Solar Wind Electron Kinetic Instability Postprint

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Abstract

Electrons constitute one of the most important components of solar wind particles and can influence the solar wind through multiple mechanisms. Electrons in the solar wind typically exhibit two types of non-thermal equilibrium distribution characteristics: temperature anisotropy and beams. These deviations from thermal equilibrium can excite electron instabilities and plasma waves via wave-particle interactions; the excited plasma waves can subsequently modulate the distribution of solar wind particles through wave-particle interactions, thereby heating the background particles in the solar wind. Consequently, electron kinetic instabilities play a crucial role in the evolution of the solar wind. This work provides a detailed overview of common electron kinetic instabilities in the solar wind, and based on plasma kinetic theory, comprehensively describes various instabilities that emerge during solar wind propagation, particularly the electron-acoustic heat flux instability and lower-hybrid heat flux instability occurring in the inner heliosphere and solar atmosphere, and analyzes their wave-particle interaction mechanisms to facilitate deeper investigation into the evolution of electron distribution functions during solar wind propagation.

Full Text

Preamble

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Electron Kinetic Instabilities in the Solar Wind

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Abstract

Electrons constitute one of the most important components of solar wind particles and can influence the solar wind through multiple mechanisms. Solar wind electrons typically exhibit two non-thermal equilibrium distribution features: temperature anisotropy and beam drift. These deviations from thermal equilibrium can excite electron kinetic instabilities and plasma waves via wave-particle interactions, and the generated plasma waves can in turn modulate the distribution of solar wind particles, thereby heating background particles in the solar wind. Consequently, electron kinetic instabilities play an extremely important role in the evolution of the solar wind. This paper provides a detailed introduction to common electron kinetic instabilities in the solar wind. Based on plasma kinetic theory, we discuss various instabilities that emerge during solar wind propagation, particularly the electron acoustic heat flux instability and lower hybrid heat flux instability in the inner heliosphere and solar atmosphere, and analyze their wave-particle interaction mechanisms to enable more profound investigation of electron distribution function evolution during solar wind propagation.

Keywords: solar wind, magnetic field, plasma instability, whistler wave

1. Introduction

The solar wind is a continuous outflow of high-temperature, high-speed plasma from the solar atmosphere and represents the only stellar wind that humans can measure in situ. It exerts noticeable effects on Earth' s magnetic field and has therefore attracted widespread attention in the astrophysics community. The solar wind consists primarily of electrons, protons, a small number of helium ions, and trace heavy ions, with protons and electrons comprising the vast majority of solar wind particles. Since the electron mass is only 1/1836 that of the proton, electrons have minimal impact on macroscopic solar wind properties such as mass, momentum, and angular momentum. However, electrons can regulate the total momentum balance in the solar wind through their thermal pressure gradient [**?**, **?**] and modulate the total energy balance through electron heat flux [**?**, **?**]. At small scales, electron thermal effects significantly influence plasma dynamics, which in turn affects the overall evolution of the solar wind. Electrons also play an important role in the dissipation of plasma turbulence [**?**]. Therefore, electrons constitute a non-negligible factor in solar wind research.

Space satellite observations indicate that solar wind electron velocity distribution functions are often in non-thermal equilibrium states. Since solar wind plasma is extremely tenuous and generally considered collisionless, particle collisions cannot drive non-thermal distributions toward thermal equilibrium. Consequently, collective behavior in solar wind plasma can only be achieved through wave-particle interactions. When the solar wind electron velocity distribution deviates significantly from thermodynamic equilibrium, it can generate electron kinetic instabilities that excite plasma waves. These waves then interact with background plasma through wave-particle interactions, modulating solar wind particle distribution functions and enabling energy transfer between plasma waves and solar wind particles. The plasma waves excited by electrons in this process have received considerable attention in the solar wind community, including whistler waves, electron acoustic waves, and electron electrostatic waves, which appear frequently in observations, indicating that electrons have relatively active kinetic characteristics in the solar wind environment. Through combined wave and particle studies, we can obtain a general picture of electron kinetics in the solar wind, providing insights for solving the solar wind heating and acceleration problem.

