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The role of wave-particle interactions in cold and warm plasma heating

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Cold plasma originating from the ionosphere is a highly influential component of the magnetosphere, dominating its mass. It is typically treated as a passive background represented as an empirical density in models of the ring current, outer radiation belt, and wave propagation. While it is well established that cold plasma density plays a critical role in controlling wave properties - such as amplitude and wave vector - increasing theoretical and observational evidence suggests that cold plasma populations may actively couple with waves, exchanging energy through processes that are not yet fully understood. Importantly, these processes can energize cold plasma, gradually transforming it into warm and eventually hot plasma. This mini-review explores the role of wave-particle interactions in cold and warm plasma heating, highlighting their significance in facilitating coupling between different plasma populations in Earth's magnetosphere.

KEYWORDS

wave-particle interactions, warm plasma, cold plasma, plasmasphere, warm plasma cloak, plasma heating

Introduction

Cold (~eV) plasma from the ionosphere is a key player in geospace dynamics, especially during magnetic storms, serving as a primary magnetospheric plasma source (Chappell et al., 1987; Kistler et al., 2023) and engaging in energy exchange with other populations. Simulations of the ring current (Jordanova et al., 2022), outer radiation belt (Shprits et al., 2015), and wave propagation (Walker, 1976; Usanova et al., 2022) often treat cold plasma as a density-based, passive medium. However, growing evidence highlights the need to account for energy exchange processes that modify cold plasma properties and link it to higher-energy populations, integrating it more dynamically into the geospace system (Delzanno et al., 2021).

The energy exchange between different plasma populations can be mediated by wave-particle interactions, which play an important role in heating cold plasma within the Earth's magnetosphere. Wave-particle interactions allow for a gradual energy build-up, altering the local plasma environment and contributing to magnetospheric dynamics. These interactions can occur at various locations along magnetic field lines, including the equatorial plane and higher magnetic latitudes, influencing different magnetospheric particle populations. They can enhance ionospheric plasma

outflow into the magnetosphere (Chaston et al., 2006; Liemohn et al., 2024), lead to particle acceleration in the auroral zone (André, 1997), and contribute to the formation of the warm plasma cloak (Chappell et al., 2021) and the ring current (Daglis et al., 1999; Keika et al., 2013).

Wave-particle interactions

Resonant interactions serve as an efficient mechanism for energy transfer between particles and waves, primarily through cyclotron and Landau resonances. Cyclotron resonance takes place when the Doppler-shifted wave frequency matches the particle's cyclotron frequency: $\omega - k_{\parallel}v_{\parallel} = \frac{n\Omega}{\gamma}$, $n = \pm 1, \dots$, where $k_{\parallel}$ is the wave number and $v_{\parallel}$ is the particle velocity along the background magnetic field and γ is the relativistic factor.

Landau resonance occurs when charged particles with velocities close to the wave's phase velocity exchange energy with the wave (Lifshitz and Pitaevski, 1981). The condition for this resonance is satisfied when $\omega = k_{\parallel}v_{\parallel}$. For plasma with a Maxwellian distribution, this process results in wave damping and plasma heating.

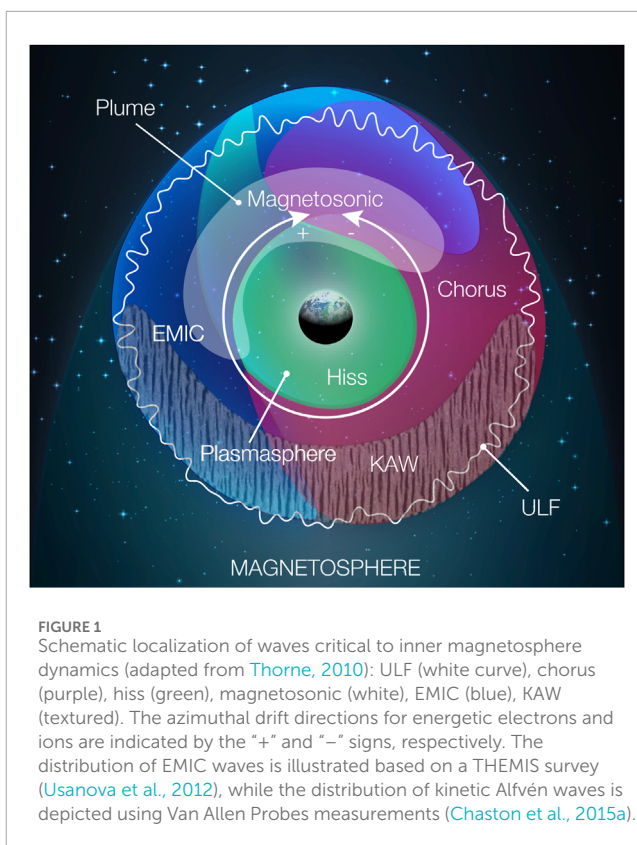
Other resonance interactions, such as bounce and drift-bounce resonances, have also been identified (Southwood et al., 1969; Schulz and Lanzerotti, 1974). Drift-bounce resonance arises from a particle's combined drift and bounce motion, occurring when the wave frequency matches the drift-bounce frequency: $\omega - m\omega_d = N\omega_b$, where ω_d and ω_b are the particle's bounce-averaged drift and bounce angular frequencies, m is the azimuthal wavenumber and N is an integer. Bounce resonance interactions occur when the particle's bounce period between conjugate hemispheres (or an integer multiple of this period) matches the wave period, satisfying $\omega = N\omega_b$ for $m = 0$.

