



On the Impacts of Ions of Ionospheric Origin and Their Composition on Magnetospheric EMIC Waves

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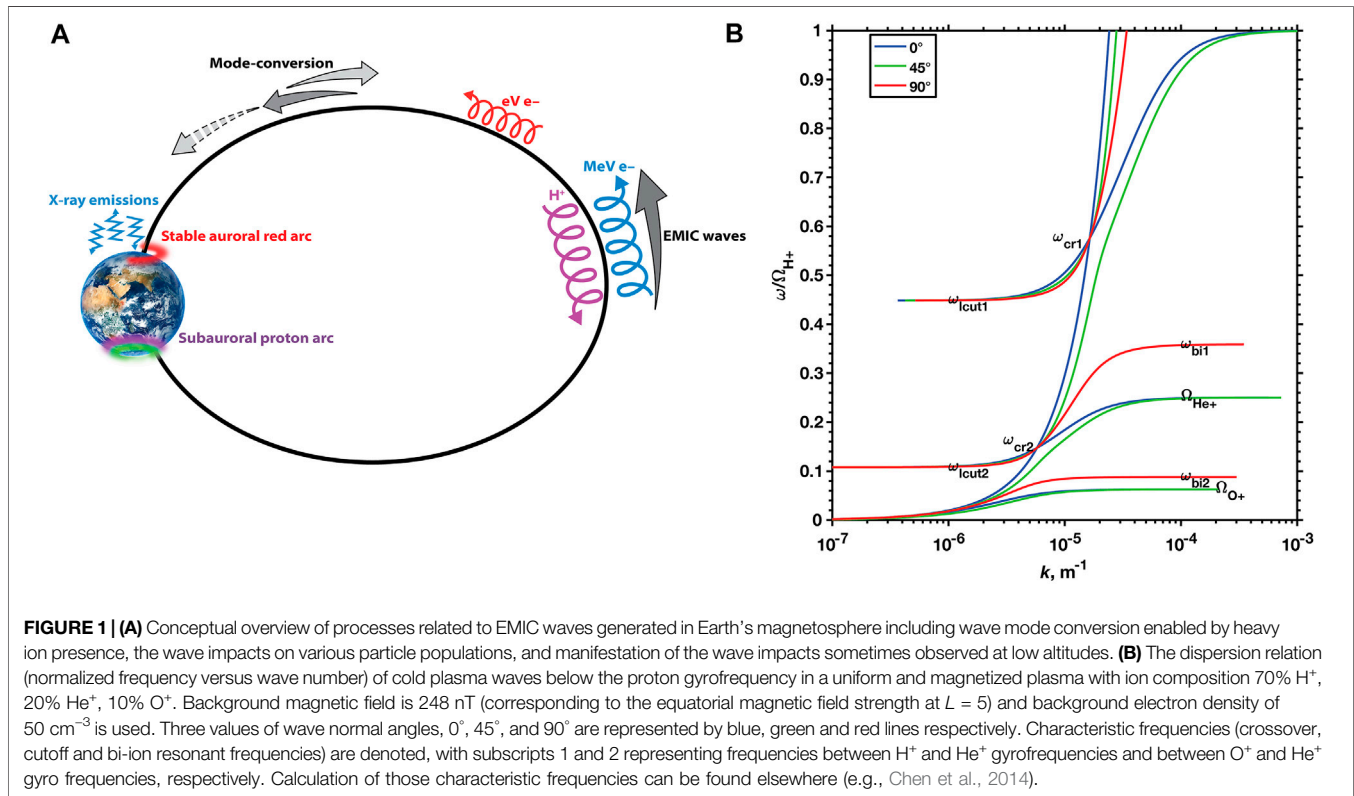
Large numbers of theory and observation studies have been conducted on electromagnetic ion cyclotron (EMIC) waves occurring in Earth's magnetosphere. Numerous studies have shown that accurately specifying the ions of ionospheric origin and their composition can greatly improve understanding of magnetospheric EMIC waves, specifically their generation, their properties, and their effects on the magnetospheric plasma populations. With the launch and operations of multiple recent missions carrying plasma instrumentation capable of acquiring direct measurements of multiple ion species, we use this opportunity to review recent magnetospheric EMIC wave efforts utilizing these new assets, with particular focus on the role of ions of ionospheric origin in wave generation, propagation, and interaction with particles. The review of progress leads us to a discussion of the unresolved questions to be investigated using future modeling capabilities or when new missions or instrumentation capabilities are developed.