2. Electron Distribution Characteristics and Common Instabilities in the Solar Wind

Solar wind electrons exhibit two primary non-thermal equilibrium distribution features. The first is temperature anisotropy, where electron temperatures differ between directions parallel and perpendicular to the magnetic field. The second is beam drift, where a small fraction of electrons have relatively high drift velocities parallel or anti-parallel to the background magnetic field. Based on observations from various spacecraft, we know that near 1 AU, solar wind electrons consist mainly of three components: low-temperature, high-density core electrons (energy ~10 eV, 95% relative number density), high-temperature halo electrons with some drift velocity (energy ~50 eV, ~4% relative number density), and strahl electrons (energy ~100–1000 eV, 1% relative number density) [**?**, **?**, **?**, **?**, **?**, **?**]. The work of Pilipp et al. [**?**] and Štverák et al. [**?**] demonstrated that the velocity distribution of core electrons exhibits axial asymmetry between parallel and perpendicular directions relative to the magnetic field, while Berčić et al. (2019) showed that higher-temperature, lower-density halo electrons also exhibit temperature anisotropy [**?**]. [Figure 1: see original paper] illustrates the typical three-component electron distribution function in the solar wind [**?**].

Electron temperature anisotropy and beam distributions can trigger multiple types of plasma instabilities. For electron temperature anisotropy, when the perpendicular electron temperature $T_{e\perp}$ exceeds the parallel temperature $T_{e\parallel}$, it can excite electromagnetic electron cyclotron instability (also called whistler instability), electron mirror instability, and Weibel instability, generating whistler waves, electron mirror-mode waves, and Weibel-mode waves, respectively. Weibel-mode waves primarily appear in unmagnetized plasma and are therefore extremely rare in the solar wind environment. When $T_{e\perp} < T_{e\parallel}$, it can excite parallel electron firehose instability, oblique electron firehose instability, and ordinary mode instability, generating Alfvén waves, oblique electron firehose-mode waves, and quasi-perpendicularly propagating ordinary-mode waves. These excited waves modulate electron temperatures in parallel and perpendicular directions, driving them below excitation thresholds and toward temperature isotropy.

When $T_{e\perp} > T_{e\parallel}$, the electromagnetic electron cyclotron instability excites right-hand polarized fast magnetosonic/whistler waves in the parallel direction. Kennel et al. (1966) proposed that this instability requires the condition $T_{e\perp}/T_{e\parallel} - 1 > |\omega_{ce}|/\omega_r$, where ω_{ce} is the electron cyclotron frequency and ω_r is the real wave frequency [?]. Gary (1993) summarized the dispersion relation for excited fast magnetosonic/whistler waves as [?]:

$$\omega_r \simeq k_\parallel v_A \left[1 + \frac{\beta_{e\parallel}}{2}\left(1 + \frac{T_{e\perp}}{T_{e\parallel}}\right)\right]^{1/2}$$

where ω_{cp} is the proton cyclotron frequency, $k_\parallel$ is the parallel wave number, d_p is the proton inertial length, and $\beta_{e\parallel}$ is the ratio of parallel electron thermal pressure to magnetic pressure. Since the excited wave frequency far exceeds proton characteristic frequencies, whistler waves generated by electromagnetic electron cyclotron instability rarely undergo wave-particle interactions with solar wind protons. The work of Gary et al. [?] and Lazar et al. [?] investigated instabilities excited by anisotropic core and halo electrons, finding that anisotropic halo electrons can also excite parallel-propagating whistler waves through the same electron cyclotron resonance mechanism as anisotropic core electrons. By analyzing MMS (Magnetospheric Multiscale) satellite data, Zhao et al. discovered numerous electromagnetic electron cyclotron instabilities in Earth' s magnetosheath, where electron beams cause different intensities of instability propagation along and against the magnetic field direction [?].