Cyclotron and Landau resonance interactions primarily involve particles with energies ~ 100 eV, typically classified as warm plasma. In contrast, non-resonant mechanisms can heat plasma considered cold in the context of resonant wave-particle interactions, where particle thermal velocities are much lower than the phase velocities of propagating waves.

Quasilinear diffusion theory is a fundamental framework for describing energy and momentum exchange in both resonant and non-resonant wave-particle interactions. It applies to systems where wave amplitudes are small and the waves are broadband and randomly phased, allowing for a statistical treatment of diffusion in velocity space (Kennel and Engelmann, 1966). Most applications of quasilinear diffusion theory in space plasmas focus on resonant interactions, as these effects typically dominate (Albert et al., 2009). Non-resonant interactions become significant when wave packets are short, leading to a spread in wavenumber space (An et al., 2022).

For large-amplitude waves, nonlinear effects such as phase trapping and phase bunching become important. They are described by nonlinear theory (Artemyev et al., 2021 and references therein) and simulated using test-particle, particle-in-cell, and Vlasov codes (da Silva et al., 2018; Omididi et al., 2010; Nunn, 2021). Nonlinear interactions can also influence cold plasma populations, as discussed in the sections below.

Key wave modes contributing to plasma heating include whistler-mode waves (chorus and hiss), electromagnetic ion



cyclotron (EMIC) waves, ultra-low-frequency (ULF) waves, and kinetic Alfvén waves (KAWs). Their typical locations within the inner magnetosphere are schematically illustrated in Figure 1. The following sections examine the role of these wave modes in cold plasma energization.

Ultra-low-frequency waves

ULF waves are the longest-period waves in the magnetospheric system, with frequencies ranging from 1 mHz to 5 Hz (Jacobs et al., 1964; Hartinger et al., 2022). This frequency range also includes electromagnetic ion cyclotron waves, discussed separately in a later section. ULF waves can be driven by various mechanisms and are observed across different regions of the magnetosphere. Drivers include solar wind impulses (McPherron, 2005; Shen et al., 2015), ion foreshock instabilities on the dayside (Eastwood et al., 2011; Hartinger et al., 2013), the Kelvin-Helmholtz instability on the flanks (Southwood, 1974; Mann et al., 1999; Claudepierre et al., 2008), and plasma instabilities in fast flows on the nightside (Zolotukhina et al., 2008; Yeoman et al., 2010). Additionally, ULF waves can result from resonance interactions with energetic ions in the inner magnetosphere (Ozeke and Mann, 2008).

ULF waves play a crucial role in energizing plasmaspheric and ionospheric populations, as well as modulating their fluxes. The ion $E \times B$ drift driven by the wave's electric and magnetic fields has been proposed as a key mechanism behind the observed enhancements in ion flux at energies of tens of eV (Zong et al., 2012; Zhang et al., 2019). Additionally, Zong et al. (2012) suggested that ULF waves can

interact with the oxygen torus (Chappell, 1982; Fraser et al., 2005), enhancing its density by a factor of two to three.

Betatron acceleration caused by ULF wave magnetic fields has been identified as an alternative mechanism for the acceleration of hydrogen and helium ions with energies below 100 eV, particularly in cases where $E \times B$ drift alone cannot fully account for the observed flux enhancements (Yue et al., 2016).

