



Energy Exchange Between Electromagnetic Ion Cyclotron (EMIC) Waves and Thermal Plasma: From Theory to Observations

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The cold plasmaspheric plasma, the ring current and the radiation belts constitute three important populations of the inner magnetosphere. The overlap region between these populations gives rise to wave-particle interactions between different plasma species and wave modes observed in the magnetosphere, in particular, electromagnetic ion cyclotron (EMIC) waves. These waves can resonantly interact with multiple particle species, being an important loss process for both ring current ions and radiation belt electrons, as well as a cold plasma heating mechanism. This mini-review will focus on the interaction between EMIC waves and cold and thermal plasma, specifically the role of EMIC waves in cold and thermal electron and ion heating. It will discuss early theoretical results in conjunction with numerical modelling and recent satellite observations, and address outstanding problems and controversies in this field.

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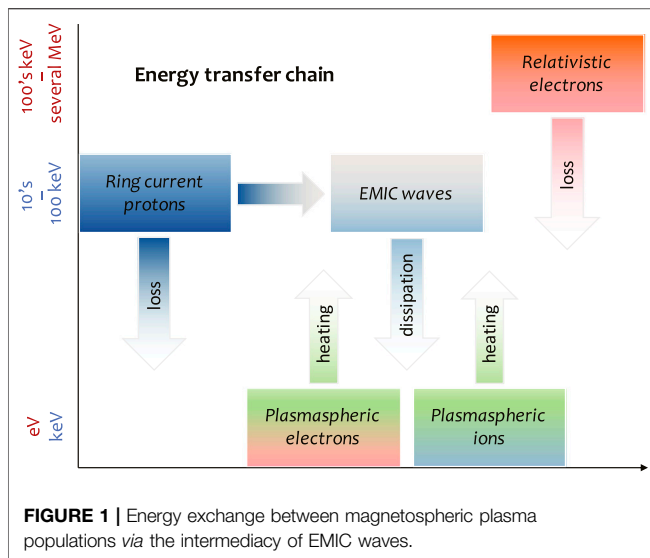
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INTRODUCTION

Electromagnetic ion cyclotron (EMIC) waves are transverse plasma waves generated in the equatorial magnetosphere by $\sim 10\text{--}100$ keV ion distributions with temperature anisotropy ($T_{\text{perp}} > T_{\text{para}}$, where perpendicular and parallel are defined with respect to the background magnetic field) (Cornwall, 1965). They are typically observed in space and on the ground in the Pc1-2 frequency range between 0.1–5 Hz, though can be observed even at higher frequencies deep in the inner magnetosphere (Sakaguchi et al., 2013). Minor ion species, helium and oxygen, also present in a magnetospheric plasma, produce forbidden band gaps for EMIC wave generation and propagation that split the wave spectrum into multiple branches below the H^+ , He^+ , and O^+ gyrofrequencies (e.g., Fraser, 1985). For each branch, the wave growth rate and cut-off frequencies are determined by a proton temperature anisotropy, ion composition, and cold plasma density (e.g., Kozyra et al., 1984). Statistical surveys from various satellite missions, covering the whole magnetosphere have reported EMIC wave observations throughout all magnetic local times (MLTs) and L-shells and examined their properties and occurrence distributions depending on geomagnetic conditions and solar wind drivers (Anderson et al., 1992; Denton et al., 2002; Fraser and Nguyen, 2001; Halford et al., 2010; Usanova et al., 2012; Keika et al., 2013; Meredith et al., 2014; Allen et al., 2015; Saikin et al., 2015; Wang et al., 2015; Jun et al., 2019; Grison et al., 2021).