In directions oblique to the background magnetic field, $T_{e\perp} > T_{e\parallel}$ can excite electron mirror instability with zero real frequency. Basu et al. (1984) first identified this instability, calling it field-swelling instability when $\beta_{e\parallel} > 1$ [?]. Pokhotelov et al. (2002) argued that electron mirror force is the fundamental driver and named it electron mirror instability [?]. Both electromagnetic electron cyclotron and electron mirror instabilities are excited under perpendicular temperature anisotropy conditions but at different propagation angles. Gary et al. (2006) conducted a detailed comparison of these instabilities' intensities, showing that electromagnetic electron cyclotron instability has stronger growth rates and lower excitation thresholds for $0.1 \leq \beta_{e\parallel} \leq 1000$ [?].

Under $T_{e\perp} < T_{e\parallel}$ conditions, two types of electron firehose instabilities are excited: periodic firehose instability in the parallel direction and aperiodic firehose instability in oblique directions. Periodic electron firehose instability was first discovered by Hollweg et al. (1970) [?]. For weak temperature anisotropy, it excites backward-propagating, right-hand fast magnetosonic/whistler waves; as temperature anisotropy strengthens, these become left-hand polarized fast magnetosonic/whistler waves. Aperiodic electron firehose instability was first identified by Paesold et al. (1999) [?], exciting non-propagating waves ($\omega_r = 0$). They compared the intensities of both firehose instabilities, demonstrating that aperiodic electron firehose instability has stronger growth rates under identical parameters. Additionally, ordinary mode instability appears in quasi-perpendicular directions, exciting ordinary-mode waves with real frequencies between $n\omega_{ce}$

and $(n+1)\omega_{ce}$, where n is a natural number [?]. [Figure 2: see original paper] shows the distribution of electromagnetic electron cyclotron, electron mirror, and periodic electron firehose instabilities in $(T_{e\perp}/T_{e\parallel}, \beta_e)$ space, with observed electron distribution parameters overlaid for comparison. The figure clearly demonstrates that electron anisotropy distributions in the solar wind are constrained by temperature anisotropy instabilities, though this study neglected the effects of aperiodic electron firehose instability [?].

Compared to electron temperature anisotropy, electron beams have received more attention in recent years. Electron beams can excite various plasma wave modes under different conditions, including Alfvén waves, whistler waves, electron acoustic waves, etc. Gary [?, ?] comprehensively summarized common electrostatic instabilities in the solar wind in 1985, including their excitation sources, characteristic frequencies, wave numbers, and environments, as shown in . In the table, ω_r is the real wave frequency, ω_{ce} is the electron cyclotron frequency, k is the wave number, v_e is the background electron thermal velocity, v_b is the beam electron thermal velocity, v_{0b} is the beam electron drift velocity, v_{0c} is the background electron drift velocity, k_e is the wave number normalized to electron inertial length, c_s is the sound speed of each component, and T_i, T_e, T_b are the temperatures of protons, background electrons, and beam electrons, respectively. T_{cool} and T_{hot} represent the colder and hotter components in two-component electron distributions, k_{cool} and k_{hot} are the corresponding normalized wave numbers, and c_{cool} is the colder component sound speed. Regarding these electrostatic instabilities, Lu et al. (2005) conducted detailed PIC (Particle-In-Cell) simulations, showing that Langmuir waves, electron acoustic waves, and beam-mode electrostatic waves can all be excited by electron beams [?]. Sentman et al. (1983) proposed that electron beams with drift velocities above a certain threshold can excite obliquely propagating whistler waves [?]. Different beam drift velocities trigger different beam instabilities, though identifying wave modes in actual environments remains complex. Shi et al. (2020) studied waves observed in Jupiter’ s polar region, combining theoretical calculations to argue that electron beams there excite whistler waves rather than electrostatic waves [?]. These plasma waves excited by beam electrons can interact with solar wind particles, consuming free energy from beam electrons to generate plasma waves while the waves modulate particle distribution functions, thereby achieving beam modulation, scattering, and background particle heating.

