probability density distribution of background solar wind, the probability density distribution of left-handed EMIC waves shows enhanced regions in the $\beta_{p\parallel}$ and proton perpendicular-to-parallel temperature ratio $T_{p\perp}/T_{p\parallel} > 1$ region. Zhao et al.'s statistical results indicate that both V_d/V_A and N_α/N_p have important effects on the occurrence rate of EMIC waves, with the latter appearing to be more sensitive to the wave occurrence rate [48]. This suggests that comprehensive parameters including N_α/N_p should help understand the influence of α particle drift velocity on the occurrence rate of EMIC waves. Considering the effects of both V_d/V_A and N_α/N_p, Zhao et al. introduced the normalized kinetic energy parameter $\epsilon_\alpha = (m_\alpha N_\alpha V_d^2)/(m_p N_p V_A^2)$ [48], where m_α (m_p) represents the mass of α particles (protons).

[Figure 14: see original paper] shows the distribution of EMIC wave occurrence rates as a function of normalized kinetic energy ϵ_α, where the left and right columns represent left-handed and right-handed EMIC waves, respectively, and the top and bottom rows represent slow and fast solar wind, respectively [48]. The dependence of EMIC wave occurrence rates on ϵ_α differs for different solar wind types and different polarized waves. In slow solar wind, when ϵ_α is very small, the occurrence rates of left-handed and right-handed EMIC waves are comparable. As ϵ_α increases from nearly 0 to 0.07, the occurrence rate of left-handed EMIC waves rapidly increases from \$ \$0.3% to 1.8%; when ϵ_α exceeds 0.07, the occurrence rate of left-handed EMIC waves shows large fluctuations. For right-handed EMIC waves, although the occurrence rate increases from \$ \$0.4% to 0.9% as ϵ_α approaches 0.04, the occurrence rate of right-handed EMIC waves does not change significantly with ϵ_α compared to left-handed EMIC waves. In fast solar wind environments, when ϵ_α is 0.08, the occurrence rate of left-handed EMIC waves is mainly around 2.7%. As ϵ_α increases, the occurrence rate of left-handed EMIC waves rapidly rises to around 4.4%. For right-handed EMIC waves in fast solar wind, as ϵ_α increases, their occurrence rate appears to decrease and remains lower than that of left-handed waves.

Whether in slow or fast solar wind, the distribution of left-handed EMIC waves shows a trend of increasing with proton temperature anisotropy. Additionally, Zhao et al. analyzed the temperature characteristics of protons and α particles [48], finding that the temperatures of protons and α particles are not only related to the magnitude of their relative velocity but also significantly correlated with the direction of the relative velocity. This correlation is in good agreement with the theoretically predicted ion cyclotron resonance behavior, strongly supporting the cyclotron resonance heating mechanism of ion cyclotron waves.

3.5 Research Progress on EMIC Waves in Earth's Magnetosphere

EMIC waves exist not only in the solar wind plasma environment but also ubiquitously in Earth's magnetosphere. In Earth's magnetospheric plasma environment, small-amplitude EMIC fluctuations have been widely studied; however, large-amplitude EMIC waves have not received much attention. Based on Magnetospheric Multiscale (MMS) satellite observations, Zhao et al. studied EMIC wave events observed on the dusk side of Earth's magnetosheath [67] and found that the perturbation magnetic field of these waves was 1–2 nT, with an amplitude relative to the background magnetic field of about 0.1. The magnetic field perturbations of the waves can cause periodic changes in the pitch angles of ions and electrons, with the trapping effect becoming more significant as the wave amplitude increases. Zhao et al. further studied EMIC wave events observed on the dawn side of Earth's magnetosheath [68] and found that the perturbation magnetic field of these waves was about 2 nT, with an amplitude relative to the background magnetic field of about 0.16. The characteristic frequency and characteristic scale of the waves were 0.2 Hz and 1028 km, respectively. Additionally, using fitted parameters of ion and electron phase space density combined with plasma kinetic theory, it was found that local plasma temperature anisotropy can provide free energy to excite EMIC fluctuations.