Keywords: EMIC waves, cold plasma, wave-particle interactions, cold ions, energetic particle precipitation

INTRODUCTION

Electromagnetic ion cyclotron (EMIC) waves play a large role in magnetospheric dynamics, from heating of thermal plasma to scattering of radiation belt electrons into Earth's atmosphere (see Thorne et al., 2006, and references therein). **Figure 1A** illustrates some of the main processes involving EMIC waves in Earth's magnetosphere and **Figure 1B** provides an example of complex linear wave dispersion properties introduced when multiple ion species are present in the ambient plasma. Key to determining both wave properties themselves as well as wave impacts on various magnetospheric particle populations is a knowledge of the detailed plasma environment, including the cold ion populations that are often impossible to measure. In particular, ion density, temperature, and ion composition all play important roles in EMIC wave generation, propagation, and subsequent interaction with particles (Anderson et al., 1996; Anderson and Fuselier, 1994; Fuselier and Anderson, 1996; Kozyra et al., 1984; Gomberoff and Neira, 1983; Gomberoff et al., 1996; Gary et al., 2012; Chen et al., 2011; Silin et al., 2011; Lee et al., 2021, and references therein).

In the following sections, we outline recent progress towards understanding the influence of ions of ionospheric origin on EMIC waves both through theoretical, modeling and observational studies. Recent space missions, with improved data quality and data processing tools, have allowed for significant progress characterizing the occurrence and distribution of magnetospheric EMIC waves and the hot proton free energy source that is expected to drive wave generation. However, puzzles remain for developing a more complete understanding of EMIC wave generation and the effects of waves on magnetospheric particles, many centered around measurement challenges and a lack of



routine observations of the cold ion properties including the ion mass composition. These measurements are needed to characterize the variability of abundances of cold and hot ionospheric-originating ions in different magnetospheric regions so that improved understanding can be developed on how they impact wave generation and subsequent wave-particle interactions. Progress as well as remaining questions and challenges on these topics are presented in *Recent Progress and Challenges* Section, and future needs or opportunities discussed in *Discussion and Future Opportunities* Section.

RECENT PROGRESS AND CHALLENGES

Wave Generation and Properties

The large number of satellite missions flying magnetometers are supporting continued studies of EMIC wave properties throughout Earth's magnetosphere. The analysis methods utilized have become somewhat standardized across studies and capable computing systems allow for efficient processing of large spacecraft datasets. Following coordinate transformation routines, most EMIC wave studies rely on Fourier analysis to derive wave power and polarization spectra in the frequency-time domain for interpretation of the wave emissions properties needed to identify the occurrence and properties of EMIC waves. Low wave normal angle coupled with polarization spectra that rotate left-handed with respect to the dominant

geomagnetic field component are typically used to identify the presence and generation region of EMIC waves. This is because of linear dispersion theory and solutions that indicate the growth rate of EMIC waves typically maximizes for the left-handed circularly polarized (parallel propagating) mode (Gary et al., 2012 and references therein). When electric field measurements are also available, calculations of the Poynting vector properties in time or frequency domains are applicable to identifying possible wave generation regions and the properties of wave energy (e.g. Vines et al., 2019 and references therein).

Although magnetometer and electric field instrumentation continue to improve in capability, the role of the superposition of multiple wave packets that results in constructive/destructive interference to the detriment of wave analysis methods will continue to complicate analysis of wave properties and applications of the derived properties to investigating theories on wave generation (and propagation, discussed in a later section). For example, recent statistical and case studies showed that experimentally measured EMIC waves do not always have left-hand circular polarization and are often more linear or right-hand polarized, particularly on the morning side of the magnetosphere (Min et al., 2012; Allen et al., 2015; Allen et al., 2016; Saikin et al., 2015; Lee et al., 2019). Although EMIC wave polarization properties can evolve from left-handed to linear and then to right-handed during propagation through a region where wave frequency matches crossover frequencies (as noted by ω_{cr1} and ω_{cr2} in **Figure 1B**), wave superposition can be another reason