Ren et al. (2017), Ren et al. (2019) explored the connection between ULF waves and electrons with energies below 200 eV. Their findings show that ULF waves can accelerate electrons in the $\sim$ eV to tens of eV range along the parallel direction, consistent with the drift-bounce resonance mechanism.

Whistler-mode waves: chorus and hiss

Chorus and hiss waves are right-hand circularly polarized electromagnetic waves that propagate predominantly along magnetic field lines in the magnetosphere. Chorus waves typically range in frequency from a few hundred Hz to several kHz, below the electron cyclotron frequency (f_{ce}). They are observed at frequencies $0.1\text{--}0.8 f_{ce}$, with a gap near $0.5 f_{ce}$ splitting the emissions into two bands: lower-band and upper-band chorus (Tsurutani and Smith, 1977). These waves are generated by anisotropic electron distributions ($\sim$ tens of keV) with $T_{\text{perp}} > T_{\text{para}}$ (perpendicular temperature exceeding parallel temperature) (Omura et al., 2008). Chorus waves are primarily observed outside the plasmopause and are most common in the dawn sector of the magnetosphere, at distances between 4 and 9 Earth radii (Li et al., 2011).

Resonant interactions with oblique waves can mediate energy exchange between different particle populations (e.g., Shklyar, 2017). For example, cyclotron interactions with higher-energy particles drive chorus wave growth, while lower-energy particles can gain energy through other resonances. Chorus waves can accelerate warm (>100 eV) electrons via Landau resonance (Bortnik et al., 2007; Chen et al., 2013).

Recent studies have shown that quasi-field-aligned whistler waves can generate parametric nonlinear instabilities due to transverse currents as they propagate through cold plasma (Roytershteyn and Delzanno, 2021; Roytershteyn et al., 2024). This process leads to the damping of quasi-field-aligned waves, the excitation of oblique electrostatic modes, including electron Bernstein and oblique electrostatic whistler modes and parallel heating of cold plasma. This mechanism provides a potential pathway for transferring energy from chorus waves to cold electrons. Notably, the instability that generates oblique electrostatic waves is sensitive to the shape of the low-energy electron distribution, which highlights the importance of cold plasma distribution measurements in future missions.

Hiss waves, a subset of whistler-mode electromagnetic waves, are characterized by a broad and incoherent frequency spectrum, typically ranging from about 20 Hz to several kHz. Plasmaspheric hiss waves are observed primarily inside the plasmopause, within the plasmasphere and plasmaspheric plumes (Hayakawa and Sazhin, 1992).

Two distinct populations of hiss waves have been identified: low-frequency hiss ($f < 100$ Hz) and high-frequency hiss ($f > 100$ Hz) (Malaspina et al., 2017, and references therein). In addition,

more recently, Meredith et al. (2021) distinguished a medium frequency range ($200 < f < 2,000$ Hz) population. These populations exhibit unique spatial distributions and amplitude characteristics, suggesting that different generation mechanisms are at play. Despite extensive research, the exact origins of hiss waves remain an active topic of investigation.

Several mechanisms have been proposed for the generation of plasmaspheric hiss waves. Lightning-generated whistlers (Meredith et al., 2006), mode conversion of chorus waves (Bortnik et al., 2008), and local generation by substorm injections (Li et al., 2023) are among the leading hypotheses. Specifically, Li et al. (2023) suggested that low-frequency hiss waves might result from *in situ* cyclotron wave growth driven by freshly injected electrons at low L shells. Chen et al. (2014) demonstrated that repeated wave amplification, supported by guided propagation along the plasmopause, can lead to a significant wave gain over multiple reflections between conjugate hemispheres.

Hiss waves play a crucial role in magnetospheric dynamics. For instance, quasilinear calculations by Li et al. (2019) confirmed that hiss waves can rapidly accelerate suprathermal electrons parallel to the magnetic field via Landau resonance, with acceleration occurring on timescales as short as 10 min. Similarly, Wang et al. (2019) showed that hiss waves can significantly enhance field-aligned electron fluxes in the 50–300 eV range. Through Landau damping, these fluxes can increase by a factor of 10 within approximately 1 hour.

Although Landau resonance does not directly heat the core cold plasma population - since the resonance energy is higher - the acceleration of suprathermal electrons by chorus and hiss waves, followed by their Coulomb collisions with core magnetospheric and ionospheric electrons, can contribute to energy transfer to the cold electron population (Khazanov et al., 2022).