Subsequently, Zhao et al. studied the influence of ion and electron beams on the excitation mechanisms of EMIC and mirror waves in the magnetosheath [69]. The results indicated that ion beams significantly affect the growth of forward- and backward-propagating Alfvén/ion cyclotron waves. As the ion beam drift velocity increases, the growth rate of backward-propagating Alfvén/ion cyclotron waves becomes greater than that of forward-propagating Alfvén/ion cyclotron waves, even exceeding that of mirror waves. The drift velocity of electron beams significantly affects the frequency range of forward- and backward-propagating magnetosonic/whistler waves. As the electron beam drift velocity increases, the growth rates of both forward- and backward-propagating magnetosonic/whistler waves decrease. These results demonstrate that ion beams promote the growth of backward-propagating Alfvén/ion cyclotron waves but inhibit the growth of forward-propagating Alfvén/ion cyclotron waves; electron beams have an inhibitory effect on the growth of both forward- and backward-propagating magnetosonic/whistler waves.

4 Excitation Mechanisms of EMIC Waves and Wave-Particle Phase

Given the ubiquity of EMIC waves in the solar wind, their generation and excitation mechanisms have received widespread attention. Theoretically, many forms of free energy can effectively excite EMIC waves, such as temperature anisotropy, beam instability, ion and electron loss-cone distributions, and pickup ion instability. This section provides a detailed introduction to the excitation of EMIC waves by beam and temperature anisotropy instabilities.

4.1 Beam Instability of EMIC Waves and Its Role in Beam Deceleration

Solar wind observations indicate that proton beams are ubiquitous in the solar wind, with drift velocities typically faster than background protons and propagation directions parallel to the background magnetic field. Plasma waves excited by proton beams are also common in the solar wind, and existing studies have shown that proton beam instability can excite various types of electrostatic and electromagnetic waves. Based on plasma kinetic theory, Gary et al. theoretically studied in detail the excitation of plasma waves by parallel-propagating proton beams [70–72]. The results showed that when the proton beam exceeds a certain threshold, proton beam instability can effectively excite resonant magnetosonic/whistler waves, non-resonant magnetosonic/whistler waves, and Alfvén/ion cyclotron waves. When proton beams propagate obliquely to the background magnetic field, Daughton et al.'s results indicated that when the plasma thermal-to-magnetic pressure ratio $\beta > 1$, proton beam instability can effectively excite parallel-propagating magnetosonic/whistler waves; when $\beta < 1$, obliquely propagating Alfvén/ion cyclotron waves are more easily excited [73].

In plasma instability scenarios, there typically exist macroscopic reactive instabilities and microscopic kinetic instabilities. Reactive instabilities are excited by macroscopic free energy composed of non-resonant particles from the excitation source, similar to fluid instabilities. Kinetic instabilities are excited by Landau resonance interactions, with free energy coming from resonant particles, representing a microscopic instability. To distinguish the influence of reactive and kinetic instabilities on wave excitation mechanisms from a microscopic physical perspective, Xiang et al. studied the reactive and kinetic instability excitation mechanisms of Alfvén/ion cyclotron waves and explored the influence of these two instabilities on the generation mechanism of Alfvén/ion cyclotron waves in the solar wind [41]. [Figure 15: see original paper] describes the dependence of wave frequency and growth rate on the normalized wavenumber $k_z\rho_i$ (where k_z and ρ_i represent the wavenumber in the z-direction and ion cyclotron radius, respectively), with solid and dashed lines representing reactive and kinetic instabilities, respectively, and different curves representing different proton beam drift velocities $v_{bi}/v_A = 1, 3, 3.5, 4$, and 4.5. As shown in [Figure 15: see original paper], compared with reactive instability, kinetic instability has a lower beam velocity threshold $v_{bi}/v_A > 1$. However, when the beam drift velocity exceeds the velocity threshold of reactive instability, i.e., $v_{bi}/v_A > 2$, the growth rate of reactive instability becomes much larger than that of kinetic instability.

Although the growth rate of reactive instability is greater than that of kinetic instability, the velocity threshold of kinetic instability is smaller than that of reactive instability. This indicates that ion cyclotron waves can still be excited through kinetic instability under low proton beam drift velocity conditions. [Figure 16: see original paper] describes the dependence of kinetic instability's real frequency and growth rate on the proton beam drift velocity v_{bi}/v_A, with different curves representing different normalized wavenumbers $k_z\rho_i = 0.1, 0.15, 0.2, 0.25$, and 0.3 [41]. As shown in [Figure 16: see original paper], the maximum growth rate of kinetic instability appears in the drift velocity range $1 < v_{bi}/v_A < 2.5$, indicating that when the proton beam drift velocity is greater than or close to the local Alfvén speed, kinetic instability can be effectively driven by the proton beam, thereby exciting left-handed EMIC waves, i.e., Alfvén/ion cyclotron waves.