for the observed linear polarized wave spectra (Denton et al., 1996; Anderson et al., 1996; Lee and Angelopoulos, 2014a). But EMIC waves may also be generated with linear polarization under specific plasma conditions (Denton et al., 1992), the presence of cold heavy ions can favor the conversion of left-handed waves to linear (Hu et al., 2010), and cold proton presence may enable self-consistent generation of oblique EMIC waves with linear polarization (Toledo-Redondo et al., 2021). Verifying the occurrence of superposed wave packets is needed to further clarify the conditions when linear EMIC waves can grow preferentially. The importance of this extends to multi-satellite wave analysis methods (e.g. Balikhin et al., 2003; Bellan, 2016; Vines et al., 2021), in which recent studies showed superposed waves limit the effectiveness of multi-satellite wave vector determination (Lee et al., 2019, Lee et al., 2021). The application of wave properties not accounting for superposition can lead to misrepresentation of true wave properties, and this can be propagated when deriving particle pitch angle diffusion coefficients, for example, leading to inaccurate predictions of the effectiveness of EMIC waves in diffusing particles from high to low pitch angles. Future studies should identify and treat time intervals when superposed waves are likely with caution to ensure accurate characterization of EMIC waves.

Improvements to plasma instruments with ion mass discrimination have allowed for a small number of studies to consider and apply multiple ion species measurements to improve understanding of EMIC wave generation. Overall, there continue to be differing methods of utilization of available particle data for investigating EMIC wave generation. Adequate energy range of plasma instrumentation is needed to cover the ions and electrons relevant for EMIC wave studies. As summarized in **Table 1**, this is a broad energy range because EMIC waves can interact with cold and hot ions as well as cold/thermal and relativistic electrons. For hot, energetic (>keV) ions, a sufficiently broad instrument energy range supports accurate specification of the hot ion free energy for wave generation or the hot heavy ions that may damp the waves. Recent studies combining ion measurements from multiple instruments onboard a Van Allen Probes spacecraft have been able to calculate full ion moments (from ~1 eV to 600 keV), for comparison to quasilinear theory for EMIC wave growth (Yue et al., 2019; Noh et al., 2018, Noh et al., 2021). While these studies investigated the relationship of EMIC wave occurrence relative to the hot proton anisotropy, they focused on the role of protons and temperature anisotropy for providing free energy needed for wave instability. This is despite theory showing the importance of heavier ion species in defining the band structure as well as wave growth in each band generally organized by the heavy ion species (e.g. Kozyra et al., 1984; Denton et al., 2014). Provided the cyclotron resonance condition is met, it is possible that heavy ion species with temperature anisotropy could also contribute to wave growth below the corresponding ion gyrofrequency. These contributions of heavy ions to EMIC wave occurrence are pending additional investigation. Investigations of ion composition data with improved availability have shown how the relative flux of inner magnetosphere heavy ions changes with

geomagnetic activity (Kistler et al., 2006; Kistler et al., 2016). Similar trends were seen in the outer magnetosphere (Lee et al., 2021). Future efforts will continue to improve understanding how evolution of cold and energetic heavy ions with solar/geomagnetic activity affects EMIC wave growth. The cold ion species, however, are often problematic to characterize.

Measurements of the cold ion species supports the derivation of accurate cold (0–10 eV) ion moments of solar wind and ionospheric ion species for testing theory of linear wave growth. Routine cold ion measurements are necessary for accurately determining the times or magnetospheric regions where warm plasma effects influence wave growth and subsequent wave-particle interactions, as explored in modeling studies (Chen et al., 2011; Silin et al., 2011). But because of spacecraft positive charging effects, cold ion measurements are often challenging to make and are not available routinely. Active spacecraft potential control (ASPOC) is one method that helps mitigate the positive charging effect (Torkar et al., 2016), decreasing the amount of positive charging but not completely neutralizing it. Few eV ions remain unmeasured most of the time except when plasma bulk flows and ULF waves assist with accelerating these ions above the remnant spacecraft potential energy (André and Cully, 2012; Engwall et al., 2009; Lee et al., 2012, Lee et al., 2019, Lee et al., 2021). Continued efforts (Zurbuchen and Gershman, 2016; Toledo-Redondo et al., 2019; Barrie et al., 2019) to overcome this charging problem can improve understanding of the contribution of cold ions and their mass composition to the generation of EMIC waves and their properties. In the absence of wave measurements themselves, a linear theory proxy based on a proton-electron plasma and the bulk plasma parameters that can be extracted from spacecraft datasets has helped identify when EMIC wave growth is likely (Allen et al., 2016; Blum et al., 2009, Blum et al., 2012); though this proxy method does not always yield agreement, predicting wave growth when no waves were observed (Lin et al., 2014; Zhang et al., 2014). It may be possible that future improvements to this proxy through inclusion of additional measurable ion population parameters can be helpful for interpreting EMIC wave generation.