Magnetosonic waves (also known as equatorial noise)

Magnetosonic waves are longitudinal electromagnetic plasma waves that propagate nearly perpendicular to the background magnetic field. They were first identified as emissions near the geomagnetic equator (hence their name) by Russell et al. (1970). These waves are typically observed at frequencies between the proton gyrofrequency (f_{cp}) and the lower hybrid resonance frequency (f_{LHR}), generally in the range of a few Hz to 100 Hz (Chen and Bortnik, 2020). Near the proton gyrofrequency, magnetosonic waves often exhibit a harmonic structure (Gurnett, 1976). The primary source of free energy for these waves is ~ 10 keV protons with positive gradients in their perpendicular velocity distribution (Perraut et al., 1982).

Enhanced fluxes of electrons and ions with energies from tens to hundreds of eV have been observed in association with magnetosonic waves (Gurnett, 1976; Olsen, 1981). To explain these observations, Horne et al. (2000) performed a ray-tracing analysis and demonstrated that magnetosonic waves can resonantly interact with both electrons and ions and increase their perpendicular energy, although the nature of these interactions differs. Electrons interact with magnetosonic waves via Landau resonance, with resonance energy around 1 keV for perpendicular

wave propagation, decreasing to a few eV at smaller propagation angles. Cold protons, conversely, can undergo cyclotron resonance with magnetosonic waves, resulting in heating transverse to the ambient magnetic field. This transverse proton heating becomes more significant outside the plasmasphere, where thermal proton temperatures increase up to ~ 100 eV. The resonance energy decreases into the eV range but only at frequencies near the proton cyclotron frequency harmonics. These findings are consistent with the suprathermal particle distributions reported in the region (Olsen, 1981). More recently, the formation of suprathermal proton fluxes due to magnetosonic waves has been identified as an energy source for EMIC waves (see section below), highlighting a complex interplay between various wave modes and particle populations (Asamura et al., 2021).

In addition to protons, magnetosonic waves can resonantly heat 10–100 eV He^+ ions (Yuan et al., 2018) and O^+ ions (Hill et al., 2020). As demonstrated by Ma et al. (2019), magnetosonic waves can interact with thermal minor ion species at pitch angles up to $\sim 80^\circ$, mediated by multiple harmonic cyclotron resonances.

Electromagnetic ion cyclotron waves

Electromagnetic ion cyclotron (EMIC) waves are plasma waves that typically propagate along, or at a slight oblique angle to, the ambient magnetic field. They are generated by the ion cyclotron instability, driven by 10–100 keV protons with anisotropic temperatures ($T_\perp > T_\parallel$) (Kennel and Petschek, 1966). EMIC waves can form in multiple bands corresponding to the ion cyclotron frequencies of H^+ , He^+ , and O^+ ions. Additional ion bands, such as He^{++} (Anderson and Fuselier, 1993; Engebretson et al., 2018), N^+ (Bashir and Ilie, 2021; Usanova et al., 2024), and O^{++} (Yu et al., 2021; Usanova et al., 2024), have also been reported. In this section, we highlight key aspects of EMIC wave interactions with cold plasma, which are explored more extensively in Usanova (2021).

Cold electron heating by oblique EMIC waves (Zhou et al., 2013; Yuan et al., 2014) may contribute to the formation of stable auroral red arcs (Cornwall et al., 1971; Thorne and Horne, 1992; Kozyra et al., 1997). EMIC waves can also heat He^+ ions, raising their energies from $\sim \text{eV}$ to ~ 100 eV (Young et al., 1981; Roux et al., 1982; Kim et al., 2023). Quasilinear theory shows that EMIC waves can similarly heat thermal O^+ ions at energies and pitch angles up to $\sim 80^\circ$ through multiple harmonic cyclotron resonances (Ma et al., 2019). EMIC waves have been suggested as a potential source of the warm plasma cloak (Gamayunov et al., 2024).

Nonlinear processes can generate secondary electrostatic waves, resulting in parallel heating of cold He^+ and H^+ ions (Omidi et al., 2010; Bortnik et al., 2010). Additionally, phase bunching effects can cause nonlinear energization of cold H^+ and He^+ ions (Kitamura et al., 2018; Abid et al., 2021; Li et al., 2023). Notably, the presence of cold ion populations can facilitate the nonlinear coupling of different wave modes, for example, the formation of lower hybrid waves through polarization drifts induced by EMIC waves (Khazanov et al., 2017). Gamayunov et al. (2014) emphasized the need to incorporate a nonlinear energy cascade from the ULF

to EMIC range, along with a dynamic model of plasmaspheric ion composition, into a global EMIC wave model.