Satellite in-situ detection results show that the drift velocity of proton beams in the solar wind is less than $2v_A$. This means that local proton beams in the solar wind are difficult to drive reactive instability but can effectively drive kinetic instability. For typical solar wind plasma parameters, the normalized density of proton beams $n_{bi}/n_0 \lesssim 0.2$ (where n_{bi} and n_0 represent the proton beam density and background electron density, respectively), the drift velocity of proton beams $v_{bi}/v_A \lesssim$ 1–2, and the corresponding growth rate of kinetic instability is $\gamma \lesssim 10^{-2}\Omega_{ci}$ (where Ω_{ci} represents the ion cyclotron frequency). On the other hand, Gary et al. gave the growth rate of Alfvén/ion cyclotron waves excited by temperature anisotropy instability as $\gamma \lesssim 10^{-3}\Omega_{ci}$, which is much smaller than the growth rate of kinetic instability [27]. This indicates that when the drift velocity of proton beams in the solar wind is very low, proton beams can still effectively drive kinetic instability and thus excite Alfvén/ion cyclotron waves.

Subsequently, given the importance of α particles in the solar wind, Xiang et al. studied the joint excitation of EMIC waves by proton and α beam instabilities and analyzed the influence of α beam drift velocity and density on the wave characteristics of EMIC waves [42]. [Figure 17: see original paper] shows the relationship between wave frequency and growth rate and the proton beam density and drift velocity, where solid and dashed lines represent Alfvén/ion cyclotron waves and magnetosonic/whistler waves, respectively, and black, red, and magenta lines correspond to α beam drift velocities $v_\alpha/v_A = 0, 0.6$, and 1.8 [42]. As shown in [Figure 17: see original paper], there exist instability thresholds for proton beam instability of Alfvén/ion cyclotron waves and magnetosonic/whistler waves, i.e., critical proton beam density $n^{bi}_{L(R)}$ and critical proton beam drift velocity $v^{bi}_{L(R)}$, where the superscripts L and R correspond to Alfvén/ion cyclotron waves and magnetosonic/whistler waves, respectively.

When $n_{bi} < n^{bi}_{L(R)}$ and $v_{bi} < v^{bi}_{L(R)}$ or $v_{bi} > v^{bi}_{L(R)}$, the wave growth rate is zero, indicating that the instability cannot excite Alfvén/ion cyclotron waves (magnetosonic/whistler waves); when $n_{bi} > n^{bi}_{L(R)}$ and $v_{bi} < v^{bi}_{L(R)}$ or $v_{bi} > v^{bi}_{L(R)}$, the wave growth rate is greater than zero, indicating that Alfvén/ion cyclotron waves (magnetosonic/whistler waves) can be generated through instability. By comparing the threshold conditions of these two waves, it is found that $v^{bi}_L > v^{bi}_R$, indicating that magnetosonic/whistler waves have lower threshold conditions than Alfvén/ion cyclotron waves. As the α beam drift velocity v_α/v_A increases, the threshold condition for Alfvén/ion cyclotron waves first increases and then decreases, while the threshold condition for magnetosonic/whistler waves first remains unchanged and then decreases. This indicates that the instability threshold conditions for both Alfvén/ion cyclotron waves and magnetosonic/whistler waves are sensitively dependent on the drift velocity of the α beam. When $v_\alpha/v_A < 0.8$, as the α beam drift velocity increases, the threshold condition for Alfvén/ion cyclotron waves increases, while the threshold condition for magnetosonic/whistler waves remains almost unchanged; when $v_\alpha/v_A > 0.8$, as the α beam drift velocity increases, the threshold conditions for both magnetosonic/whistler waves and Alfvén/ion cyclotron waves decrease.