In addition to EMIC waves characterized in terms of linear theory, triggered (or rising tone) nonlinear EMIC wave emissions are known to evolve out of the linear instability and associated cut-off wave frequencies determined by the ion composition (Omura et al., 2010). The subsequent nonlinear growth of the triggered emissions at their source region is determined by the frequency sweep rate that is proportional to the wave group velocity, which is again influenced by the ion composition. A few studies on observations or simulations of triggered emissions have used estimated or assumed ion composition to investigate the magnetospheric conditions supporting these nonlinear emissions (Pickett et al., 2010; Shoji and Omura, 2013; Grison et al., 2013; Nakamura et al., 2015; Grison et al., 2016, Nakamura et al., 2016). It remains unknown the role of ion composition in nonlinear wave evolution. More frequent and accurate measurements of comprehensive ion composition will support additional studies of nonlinear growth of EMIC waves.

TABLE 1 | Summary of relevant desired particle and field observations for future EMIC wave studies, including instrument challenges for making these measurements.

Observation	Dynamic Range	Measurement details	Measurement challenges	Potentially relevant past instruments
Low-energy/cold ions	0–100 s eV	<ul style="list-style-type: none"> • Mass discrimination • Charge state • Pitch angle distributions 	Remedies for positive spacecraft charging, sufficient sensor geometry factor and collection time	DE 1 IMS, e-POP IRM, Cluster CODIF, RBSP HOPE, MMS HPCA, Arase LEPI
Hot ions	100 s eV–100 keV	<ul style="list-style-type: none"> • Mass discrimination • Charge state • Pitch angle distributions 	Cross-calibration of ion instruments covering broad energy range	RBSP HOPE + RBSPICE, MMS HPCA + EIS, Arase LEPI + MEPI
Low-energy/cold electrons	0–100 s eV	<ul style="list-style-type: none"> • Differential energies • Pitch angle distributions 	Remedies for spacecraft-emitted photoelectrons and secondary electrons	RBSP HOPE, MMS FPI, Arase LEPE, e-POP SEI
Hot/relativistic electrons	100 s keV—several MeV	<ul style="list-style-type: none"> • Differential energies • Pitch angle distributions 	Loss cone resolution	RBSP MagEIS/REPT, MMS FEEPS, Arase XEP
Magnetic and electric fields	DC—200 Hz sampling frequency	<ul style="list-style-type: none"> • Vector E and B measurement • Simultaneous field measurement capability 	3rd (axial) component of E field	RBSP EFW, MMS FIELDS, SWARM ASM, THEMIS FGM/EFI

Finally, recent studies have utilized multipoint measurements and simultaneous wave, hot, and cold plasma measurements to explore the spatio-temporal structure of EMIC wave active regions and their relation to plasma structures (Engebretson et al., 2018; Blum et al., 2017). Coordinated EMIC wave measurements at multiple local times, radial distances, as well as on the ground have revealed that these waves are often radially narrow but extended in time and azimuth (e.g. Mann et al., 2014; Paulson et al., 2014; Blum et al., 2020). Direct associations between EMIC waves and hot ion structures, such as particle injections, have been found across the dusk-side magnetosphere (Remya et al., 2018; Jun et al., 2019; Chen et al., 2020; Blum et al., 2015; Remya et al., 2020), whereas other studies observe EMIC waves well-confined to cold plasma density enhancements and gradients (Usanova et al., 2014; Tetrick et al., 2017; Blum et al., 2020; Yuan et al., 2019). Coordinated multipoint measurements and improved orbital configurations aid in mapping out the spatio-temporal properties of EMIC waves, needed for quantifying their impact on energetic particle populations as discussed more in *Wave Effects* Section, while comprehensive wave and plasma measurements can help reveal the drivers of the wave spatial and temporal properties.