Electron temperature anisotropy and electron beams, as the most common non-thermal equilibrium features of solar wind electrons, often coexist in the solar wind environment. Therefore, it is essential to consider both effects simultaneously when studying electron kinetic instabilities in the solar wind. Saeed et al. [?] and Shaaban et al. [?, ?] investigated electron kinetic instabilities under combined electron temperature anisotropy and beam conditions, finding that the superposition of two free-energy sources significantly modifies excitation thresholds and wave properties of both temperature anisotropy and beam instabilities. However, these studies have limitations: first, they discuss only parallel propagation cases with limited investigation of oblique propagation; second, they lack analysis of electromagnetic polarization information for excited plasma waves, making wave identification difficult in observations; third, they lack analysis of wave-particle interactions between plasma waves and solar wind particles, limiting many works to parameter studies without discussion of fundamental physical mechanisms and failing to explain how plasma waves heat and accelerate the solar wind.

Since the solar wind is always in a dynamic, outward-propagating process, research should incorporate parameters at different radial distances. Previous work often adopted solar wind parameters near 1 AU, which cannot clearly illustrate the evolution of plasma instabilities during solar wind propagation. With increasing numbers of space satellites launched, we have obtained more plasma parameters at different heliocentric radial distances. Combining these parameters to investigate solar wind plasma characteristics, particularly plasma waves in the inner heliosphere and solar atmosphere, represents a key focus for current researchers.

To address these questions, our work conducts comprehensive and in-depth studies of electron kinetic instabilities in the solar wind, simultaneously considering beam and temperature anisotropy conditions to provide a universal picture of solar wind electron kinetic instabilities. We deeply investigate the characteristics of these plasma waves, including wave modes excited by solar wind electrons, wave-particle interaction patterns, and energy transport in different directions and among different particles, providing clear insights for revealing plasma processes in the solar wind.

3. Electron Kinetic Instabilities Under Combined Temperature Anisotropy and Electron Beam Conditions

Solar wind electrons generally exhibit anisotropic temperature distributions, combined with the widespread existence of electron beams. Therefore, our research must consider both non-thermal equilibrium conditions simultaneously to obtain a more comprehensive picture of electron kinetic instabilities in the solar wind and conduct in-depth studies of excitation mechanisms and wave-particle interactions.

In this study, we adopt solar wind parameters near 1 AU and consider a plasma composed of three components: protons (“p”), background electrons (“ec”), and electron beam (“eb”), where protons and beam electrons are temperature-isotropic while background electrons are temperature-anisotropic. Based on these parameters, we employ plasma kinetic theory to investigate instabilities, using theoretical calculations and numerical solutions to examine various electron kinetic instabilities and their characteristics in detail, including growth rates, real frequencies, and electromagnetic polarization features. Additionally, we developed a method to calculate energy transfer rates between waves and particles. By computing perturbed currents for each particle component, we quantitatively obtain energy transfer rates between different particle components and waves, enabling more effective analysis of wave excitation mechanisms and background particle heating [?].

[Figure 3: see original paper] and [Figure 4: see original paper] display the distribution of electron kinetic instabilities in $(\beta_{ec\parallel}, A_{ec})$ space, where we adopt an electron beam velocity of $V_{eb} = 30V_A$, the vertical coordinate is $A_{ec} = T_{e\perp}/T_{e\parallel}$, and the horizontal coordinate is the ratio of parallel background electron thermal pressure to magnetic pressure $\beta_{ec\parallel}$. By analyzing wave characteristics in each region, we identify detailed instability types. [Figure 3: see original paper] presents cases for $\theta = 0^\circ$ and 180° propagation, showing that electron acoustic, whistler, electromagnetic electron cyclotron, and parallel electron firehose instabilities are all excited. In the $\beta_{ec\parallel} < 0.05$ region, electron acoustic instability is strongest at $\theta = 0^\circ$. When $\beta_{ec\parallel} > 0.05$, whistler heat flux, periodic electron firehose, and electromagnetic electron cyclotron instabilities dominate different parameter spaces, with electromagnetic electron cyclotron instability in the $A_{ec} > 1$ region, periodic electron firehose instability in the $A_{ec} < 1$ region, and whistler heat flux instability dominating the A_{ec} region between solid and dotted lines ([Figure 3: see original paper]a).