Xiang et al. further analyzed the influence of α beams on the dispersion characteristics of Alfvén/ion cyclotron waves and magnetosonic/whistler waves [42]. [Figure 18: see original paper] shows the relationship between wave frequency and growth rate and the α beam drift velocity and density, where solid and dashed lines represent Alfvén/ion cyclotron waves and magnetosonic/whistler waves, respectively, and black, red, and magenta lines correspond to wavenumbers $k_z\rho_i = 0.02, 0.03$, and 0.04. As shown in [Figure 18: see original paper], as the α beam drift velocity increases, the growth rates of Alfvén/ion cyclotron waves and magnetosonic/whistler waves show a trend of first decreasing and then increasing, and when $v_\alpha = v^{bi}_{L(R)}$, the growth rates of Alfvén/ion cyclotron waves and magnetosonic/whistler waves reach their minimum values. When $v_\alpha < v^{bi}_{L(R)}$, the wave growth rate decreases with increasing α beam density or drift velocity, while when $v_\alpha > v^{bi}_{L(R)}$, the wave growth rate increases with increasing α beam density or drift velocity. This indicates that in the $v_\alpha < v^{bi}_{L(R)}$ range, α beams limit the growth of Alfvén/ion cyclotron waves and magnetosonic/whistler waves, while in the $v_\alpha > v^{bi}_{L(R)}$ range, α beams promote the growth of Alfvén/ion cyclotron waves and magnetosonic/whistler waves.

From [Figure 18: see original paper], it can also be seen that the proton beam drift velocity thresholds for Alfvén/ion cyclotron waves and magnetosonic/whistler waves are $v^{bi}_L/v_A \lesssim 2.2$ and $v^{bi}_R/v_A \lesssim 1.8$, respectively. In the solar wind, the observed proton beam drift velocity v_{bi} is less than or close to $2v_A$, which is smaller than the theoretically calculated velocity threshold. This indicates that the drift velocity of proton beams can be constrained by proton beam instability, and wave excitation converts the kinetic energy of proton beams into wave energy, thereby reducing the drift velocity of proton beams. This theory provides a theoretical explanation for the distribution of proton beam drift velocities in the range $1.5 < v_{bi}/v_A < 2$ observed in the solar wind.

Based on plasma kinetic theory, Xiang et al. studied the influence of electron temperature anisotropy on proton beam instability and analyzed the role of wave-particle interactions in proton beam deceleration [74]. [Figure 19: see original paper] shows the dependence of instability threshold velocity v_{bi}/v_A on the electron temperature anisotropy ratio $T_{e\perp}/T_{e\parallel}$, where different lines represent different ratios of electron parallel thermal pressure to magnetic pressure $\beta_{e\parallel} = 0.1, 0.3, 1$, and 2, and solid and dotted lines represent magnetosonic/whistler waves and Alfvén/ion cyclotron waves, respectively [74]. Red and blue solid circles represent WIND satellite observational data below and above the instability thresholds, respectively. As shown in [Figure 19: see original paper], as the electron temperature anisotropy ratio $T_{e\perp}/T_{e\parallel}$ increases, the velocity thresholds v_{bi}/v_A for Alfvén/ion cyclotron waves and magnetosonic/whistler waves increase, especially in the case of $\beta_{e\parallel} > 1$, where the velocity threshold change trend is more pronounced. This means that electron temperature anisotropy $T_{e\perp} < T_{e\parallel}$ is conducive to reducing the velocity thresholds of Alfvén/ion cyclotron waves and magnetosonic/whistler waves.

[Figure 20: see original paper] shows the dependence of instability threshold velocity v_{bi}/v_A on plasma $\beta_{e\parallel}$, where different lines represent different electron temperature anisotropy ratios $T_{e\perp}/T_{e\parallel} = 0.25, 0.5, 0.75, 1$, and 1.25, and solid and dotted lines represent magnetosonic/whistler waves and Alfvén/ion cyclotron waves, respectively [74]. Red and blue solid circles represent WIND satellite observational data below and above the instability thresholds, respectively, and green triangles represent Helios satellite observational data. As shown in [Figure 20: see original paper], when electron temperature anisotropy $T_{e\perp}/T_{e\parallel}$ decreases from 1.25 to 0.25, the velocity thresholds v_{bi}/v_A for Alfvén/ion cyclotron waves and magnetosonic/whistler waves decrease from 2 and 1.8 to 1.2 and 1, respectively. On the other hand, the observed proton beam drift velocity is less than or close to the theoretically calculated proton beam drift velocity. Therefore, in the case of $\beta_{e\parallel} < 0.5$, Alfvén/ion cyclotron waves can effectively limit the drift velocity of proton beams; in the case of $\beta_{e\parallel} > 0.5$, magnetosonic/whistler waves driven jointly by electron temperature anisotropy and proton beams can further decelerate proton beams, making their drift velocity close to the local Alfvén speed ($v_{bi}/v_A \lesssim 1$). This provides a theoretical basis for explaining the distribution of proton beam drift velocities in the solar wind in the range $1 < v_{bi}/v_A < 1.5$.