Wave Propagation

EMIC waves of magnetospheric origin have been measured by ground magnetometers and fall into the Pc1-2 (continuous pulsation) frequency range. Magnetically conjugate observations have confirmed that equatorially-generated EMIC waves can propagate all the way to the ground (e.g. Usanova et al., 2008, and references therein). But this is not always the case, particularly during the main phase of geomagnetic storms when a distinct lack of Pc1-2 waves is observed at ground magnetometers compared to *in situ* observations (Engebretson et al., 2008; Posch et al., 2010). Ray tracing of EMIC waves suggests as waves propagate from the equator, the waves should become oblique and eventually reflect at middle magnetic latitude when the wave frequency falls just below the bi-ion hybrid resonant frequency (Rauch and Roux, 1982; Horne and Thorne 1990; Rönnmark and André, 1991; Chen et al., 2014). This bi-ion hybrid resonant

frequency (e.g., ω_{bi1} and ω_{bi2} depicted in **Figure 1B**) is also known as the Buchsbaum resonance (Buchsbaum, 1960) and defines a forbidden region of wave propagation. But several potential mechanisms can explain the access of EMIC waves to low altitudes. First, full wave simulations (e.g. Kim and Johnson, 2016) suggest waves can tunnel through the evanescent region via mode conversion at locations where the wave frequency matches the local crossover frequency (e.g. ω_{cr1} and ω_{cr2} depicted in **Figure 1B**). Second, left-handed O^+ band EMIC waves can propagate along the field line toward higher magnetic field regions without being subject to bi-ion hybrid resonance (since O^+ ions are the presumed heaviest ions in the magnetosphere). Third, density irregularities and gradients, such as at the plasmopause (e.g. Chen et al., 2009; de Soria-Santacruz et al., 2013) can keep the EMIC wave normal more or less aligned with the magnetic field, and therefore avoid encountering of the bi-ion hybrid resonance which occurs at perpendicular propagation. Further investigations of the plasma conditions resulting in EMIC wave propagation to the ground, and their dependence on location and geomagnetic activity, will enable us to improve understanding of these phenomena.

Based on known and theorized properties of propagating EMIC waves, satellite wave observations have also been used to infer information about the local plasma environment. The propagation of EMIC waves to and across local crossover frequencies in a multi-ion plasma can allow waves to achieve linear or right-handed polarization. Thus, under certain assumptions on wave generation, wave properties from Fourier spectra and the possibility of crossover frequencies enabling mode-conversion during propagation have been used to infer the ion composition or presence of minor ion species in Earth's magnetosphere (Min et al., 2015; Miyoshi et al., 2019; Engebretson et al., 2018; Bashir and Ilie, 2021). Wave modeling and mode conversion at the bi-ion hybrid resonance has also been presented as a method to derive magnetospheric ion composition (E. H. Kim et al., 2015). While event studies have suggested the presence of He^{++} (Engebretson et al., 2018; Lee et al., 2019), N^+ (Bashir and Ilie, 2021), as well as the more typically assumed O^+ and He^+ species, direct observations of

these ions are often lacking, posing challenges for verification of these techniques to infer ion composition from the properties of propagated EMIC waves. Very few examples exist showing that the ion composition derived using wave spectra in the vicinity of the crossover frequency is consistent with the measured ion composition due to the cold ion populations being partially hidden from detectors because of spacecraft positive charging (Fuselier and Anderson, 1996; Lee and Angelopoulos, 2014b; Lee et al., 2019). Because of various complexities in wave analysis, it would be helpful to future EMIC wave studies to consider particle measurements to support interpretation of wave propagation and mode conversion.