[Figure 4: see original paper] shows cases for propagation angles $\theta = 60^\circ$ and 89°. In the $\beta_{ec\parallel} < 0.05$ region, electron magnetosonic instability appears at $\theta = 60^\circ$ and ordinary mode instability at $\theta = 89^\circ$. In the $\beta_{ec\parallel} > 0.05$ region, electron mirror instability appears when $A_{ec} > 1$ and aperiodic electron firehose instability when $A_{ec} < 1$. In the intermediate $\beta_{ec\parallel}$ region with $A_{ec} < 1$, right-hand polarized oblique fast magnetosonic/whistler instability ($\theta = 60^\circ$) and left-hand polarized ordinary mode instability ($\theta = 89^\circ$) appear. The oblique fast magnetosonic/whistler instability exhibits harmonic characteristics, experiencing strong proton cyclotron resonance damping when wave frequencies approach integer multiples of ω_{cp}, thereby heating background protons.

Beyond analyzing instability growth rates and electromagnetic polarization, we also examined excitation mechanisms by calculating energy transfer rates between waves and particles. Zhao et al. (2022) used a similar method to analyze energy transfer rates between Alfvén waves and particles in the solar wind, verifying the method's accuracy [?]. For parallel/anti-parallel instabilities, we found that for whistler heat flux, electromagnetic electron cyclotron, and periodic electron firehose instabilities, energy transfer is contributed solely by perpendicular electric fields. Energy transfer for electron acoustic instability in low-$\beta_{ec\parallel}$ regions is dominated by parallel electric fields. Whistler heat flux instability is excited primarily through beam electron cyclotron resonance, while electromagnetic electron cyclotron instability is excited mainly through core electron cyclotron resonance, allowing distinction through energy transfer rates with different particles. Periodic electron firehose instability receives energy from parallel electric fields of temperature-anisotropic core electrons, with beam electrons playing a complex role—hindering instability growth at low β_{ec} and weak temperature anisotropy, but transferring energy to waves and promoting excitation at high β_{ec} and strong temperature anisotropy. Protons act as a damping mechanism in these processes. For electron acoustic instability in low-$\beta_{ec\|}$ regions, calculations show energy transfer is dominated by beam electrons under parallel electric fields, indicating excitation through beam electron Landau resonance.

We also analyzed oblique electron instabilities. When propagation angles are oblique to the background magnetic field, they exhibit energy transfer rates in both parallel and perpendicular directions, indicating multiple resonance mechanisms can excite instabilities. Electron mirror instability is primarily excited by anisotropic core electrons through $\omega_r - k_\| V_{ec0} = 0$ resonance, where V_{ec0} is the core electron drift velocity. Periodic electron firehose instability is excited mainly through wave-particle resonances at $\omega - k_\| V_{ec0} - \omega_{ce} = 0$ and $\omega - k_\| V_{ec0} + \omega_{ce} = 0$. Oblique fast magnetosonic/whistler instability is excited primarily by beam electron resonance, with core electrons and protons absorbing wave energy through Landau and cyclotron resonances when oblique fast magnetosonic waves are excited. Ordinary mode instability transfers energy mainly with core electrons in the parallel direction, excited primarily by core electron Landau resonance, while beam electron Landau resonance mainly provides damping.