To further explore the nonlinear evolution of proton beam instability, Xiang et al. combined plasma kinetic theory with hybrid simulation codes to study wave modes excited by proton temperature anisotropy and proton beam instability and analyzed the effect of nonlinear wave-particle interactions on proton beam deceleration [75]. [Figure 21: see original paper] shows the dependence of instability threshold velocity v_{bi}/v_A on plasma $\beta_{i\parallel}$ under the condition of proton temperature anisotropy $T_{i\perp}/T_{i\parallel} < 1$, where different lines represent different proton temperature anisotropy ratios $T_{i\perp}/T_{i\parallel} = 0.25, 0.5$, and 1, and dashed, solid, and dotted lines represent oblique Alfvén/ion cyclotron waves, parallel magnetosonic/whistler waves, and backward-propagating magnetosonic/whistler waves, respectively [75]. Black and red solid circles represent WIND satellite observational data below and above the instability thresholds, respectively; black and red triangles represent Helios satellite observational data below and above the instability thresholds, respectively.

[Figure 22: see original paper] shows the dependence of instability threshold velocity v_{bi}/v_A on plasma $\beta_{i\parallel}$ under the condition of proton temperature anisotropy $T_{i\perp}/T_{i\parallel} > 1$, where different lines represent different proton temperature anisotropy ratios $T_{i\perp}/T_{i\parallel} = 1, 1.5$, and 2, and dashed, solid, dotted, and dot-dashed lines represent oblique Alfvén/ion cyclotron waves, parallel magnetosonic/whistler waves, parallel Alfvén/ion cyclotron waves, and mirror waves, respectively [75]. Black solid circles and black triangles represent WIND and Helios satellite observational data, respectively. As shown in [Figure 22: see original paper], proton temperature anisotropy $T_{i\perp} < T_{i\parallel}$ can not only effectively reduce the velocity thresholds of oblique Alfvén/ion cyclotron waves and parallel magnetosonic/whistler waves but also effectively excite backward-propagating magnetosonic/whistler waves. As shown in [Figure 22: see original paper], proton temperature anisotropy $T_{i\perp} > T_{i\parallel}$ can not only increase the velocity thresholds of oblique Alfvén/ion cyclotron waves and parallel magnetosonic/whistler waves but also effectively excite parallel Alfvén/ion cyclotron waves and mirror waves.

Xiang et al. further studied the nonlinear wave-particle interaction processes of proton temperature anisotropy and proton beam instability [75]. [Figure 23: see original paper] shows the nonlinear evolution of oblique Alfvén/ion cyclotron waves calculated by one-dimensional hybrid simulation and its effect on proton beam deceleration [75]. The simulation results indicate that in the case of $T_{i\perp} < T_{i\|}$, oblique Alfvén/ion cyclotron waves can quickly convert particle kinetic energy into wave energy through linear wave-particle interactions. During the nonlinear evolution process, the proton beam drift velocity decreases very slowly. In the case of $T_{i\perp} > T_{i\|}$, parallel Alfvén/ion cyclotron waves and mirror waves undergo nonlinear wave-particle scattering with the proton beam, thereby reducing the proton beam drift velocity. Even in the nonlinear saturation stage, the nonlinear wave-particle interactions of these waves can gradually decelerate the proton beam, making its drift velocity close to the local Alfvén speed $v_{bi}/v_A \lesssim 1$.

4.2 Temperature Anisotropy Instability of EMIC Waves and Its Effect on Temperature Anisotropy Suppression

Temperature anisotropy is widely present in space and solar plasma environments and is one of the most important sources of free energy for generating plasma waves. When $T_{i\perp} < T_{i\|}$, proton temperature anisotropy effectively excites parallel and oblique firehose instabilities; when $T_{i\perp} > T_{i\|}$, proton temperature anisotropy effectively excites parallel Alfvén/ion cyclotron and mirror instabilities. Gary et al. pointed out that proton temperature anisotropy instability can effectively drive various plasma fluctuations, such as parallel magnetosonic/whistler waves, oblique Alfvén waves, parallel Alfvén/ion cyclotron waves, and mirror waves [76].