Ions and electrons can resonantly interact with EMIC waves if the Doppler-shifted wave frequency (in the frame of reference of the particle) is equal to an integral multiple of the particle gyrofrequency: $\omega - k_{\parallel}v_{\parallel} = n\Omega/\gamma$, $n = 0, \pm 1, \dots$ where ω is the wave frequency, k_{\parallel} is the



parallel (to the background magnetic field, \mathbf{B}) wave number, v_{\parallel} is the electron parallel velocity, $\Omega = qB/m$ is the particle cyclotron frequency, and $\gamma = 1/\sqrt{1 - (v/c)^2}$ is the relativistic correction. Both the theory and the observations have shown that EMIC wave growth leads to the isotropization of the initially unstable proton distribution and consequent pitch-angle scattering and loss of protons into the atmosphere (see, e.g., Cornwall, 1965; Usanova et al., 2010; Søraas, et al., 2013; Yahnin et al., 2021). The condition for this resonance is satisfied if protons move along the field in the opposite direction to the waves. Interaction with EMIC waves is also believed to be an important loss mechanism for \sim hundreds keV–several MeV radiation belt electrons, which can undergo cyclotron resonance with EMIC waves and consequent pitch-angle scattering into the atmosphere through the anomalous Doppler-shifted cyclotron resonance (Horne and Thorne, 1998; Summers et al., 2007; Blum et al., 2015; Capannolo et al., 2021). Since EMIC waves are predominantly left-hand polarized, electrons must overtake the wave with a velocity sufficient to Doppler shift the wave frequency to the relativistic electron cyclotron, frequency reversing the relevant sense of polarization from left-to right-handed. Cyclotron resonance with energetic electrons and ions does not change particle energy, only resulting in scattering (momentum exchange) without energy coupling. EMIC waves can also experience Landau resonance, $\omega = k_{\parallel}v_{\parallel}$, which is most significant for highly-oblique EMIC waves due to the presence of a parallel component of the wave electric field (Thorne and Horne, 1992). Landau interactions usually lead to wave attenuation and energy transfer to \sim eV-ten's eV cold/thermal electrons (Cornwall et al., 1971; Horne and Thorne, 1998; Wang et al., 2019) and \sim keV ions (e.g., Omura et al., 1985; Kitamura et al., 2018) and also contribute to scattering of relativistic electrons (Wang et al., 2016; Fu et al., 2018). Finally, EMIC waves can undergo bounce resonance interactions with energetic electrons causing particle scattering (Cao et al., 2017; Blum et al., 2019). These resonant interactions take place when the electron bounce period (or integer number of such periods) matches the

wave period (Schulz and Lanzerotti, 1974; Shprits, 2009). As a result, EMIC waves act as an intermediary that couples energy and momentum between the cold/thermal, the hot and the relativistic plasma, as schematically shown in **Figure 1**.

The focus of this mini-review is the energy transfer between EMIC waves and cold and warm plasma populations and the role of EMIC waves in electron and ion heating. For other aspects of EMIC wave generation and the role of cold plasma in EMIC wave-particle interactions please refer to the following recently published relevant reviews. The effects of cold plasma density on EMIC wave growth and its role in energetic particle precipitation is highlighted in Usanova and Mann (2016) and Blum and Breneman (2020). The role of the plasmopause and cold plasma gradients for wave growth and ducting is discussed in Usanova et al. (2016); the review also examined wave characteristics in the source region, and considers the effect of plasma composition on the wave spectrum and propagation to the ground. The contribution of ionospheric ions in wave generation, propagation, and interaction with particles and the importance of cold ion composition measurements for new satellite missions to improve understanding of EMIC waves is addressed in Lee et al. (2021). The general questions of energy coupling between EMIC waves and cold plasma are outlined in Delzanno et al. (2021).

STABLE AURORAL ARCS AND LANDAU RESONANT HEATING OF THERMAL ELECTRONS

Stable auroral red (SAR) arcs are optical emission at predominately 630 nm observed in the mid-latitude ionosphere during periods of increased magnetic activity (Roach and Roach, 1963; Cornwall et al., 1971; Inaba et al., 2020). The red line corresponds to the excitation of atomic oxygen at \sim 400 km altitudes. Despite more than 50 years of research, the generation mechanism for SARs is still controversial and may be caused by the three possible processes: Coulomb collisions of plasmaspheric electrons with ring current ions (Cole, 1965; Kozyra et al., 1987; Fok et al., 1993; Inaba et al., 2020); heating the plasmaspheric electrons via Landau resonance with EMIC waves (Cornwall et al., 1971; Thorne and Horne, 1992; Zhou et al., 2013) and acceleration of plasmaspheric electrons into the ionosphere by kinetic Alfvén waves (Hasegawa and Mima, 1978).