Our research reveals that for parallel propagation, electron beams break the symmetry of temperature anisotropy instabilities in forward and backward propagation directions, creating an electron acoustic instability-dominated region at low β_{ec} and making whistler heat flux instability stronger at intermediate β_{ec}. Electron beams enhance parallel electromagnetic electron cyclotron instability while weakening its anti-parallel counterpart, and enhance anti-parallel periodic electron firehose instability while weakening its parallel counterpart. When both electron beams and temperature anisotropy coexist, lower hybrid heat flux instability is excited. Compared to parallel whistler heat flux instability, this lower hybrid heat flux instability has lower excitation thresholds, was rarely mentioned in previous studies, and can excite obliquely propagating whistler waves, potentially representing an important cause of the recently highlighted beam electron scattering phenomenon [**?**]. We will discuss this in detail below.

4. Radial Evolution of Electron Heat Flux Instabilities in the Inner Heliosphere

Obliquely propagating whistler waves have attracted considerable attention recently because they may play an important role in scattering beam electrons in the solar wind. Maksimović et al. observed radial variations in the relative proportions of solar wind electron components [Figure 5: see original paper] [**?**]. As solar wind propagates outward, the relative number density of strahl electrons gradually decreases while halo electrons increase, though their combined proportion remains essentially constant. Researchers therefore hypothesize that some physical process scatters strahl electrons into halo electrons, suppressing strahl electron drift velocities and scattering them into a broader range.

Gary et al. (1994) proposed that parallel-propagating whistler waves might be responsible for modulating high-speed electron beams, an idea accepted by researchers for a considerable time [**?**]. High-speed electron beams can excite parallel-propagating whistler waves, an instability known as whistler heat flux instability. However, Gary et al. focused primarily on high-electron-β environments (heliocentric distances of 1–5 AU) and discussed low-β_e environments (inner heliosphere, heliocentric distance less than 1 AU) only briefly, while observations show strahl electron relative density decreases most rapidly within 1 AU [**?**]. In Tong et al. (2018), electrons were divided into core, halo, and strahl components [**?**]. Linear theoretical calculations revealed that in low-electron-β environments, Alfvén heat flux instability excites Alfvén waves that more effectively constrain electron beams, with these waves propagating at large angles and exhibiting kinetic Alfvén wave characteristics. Kuzichev et al. (2019) combined theory and simulation to propose that obliquely propagating whistler waves can more effectively scatter beam electrons and modulate electron heat flux compared to parallel-propagating whistler waves [**?**]. Verscharen et al. analyzed wave-particle interactions between oblique whistler waves and beam electrons in detail, using particle simulations to verify that obliquely propagating whistler waves excited by high-speed electron beams can effectively scatter strahl electrons into halo electrons [**?**]. However, these works neglected changes in plasma parameters during solar wind propagation. At different heliocentric radial distances, solar wind plasma background magnetic field, particle number density, temperature, and solar wind velocity all differ, causing different plasma instabilities to be excited. Therefore, attributing electron heat flux modulation and halo electron scattering in the solar wind to a single instability is overly simplistic.

To more clearly explain the physical process of halo electron scattering into strahl electrons, we must investigate electron plasma instabilities at different radial distances. Previous research focused primarily on instabilities near 1 AU. However, in the actual solar wind environment, plasma parameters vary with radial distance from the Sun. Addressing this characteristic, we employ radial distribution models for inner heliosphere magnetic field and plasma parameters to study the distribution and evolution of electron heat flux instabilities in the solar wind, thereby providing a complete picture of electron beam instabilities.

Based on previous observational data [**?**], we fitted solar wind plasma and magnetic field parameters. From the solar surface to 1 AU, our adopted parameters are as follows: total electron number density varies with radial distance as

$$n_e = n_{r0} \times \exp\left(3.67 R_S^{-6.0} R_5^{-7.6} R_4^{-4.9} R_3\right)$$

where $n_e = n_{ec} + n_{eb}$ and $n_{r0} = 3.26 \times 10^5\ \mathrm{cm}^{-3}$, with R_S being solar radius. n_{r0} represents typical particle number density near the solar surface.