Based on plasma kinetic theory, Sun et al. studied the influence of proton beams on proton temperature anisotropy instability [77]. [Figure 24: see original paper] shows the dependence of proton temperature anisotropy threshold on the ratio of background proton parallel thermal pressure to magnetic pressure $\beta_{pc\|}$, where different lines represent different growth rate values $\gamma/\Omega_{cp} = 0.001, 0.01$, and 0.1 (where Ω_{cp} represents the background proton cyclotron frequency) [77]. The left panel shows the instability threshold for parallel propagation, and the right panel shows the instability threshold for oblique propagation. The black dot-dashed line represents the instability threshold given by Maruca et al. [32]. As shown in [Figure 24: see original paper], due to the presence of proton beams, parallel Alfvén/ion cyclotron waves, parallel magnetosonic/whistler waves, and oblique Alfvén waves impose stricter constraints on temperature anisotropy, while mirror waves impose almost no change in constraints on temperature anisotropy.

[Figure 25: see original paper] shows the distribution of the strongest instability in the $T_{pc\perp}/T_{pc\|}$–$\beta_{pc\|}$ plane [77]. From top to bottom, the panels represent the normalized maximum growth rate $\gamma_{\max}/\Omega_{cp}$, normalized frequency ω_r/Ω_{cp}, absolute value of magnetic field ratio abs(B_y/B_x), and elevation angle of magnetic field ratio $\arg(B_y/B_x)$. The left and right panels represent propagation angles $\theta = 30^\circ$ and $\theta = 68^\circ$, respectively. As shown in [Figure 25: see original paper], in the $\beta_{pc\|} < 0.2$ region, in addition to electromagnetic ion cyclotron instability, ion beam instability excited by proton beams and α beams can also trigger oblique Alfvén waves.

To compare theoretical and observational results, Hellinger et al. explored the correlation between observational distributions of proton temperature anisotropy in slow and fast solar wind and theoretical instability thresholds [78]. [Figure 26: see original paper] shows the comparison between theoretical and observational results in the $\beta_{p\|}$–$T_{p\perp}/T_{p\|}$ plane for slow solar wind with $v_p \leq 600$ km/s, where solid and dashed lines in the left panel represent theoretical thresholds for parallel Alfvén/ion cyclotron instability and parallel firehose instability, respectively, and dotted and dot-dashed lines in the right panel represent theoretical thresholds for mirror instability and oblique firehose instability, respectively [78]. The blue pattern represents proton temperature anisotropy events observed by WIND satellite during 1995–2001. [Figure 27: see original paper] shows the comparison between theoretical and observational results in the $\beta_{p\|}$–$T_{p\perp}/T_{p\|}$ plane for fast solar wind with $v_p > 600$ km/s [78]. As shown in [Figure 26: see original paper] and [Figure 27: see original paper], in slow solar wind, mirror and oblique firehose instabilities constrain the distribution of proton temperature anisotropy, while in fast solar wind, mirror and parallel firehose instabilities constrain proton temperature anisotropy.

Based on plasma kinetic theory and hybrid simulation codes, Xiang et al. further studied the effect of nonlinear wave-particle interactions of proton temperature anisotropy and α beam instability on proton temperature anisotropy [79]. The results show that in low-β plasma environments ($\beta_{p\|} < 0.2$), α beam instability can effectively excite oblique Alfvén/ion cyclotron waves, while proton temperature anisotropy effectively excites parallel Alfvén/ion cyclotron waves. In plasma environments with $\beta_{p\|} < 0.2$ and $T_{p\perp} < T_{p\|}$, nonlinear wave-particle interactions of oblique Alfvén/ion cyclotron waves can effectively decelerate α beams, making their drift velocity lower than the local Alfvén speed, while simultaneously heating background protons perpendicularly, with weaker heating at larger $\beta_{p\|}$. Therefore, oblique Alfvén/ion cyclotron waves can effectively constrain the distribution of proton temperature anisotropy at $\beta_{p\|} < 0.2$ and $T_{p\perp}/T_{p\|} < 2$, causing it to exhibit an inverse correlation between $\beta_{p\|}$ and $T_{p\perp}/T_{p\|}$. In plasma environments with $\beta_{p\|} < 0.2$ and $T_{p\perp} > T_{p\|}$, nonlinear wave-particle interactions of oblique Alfvén/ion cyclotron waves can effectively decelerate α beams, while nonlinear wave-particle interactions of parallel Alfvén/ion cyclotron waves can effectively constrain proton temperature anisotropy, keeping it below the instability threshold. Therefore, the combined action of obliquely and parallel-propagating Alfvén/ion cyclotron waves can effectively constrain the distribution of proton temperature anisotropy in low-β plasma environments.