Wave Effects

EMIC waves can interact with a broad range of particle populations in the inner magnetosphere, through cyclotron or Landau resonance as well as non-resonant or nonlinear interactions. Through these interactions, the waves can impact electrons or ions spanning orders of magnitude in energy. We focus on the wave effects on energetic particles in this review and refer the reader to a companion paper dedicated to interactions of EMIC waves with thermal plasmas (M. E. Usanova, submitted to this issue, *Energy exchange between EMIC waves and thermal plasma: from theory to observations*).

It is known that the anomalous resonance condition between left-handed EMIC waves and electrons requires electrons (usually in the relativistic energy range) to overtake the EMIC waves so that in the frame of moving electron gyrocenter the wave polarization is seen as right-handed and the Doppler-shifted wave frequency matches the electron gyrofrequency (conceptualized in **Figure 1A**). For such a condition to be satisfied, EMIC waves with sufficiently large wavenumber ($k_z = \Omega_{ce}/v_z$) are required. In the cold plasma limit with sufficient He^+ ions, He^+ band waves just below the He^+ gyrofrequency attain large wave numbers, and therefore have been proposed as a potential candidate for resonating with relativistic electrons and producing scattering loss (Lyons and Thorne, 1972; Summers and Throne, 2003; Ukhorskiy et al., 2010; Thorne and Kennel, 1971; Shprits et al., 2016). Observational evidence of relativistic electron precipitation in association with EMIC waves has been reported by an increasing number of recent studies (e.g. Rodger et al., 2008; Li et al., 2014; Blum et al., 2015; Blum et al., 2019; Lessard et al., 2019; Qin et al., 2019; Sigsbee et al., 2020; Kim et al., 2021). However, the cold plasma approximation may fail near the He^+ gyrofrequency, and the warm plasma effect of He^+ ions on wave growth should be considered. Spacecraft observations suggest warm plasma effects may be relevant in the inner magnetosphere (Lee et al., 2012) and the inclusion of warm plasma effects in modeling (Chen et al., 2011; Silin et al., 2011; Ni et al., 2018) shows that the excitation of He^+ band waves near the He^+ gyrofrequency tends to require reduced He^+ ion density, and once generated, the warm plasma EMIC waves possess much smaller wavenumber than expected from cold plasma theory. Both points limit the capability of EMIC waves resonating with electrons ≤ 1 MeV. At the same time, sub-MeV electron precipitation associated with EMIC waves has been reported with statistical lower cut off

energy down to 300 keV (e.g. Hendry et al., 2020; Capannolo et al., 2019). Many of the low Earth orbit (LEO) satellite observations used to infer the electron precipitation caused by EMIC waves have not been energy-resolved and future direct measurements will continue to help characterize the spectrum of energetic electrons impacted by EMIC waves (cf. Hendry et al., 2016). Nonetheless, the unexpectedly low (~ 100 s keV) energy of electrons precipitated by EMIC wave interactions may be explained by a non-resonant scattering mechanism (Chen et al., 2016), when the electrons below the cyclotron resonant energy are also subject to effective scattering due to spatial structure of the EMIC wave packet. Another potential mechanism proposed by Denton et al., 2019 is the resonant interaction of electrons with low amplitude short-wavelength EMIC waves in the H^+ band (with frequency above the He^+ gyrofrequency), though it is unclear how often magnetospheric conditions allow for the generation of such waves. Observations of two components of electric field and three components of magnetic field have been applied to estimate wavenumber of EMIC waves and statistical analysis showed that H^+ band waves carry shorter wavenumber than He^+ band waves, suggesting that H^+ band waves are more likely to resonantly interact with MeV electrons and below (Chen et al., 2019a). Recent magnetospheric studies have observed evidence of EMIC wave scattering within the trapped MeV electron population near the magnetic equator, showing bite-outs at low pitch angles as well as local minima in phase space density profiles concurrent with EMIC wave activity (e.g. Bingley et al., 2019; Usanova et al., 2014; Shprits et al., 2017; Blum et al., 2020). Furthermore, nonlinear electron scattering due to EMIC waves manifested in fine-scale pitch angle distribution variation in association with EMIC waves (Zhu et al., 2020). The electron pitch angle distribution showed a reverse slope with a secondary flux peak near the loss cone at times when intense EMIC waves were present, which may be explained by competition of nonlinear phase bunching that transports electrons from low pitch angle to moderate pitch angle (Albert and Bortnik, 2009), nonlinear loss cone reflection (Su et al., 2012; Chen et al., 2016) that prevent electron scattering into the center of loss cone (e.g., zero pitch angle), and diffusive transport. These collective studies show that the frequency distribution of EMIC waves, as well as cold and warm ion populations, play major roles in determining the effectiveness of these waves in scattering and precipitation loss of energetic electrons to the atmosphere, and pitch-angle and energy-resolved measurements of energetic electrons both near the equator as well as at LEO can help confirm theoretical EMIC wave impacts on radiation belt populations. The future measurements important for characterizing the magnetospheric plasma, EMIC waves, and distribution of trapped electrons impacted by the waves are summarized in **Table 1**.