Proton temperature varies with radial distance as

$$T_p = T_{r0} R_0^{-0.6}$$

where $T_{r0} = 226.4$ eV is the typical particle temperature near the solar surface. Magnetic field strength varies with radial distance as

$$B_0 = B_{r0} \times \frac{215 R_S}{215 R_S}$$

where $B_{r0} = 4$ nT is the typical magnetic field strength near the solar surface. Solar wind velocity varies radially as

$$V_{sw} = V_{r0} \left[1 - \exp\left(-2.8 \right) \right]$$

where $V_{r0} = 430$ km/s is the typical solar wind velocity near the solar surface. Based on these parameters, we used numerical calculations to investigate the distribution of electron heat flux instabilities in heliospheric space [?].

[Figure 6: see original paper] presents the radial distribution of electron heat flux instabilities in the inner heliosphere, where V_{eb} is the electron heat flux drift velocity. Panels (a)-(d) represent growth rate γ, real frequency ω_r, propagation angle θ, and the argument of the ratio between E_y and E_x, respectively. Four instabilities appear: electron acoustic heat flux, lower hybrid heat flux, oblique Alfvén heat flux, and parallel whistler heat flux instabilities, labeled "I" , "II" , "III" , and "IV" in the figure. These four instabilities dominate different parameter spaces. Electron acoustic heat flux instability is strongest in high V_{eb} regions ($\gtrsim 1 - 2V_{Ae}$, where V_{Ae} is the electron Alfvén speed), exciting parallel-propagating high-frequency electron acoustic waves, consistent with López et al. (2020) [?]. Lower hybrid heat flux instability dominates in the region $r < 30R_S$ and $V_{eb} \sim 0.5 - 1V_{Ae}$, exciting obliquely propagating lower hybrid waves that exhibit harmonic characteristics. In the region $r < 13R_S$ and $V_{eb} \sim 0.4 - 0.6V_{Ae}$, oblique Alfvén heat flux instability dominates, exciting quasi-perpendicularly propagating kinetic Alfvén waves. In the region $r > 10R_S$ and $V_{eb} \sim 0.3 - 2V_{Ae}$, parallel whistler heat flux instability dominates, exciting parallel-propagating whistler waves commonly considered the primary mechanism for modulating solar wind electron beams. [Figure 6: see original paper] shows that electron acoustic heat flux and parallel whistler heat flux instabilities have maximum growth rates at $\theta = 0°$, lower hybrid heat flux instability is strongest at $\theta \sim 87°$, and oblique Alfvén heat flux instability has maximum growth rate at $\theta \sim 74°$.

All these electron heat flux instabilities can modulate electron heat flux but operate in different parameter spaces. As solar wind propagates outward, our research clearly reveals that multiple beam-driven instabilities can modulate electron beams, each dominating different parameter spaces. For high-speed electron beams, electrostatic-mode electron acoustic instability modulates them throughout the inner heliosphere. In the solar atmosphere near the Sun, oblique Alfvén heat flux instability modulates lower-speed electron beams, consistent with reference [?]. For medium-speed electron beams within 0–30 solar radii, lower hybrid instability modulates them by exciting lower hybrid waves. Since lower hybrid waves have the same dispersion relation as oblique whistler waves at large propagation angles, this validates theoretical studies of oblique whistler waves modulating electron heat flux.

Beyond investigating instability distributions, we analyzed excitation mechanisms by calculating energy transfer rates between waves and particles, examining the role of each particle component during wave excitation. [Figure 7: see original paper] presents the radial distribution of energy transfer rates between electron heat flux instabilities and various particles, where blue regions indicate energy flow from particles to waves and red regions indicate energy flow from waves to particles. When electron acoustic heat flux instability is excited, beam electron free energy transfers to waves while core electrons gain energy from waves—energy transfers from beam electrons to unstable waves in the parallel direction, and the waves then transfer energy to core electrons, heating background electrons. For parallel whistler heat flux instability, energy propagates only in the perpendicular direction, indicating that parallel-propagating whistler waves are excited by beam electron cyclotron resonance, with energy transferred from electron heat flux to whistler waves and then to core electrons. For lower hybrid heat flux instability, excitation is dominated by vertical electric fields interacting with resonant beam electrons, allowing wave-beam electron interactions through $n = 1$ anomalous cyclotron resonance. This resonance mechanism not only reduces beam electron drift velocities but also scatters high-speed beam electrons into more isotropic halo electrons [?]. Additionally, since lower hybrid waves experience strong proton cyclotron resonance damping near $n\omega_{cp}$, they also significantly heat background protons. In oblique Alfvén heat flux instability, core electrons transfer energy to oblique Alfvén waves in the parallel direction, while most wave energy transfers to protons and beam electrons.