4.3 Role of EMIC Waves in Solar Wind Heating and Acceleration

Since EMIC waves can undergo cyclotron resonance with ions, effectively transferring wave energy to ions, EMIC waves play a very important role in wave energy dissipation, particle heating, and acceleration phenomena in solar and space plasmas. Marsch et al. studied the effects of resonant wave-particle interactions of parallel-propagating Alfvén/ion cyclotron waves and magnetosonic/whistler waves on ion heating and acceleration [80]. The results showed that wave-particle interactions cause α particles to be preferentially accelerated. Due to the combined action of Alfvén/ion cyclotron waves and magnetosonic/whistler waves, α particles are accelerated to near the local Alfvén speed. By analyzing the wave damping rate, it was found that heavier ions are preferentially heated, causing the thermal velocity of α particles to be slightly greater than that of protons. Based on one-dimensional hybrid simulation codes, Ofman et al. further studied the influence of the energy spectral index and frequency range of ion-scale turbulence on solar wind ion heating and acceleration [81]. The results indicated that ion heating is very sensitive to the power spectral density within the frequency range of ion resonance. Due to the various forms of power spectra, heavy ions can be easily heated to temperature anisotropy, while protons are slightly heated and remain almost temperature-isotropic.

Based on WIND satellite observations, Kasper et al. found observational evidence of Alfvén/ion cyclotron dissipation in the solar wind [82]. The results showed that when the drift velocity of α beams is relatively small compared to the Alfvén speed and collisions are infrequent, α particles are preferentially heated, with their perpendicular thermal velocity increasing by more than 6 times. These characteristics are consistent with theoretical predictions of dissipation mechanisms in the presence of multiple ion species. Additionally, when the drift velocity of α beams exceeds the sound speed, α particle heating is more effective. Based on Parker Solar Probe observations, Bowen et al. found a correlation between Alfvén/ion cyclotron waves and resonant damping mechanisms [83]. The results showed that the proton distribution function absorbs wave energy from Alfvén/ion cyclotron waves at a heating rate of $10^{-14}\mathrm{K} \cdot \mathrm{m}^{-3}$ during quasi-linear evolution, indicating that Alfvén/ion cyclotron waves can heat the solar wind through cyclotron resonance damping mechanisms.

5 Discussion and Outlook

Since EMIC waves in the solar wind were reported in 2009, rich observational and theoretical research has been conducted, demonstrating considerable potential in explaining solar wind heating and acceleration problems [84]. Currently, statistical results show that EMIC waves are ubiquitous in the solar wind, typically occurring in radially distributed solar wind environments. However, due to satellite orbit limitations, most reported EMIC wave events have occurred within the ecliptic plane, with few studies on EMIC waves in high-latitude solar wind outside the ecliptic plane.

On the other hand, the solar wind is always in a highly turbulent state, encompassing large-scale structures such as interplanetary shocks, interplanetary discontinuities, ICMEs, and corotating interaction regions, which may provide different types of free energy for EMIC wave excitation. For different types of solar wind plasma, their composition and structure show significant differences. Additionally, as solar wind propagates through interplanetary space, the background plasma environment and main plasma parameters change accordingly. Particularly at different radial distances and latitudes, free energy forms such as ion and electron velocity distribution functions and temperature anisotropy differ significantly. The complex and variable plasma environment in the solar wind makes the excitation conditions for EMIC waves more complicated, leading to significant differences in wave characteristics such as frequency range, polarization properties, and duration.

Currently, research on EMIC waves in the solar wind is still in its preliminary stage, and future work should focus on combining observational studies with theoretical research and numerical simulations to study plasma waves in the solar wind. With the improvement of satellite detection technology, the Parker Solar Probe and Solar Orbiter satellites have collected a large amount of in-situ detection data from the inner heliosphere, with the former filling the gap in in-situ detection of solar wind within 0.3 AU in the ecliptic plane, while the latter provides new observational data for studying high-latitude solar wind environments. Based on new satellite data, we can expect to further deepen our understanding of EMIC waves in the solar wind in the near future.

Note: Figure translations are in progress. See original paper for figures.