Investigation of the role of EMIC waves in SAR arcs generation started with an early theoretical work by Cornwall et al. (1971) who proposed the following model. It involves energy transport between anisotropic ring current protons that serve as a source of free energy and excite EMIC waves inside the plasmopause and precipitate while the cyclotron waves are absorbed by plasmaspheric (1–10 eV) electrons. This increases the electron temperature in the direction parallel to the ambient field and leads directly to heat conduction into the ionosphere and drives SARs. The associated proton Coulomb dissipation warms plasmaspheric electrons to temperatures at which electron Landau damping becomes efficient and more prominent than

Coulomb scattering. The model predicts that SAR arcs are generated in a narrow region just inside the plasmapause (at L-shells from 2 to 4) that corresponds to their observed latitudinal extent in the ionosphere of several hundred kilometers. However, a later observational study by Kozyra et al. (1987) showed that the energetic, <20 keV O^+ ring current species can play a more important role than H^+ in the Coulomb scattering and can be responsible for heating of plasmaspheric electrons and SAR formation. Motivated by Kozyra et al. (1987), Thorne and Horne (1992) performed a wave ray tracing in a multicomponent plasma and confirmed that EMIC waves can play an important role in both the energy transfer to plasmaspheric electrons and the subsequent downward heat conduction to SAR arc altitudes. They demonstrated that EMIC waves can experience enhanced path integrated amplification along the steep plasmapause density gradient. Subsequently, when the wave propagation vector becomes highly oblique, absorption occurs during Landau resonance with thermal plasmaspheric electrons which requires an electron temperature above 1 eV. Coulomb scattering by energetic O^+ was suggested to act as the primer to heat plasmaspheric electrons for efficient ion-cyclotron wave absorption.

Further, Erlandson et al. (1993) presented simultaneous observations of EMIC waves and subauroral electron temperature enhancements on the polar orbiting DE-2 satellite and confirmed that EMIC waves were responsible for Landau heating the low energy electrons which precipitate to the ionosphere and produce ionospheric temperature enhancements. However, their observations could not pinpoint the heating region location and whether the electrons were heated at the ionospheric altitudes or near the equator. Zhou et al. (2013) observed EMIC waves generated by anisotropic 10–25 keV protons together with electron heating in the equatorial magnetosphere on THEMIS satellites. The observations were combined with calculations of the wave Landau damping rates due to the cold electron gyroresonance with EMIC waves. This work corroborated the original idea of Cornwall et al. (1971) as well as supported the possibility of equatorial electron heating by obliquely propagating EMIC waves.

Recently, Inaba et al. (2020) reported conjugate measurements of a SAR arc observed by an all-sky imager in Finland and the Arase satellite. The Arase observation shows that the SAR arc appeared in the overlap region between a plasmaspheric plume and the ring-current ions and that electromagnetic ion cyclotron waves and kinetic Alfvén waves were not observed above the SAR arc. These observations suggest that the heating of plasmaspheric electrons *via* Coulomb collision with ring-current ions is the most plausible mechanism for the SAR-arc generation. There was still a possibility that due to the measurements at ~30 degrees off the equator the waves might have reflected above the satellite location along the magnetic field line and therefore were not observed. However, this work strongly implies that the SAR generation mechanism is controversial and warrants further investigation.

The relationship between EMIC waves and electron heating in plasmaspheric plumes was investigated by Yuan et al. (2014). Using *in situ* Cluster observations, they found that the electron

heating was much stronger for field-aligned electrons, consistent with Landau damping predictions. Further, using theoretical calculations of the Landau resonant interaction between electrons and observed EMIC waves, they demonstrated that Landau damping of oblique EMIC waves is a reasonable candidate to heat cold electrons in plasmaspheric plumes.

Note that the studies based on the quasi-linear theory assume that EMIC waves are small in amplitude (in relation to the amplitude of the background magnetic field), experiencing multiple random-phase interactions with electrons which makes this process stochastic or diffusive. Since EMIC waves can exhibit nonlinear features, e.g., consisting of discrete elements that may have rising and falling tones, as well as high amplitudes, non-linear interactions are also necessary to consider (e.g., Nakamura et al., 2016; Shoji et al., 2021). The role of non-linear processes in energy exchange between EMIC waves and cold electrons was addressed by Wang et al. (2019) who conducted test-particle simulations and investigated the role of non-linear Landau resonance. They concluded that the nonlinear wave-particle interactions can occur at typical EMIC wave amplitudes (a few nT in magnetic and a few mV/m in electric field) and may play an important role in EMIC wave damping in the equatorial region, being more prominent than linear Landau damping, especially for obliquely propagating waves.