Through this analysis of electron heat flux instability excitation mechanisms, we find that multiple instabilities can modulate electron beams in the solar wind. However, lower hybrid instability, which excites lower hybrid/oblique whistler waves, has additional effects. Lower hybrid/oblique whistler waves can effectively scatter high-speed beam electrons (the strahl component), making space observations urgently needed for verification. However, the beam component fraction decreases with heliocentric distance, making beam electrons difficult to detect at larger distances and complicating verification of the relationship between oblique whistler waves and beam electrons. Early space probes had limited measurement precision and insufficient heat resistance to venture within 0.3 AU (the previous record holder, Helios, had a perihelion of ~0.3 AU). However, the Parker Solar Probe (PSP), launched in 2018, enables humanity' s first exploration of solar wind within 0.3 AU. PSP is the first spacecraft to directly probe the solar corona, with its closest approach only 10 solar radii from the

Sun. By the end of 2021, PSP had completed 10 perihelion passes and will reach its minimum perihelion of 10 solar radii by the end of 2024. Multiple studies have revealed abundant plasma waves in the near-Sun solar wind environment [**?**, **?**], urgently requiring plasma theory to explain their origins. Future work will combine theoretical predictions with PSP observational data to further investigate plasma waves in the inner heliosphere, particularly oblique whistler waves.

5. Conclusion

This paper systematically introduces common electron kinetic instabilities in the solar wind, which play crucial roles in evolving solar wind electron velocity distribution functions. Non-thermal equilibrium distributions of electrons excite plasma waves, which in turn modulate electron velocity distributions and exchange energy with other particles, indirectly enabling energy transfer between energetic electrons and background particles. Building on previous work, we considered more realistic parameter conditions to study solar wind electron kinetic instabilities more completely. Since electrostatic instabilities are summarized in , we compile common solar wind electron electromagnetic instabilities in .

Based on previous studies, we further investigated electron kinetic instabilities under combined electron temperature anisotropy and beam conditions. Referencing actual observational parameters, we studied electron kinetic instabilities at different heliocentric distances, providing a complete picture of each instability’ s role in solar wind evolution. Our findings include: (1) Parallel electromagnetic electron cyclotron and anti-parallel periodic electron firehose instabilities are enhanced by electron beams, while anti-parallel electromagnetic electron cyclotron and parallel periodic electron firehose instabilities are weakened; (2) In oblique propagation, a new oblique fast magnetosonic/whistler instability emerges, belonging to the same dispersion branch as lower hybrid heat flux instability, exciting obliquely propagating fast magnetosonic/whistler waves that experience strong proton cyclotron resonance damping near integer multiples of the proton cyclotron frequency, enabling energy exchange between energetic electrons and background protons; (3) We reveal the radial distribution of electron heat flux instabilities in the solar wind. Electron acoustic instability limits electron heat flux at all radial distances. The previously emphasized parallel whistler heat flux instability modulates low-speed electron beams at larger heliocentric distances ($r > 10R_S$). Lower hybrid heat flux and oblique Alfvén heat flux instabilities modulate electron heat flux at distances closer to the Sun ($r < 30R_S$). Furthermore, based on our analysis of energy exchange rates between waves and particles, lower hybrid heat flux instability can excite lower hybrid waves that, at large propagation angles, belong to the same wave branch as oblique whistler waves, enabling effective scattering of high-speed beam electrons in the solar wind—crucial for explaining related phenomena in solar wind electron distributions.

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