Although many studies discuss the interactions of EMIC waves with radiation belt electrons, the waves are also believed to have major effects on energetic protons in the ring current or plasma sheet, leading to their precipitation to the ionosphere where the precipitated protons may cause significant impacts to ionospheric electrodynamics. Frey et al., 2004 investigated subauroral morning proton spots (SAMPS) that were thought to be evidence of localized

but intense interactions of EMIC waves with ring current protons in association with plasmaspheric refilling after geomagnetic storms. Fuselier et al., 2004 and Spasojevic and Fuselier (2009) also explored sub-auroral proton precipitation through use of IMAGE FUV images and their association with plasmaspheric plumes in the afternoon sector. Yahnin et al., 2007 showed conjugate ground-based observations with low altitude proton measurements to confirm the role of EMIC waves as the mechanism leading to these subauroral proton spots. Such precipitation images can help map out spatial and temporal evolution of EMIC wave active regions. In addition to localized interactions, modeling studies investigated cyclotron resonant interactions of EMIC waves with central plasma sheet protons (Cao et al., 2016) to indicate protons in this magnetosphere region can be efficiently scattered by EMIC waves. Model-data investigations of proton field-line curvature (FLC) scattering were unable to reproduce measurements of enhanced proton precipitating flux at low altitude and suggested that proton scattering by EMIC waves should be considered (Chen et al., 2019b). Additional modeling work investigating the combined effects of FLC and EMIC wave scattering showed that protons scattered by EMIC waves significantly impact ionospheric electrodynamics at afternoon to dusk MLTs comparable to the electron precipitation dominant between pre-midnight to morning MLTs (Zhu et al., 2021). The LEO satellites that provided the measurements of proton precipitating flux for the above studies could be improved by expanding the energy range and spectral resolution of instrumentation. In addition, orbital coverage and networking with existing missions could enable continued studies of the asymmetric input of energetic particle flux into the ionosphere that requires resolving temporospatial processes. These future efforts will enable us to understand the quantitative effects of magnetospheric EMIC waves on the coupled magnetosphere-ionosphere system and how those effects change as functions of solar or geomagnetic activity and magnetosphere-ionosphere regions.

DISCUSSION AND FUTURE OPPORTUNITIES

A variety of recent missions have provided opportunities to launch scientific instrumentation and apply them to investigations of EMIC waves throughout Earth's magnetosphere. An ideal measurement suite for investigating EMIC waves has been summarized in **Table 1**, along with challenges for future instrumentation. In addition to developments to necessary instrumentation, future space

science missions could investigate various questions remaining related to the generation and effects of EMIC waves on magnetospheric plasma populations and potential subsequent effects on the ionosphere. To make significant progress on this topic, constellation-class missions are required. The waves should ideally be observed in their source regions in the magnetosphere and distributed members of the satellite constellation could then be able to observe how the generated waves:

1. Propagate from magnetospheric source regions to higher latitudes and often to the ground.
2. Impact trapped particle populations so that an improved quantitative understanding of EMIC wave effectiveness on particle scattering (and heating) can be developed.
3. May result in time-dependent impacts on the ionosphere and its electrodynamics.

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JL was employed by the company The Aerospace Corporation, a nonprofit corporation incorporated under the General Non-Profit Corporation Laws of the State of California.

AUTHOR CONTRIBUTIONS

JL coordinated the overall preparation of the manuscript. JL and LB focused on the review of recent observations and LC focused on the review of recent developments in theory and modeling. All authors contributed to manuscript revision, read, and approved the submitted version.

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