LANDAU HEATING OF THERMAL IONS (H^+ , HE^+ AND O^+)

Satellite measurements from different missions have shown that thermal (~10s to 100s eV) He^+ ions can be resonantly heated by EMIC waves in the direction perpendicular to the background magnetic field (e.g., Mauk et al., 1981; Roux et al., 1982; Mouikis et al., 2002). The role of EMIC waves in cold ion heating has been investigated using both quasi-linear theory and electromagnetic hybrid simulations, where ions are treated kinetically and electrons are treated as conducting fluid. The simulations focused on the self-consistent nonlinear evolution of EMIC waves in plasma consisting of electrons, protons, and He^+ and showed that the decrease of initial energetic proton temperature anisotropy results in EMIC wave growth and helium ion heating (Omura et al., 1985; Denton et al., 1993; Gary et al., 1994). Ma et al. (2019) presented Van Allen Probes observations of EMIC waves and He^+ and O^+ ions and explained the nature of EMIC wave interactions with thermal and energetic ions using a quasi-linear analysis. Their diffusion coefficient calculations indicate that H^+ -band EMIC waves can heat He^+ ions, while He^+ -band waves can energize O^+ ions at thermal energies and pitch angles up to ~80° through multiple harmonic cyclotron resonances. While thermal ions are heated in the transverse direction, the more energetic ring current ions are precipitated into the upper atmosphere through pitch angle scattering.

Anderson and Fuselier (1994) and Fuselier and Anderson (1996) examined H^+ and He^+ ion measurements in the 1–160 eV range on AMPTE/CCE to investigate the thermal ion response to the waves. They showed that for protons the perpendicular heating was modest, consistent with a non-resonant

interaction near the equator. By contrast, He⁺ energization was ~20 times stronger and peaked at pitch angles intermediate between field-aligned and perpendicular directions, consistent with a gyroresonant interaction off the equator. Omidi et al. (2010) and Bortnik et al. (2010) further examined the nonlinear evolution of EMIC waves using 2.5D hybrid simulations along with detailed test particle calculations. They found that the nonlinear evolution of EMIC waves involves generation of electrostatic waves with a wavelength half of that of the ion cyclotron waves and also results in parallel heating of cold He⁺ and H⁺ ions for substantially long periods.

The non-linear wave interactions with ions were recently investigated using high-resolution ion measurements on MMS spacecraft. Kitamura et al. (2018) presented the first observational evidence of energy transfer from energetic ring current protons to cold helium ions *via* EMIC wave-particle interactions confirming earlier simulation results. The wave-ion phase relations demonstrated that a cyclotron resonance transferred energy from 14–30 keV protons to waves, which in turn non-resonantly accelerated cold He⁺ to energies up to ~2 keV. Further, utilizing the same instrumentation and technique as in Kitamura et al. (2018), Abid et al. (2021) showed that 1–100 eV protons can also be non-linearly energized by EMIC waves through phase bunching.

CONCLUSION

Over the recent several decades of space exploration, significant progress has been made in understanding of

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energy transfer processes in the magnetosphere and the coupling between different plasma populations within this complex system. EMIC waves have been shown to act as an intermediary that couples energy and momentum between different energy magnetospheric plasma populations via various resonance mechanisms. High-resolution satellite observations, theory and self-consistent simulations have answered a lot of questions regarding the role of EMIC waves in Landau heating of plasmaspheric electrons and heavy ions. Despite the long history of research in this area, there are still open questions, for example, the role of EMIC waves in red auroral arc generation and the location of regions where the energy transfer predominately takes place. Recent studies have also underlined the significance of nonlinear processes in EMIC wave-particle interactions and placed emphasis on the potential to include those in global magnetospheric models which will be a next critical step towards predictive modeling.

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