Kinetic Alfvén waves

Kinetic Alfvén waves are a small-scale extension of shear Alfvén waves that include the kinetic behavior of ions and electrons. These waves travel along magnetic field lines, facilitating energy transfer throughout the magnetosphere. The theory of KAWs incorporates kinetic effects that become significant at spatial scales comparable to either the ion acoustic gyroradius or the electron inertial length, whichever is larger (Lysak, 2023). At these scales, the waves become dispersive and develop a parallel electric field. In spectrograms, KAWs appear as broadband electromagnetic emissions spanning frequencies from ~ 0 to kHz. They are known to be accelerators of electrons parallel to the geomagnetic field (Chen and Hasegawa, 1974) and of ions in the perpendicular direction (Johnson and Cheng, 2001).

KAWs have been observed in various magnetospheric environments, including the magnetopause (Lee et al., 1994), plasma sheet (Chaston et al., 2012), auroral regions (Goertz, 1984; Tian et al., 2022), and inner magnetosphere (Chaston et al., 2015a; b). In the inner magnetosphere, KAWs are most frequently observed during disturbed geomagnetic conditions, predominantly in the nightside local time sector down to $L \sim 3$ (Chaston et al., 2015a). Electromagnetic waves with similar characteristics have been detected in fast earthward flows in the plasma sheet at distances as far as $L \sim 12$, covering a large portion of the nightside magnetosphere (Ergun et al., 2015). These waves are often accompanied by enhancements in electron and ion temperatures (Ergun et al., 2022; Usanova and Ergun, 2022; Usanova et al., 2023a). Chaston et al. (2014) demonstrated that broadband electromagnetic waves can drive significant ion heating perpendicular to the background magnetic field at a rate of ~ 1 eV/s. Chaston et al. (2015b) reported measurements of energized outflowing ionospheric ions (ranging from tens of eV to >50 keV) and electrons heated to ~ 1 keV in the inner magnetosphere by KAWs. Suprathermal electron trapping has been suggested as a mechanism for electron acceleration to several keV (Artemyev et al., 2015).

KAWs likely play a critical role in controlling O^+ outflows along magnetic field lines into the equatorial inner magnetosphere through enhanced electron precipitation into the topside ionosphere, combined with subsequent transverse energization along magnetic field lines. The energized ionospheric O^+ ions can ultimately contribute to ring current enhancements (Chaston et al., 2016; Breneman et al., 2022).

Discussion: challenges and prospects in cold plasma research

Future efforts should address technological and scientific limitations in cold plasma research. Spacecraft charging presents a significant challenge for measuring cold plasma populations, often preventing low-energy particles from reaching detectors. Moreover, spacecraft-generated photoelectrons and secondary electrons

frequently obscure low-energy electron fluxes in the magnetosphere. Addressing these challenges requires the development of advanced instruments capable of reliably measuring cold plasma across the magnetosphere (Delzanno et al., 2023; Maldonado et al., 2023a; Maldonado et al., 2023b). These state-of-the-art instruments must also resolve the broadening of cold plasma energy distributions on timescales relevant to energization processes, with high temporal, angular, and energy resolution (Usanova et al., 2023b). Such plasma measurements are essential for characterizing, quantifying, and understanding the diverse impacts of cold particle populations on the magnetosphere. Additionally, they are crucial for improving physics-based magnetospheric plasma models, including cold electron density models (Ripoll et al., 2023). At a minimum, the development of models for cold electron and ion temperatures, which are currently lacking, is necessary. Advancing these models requires a detailed understanding of heating sources, their relative importance and spatial and temporal distributions.

Future research should prioritize the understanding and quantification of energy-exchange processes. This requires advancements in cold plasma measurement techniques to enable the simultaneous study of wave and cold plasma properties. Physics-based space weather models should incorporate wave-particle interactions to account for cold and warm plasma energization processes. Integrating machine learning techniques can further improve physics-based models' accuracy and predictive capabilities. Such integrated models can pave the way for a deeper understanding of cold and warm plasma dynamics and its impact.

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