frontiers | Frontiers in Astronomy and Space Sciences

MINI REVIEW
published: 14 April 2022
doi: 10.3389/fspas.2022.867394

ULF Wave Modeling, Effects, and Applications: Accomplishments, Recent Advances, and Future

Michael D. Hartinger[1*†], *Kazue Takahashi*[2†], *Alexander Y. Drozdov*[3†], *Xueling Shi*[4,5†], *Maria E. Usanova*[6†] *and Brian Kress*[7†]

[1]Space Science Institute, Center for Space Plasma Physics, Boulder, CO, United States, [2]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, United States, [3]Earth, Planetary, and Space Sciences Department, UCLA, Los Angeles, CA, United States, [4]Virginia Tech, Department of Electrical and Computer Engineering, Blacksburg, VA, United States, [5]High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, United States, [6]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, United States, [7]National Oceanic and Atmospheric Administration, National Centers for Environmental Information, Boulder, CO, United States

Ultra Low Frequency (ULF) waves play important roles in magnetosphere-ionosphere coupling, ring current and radiation belt dynamics, and modulation of higher frequency wave modes and energetic particle precipitation. The “ULF wave modeling, effects, and applications” (UMEA) focus group - part of the Geospace Environment Modeling effort from 2016 to 2021 - sought to improve understanding of the physics of ULF waves and their specification in geospace models. Through a series of in person and virtual meetings the UMEA focus group brought modelers and experimentalists together to compare ULF wave outputs in different models, plan observation campaigns focused on ULF waves, discuss recent advances in ULF wave research, and identify unresolved ULF wave science questions. This article summarizes major discussion points and accomplishments in the UMEA focus group over the last 6 years, recent advances and their connection to Richard Thorne and Peter Gary’s significant contributions to ULF wave research, and the future of ULF wave research.

Keywords: ULF wave, pulsation, field line resonance, magnetosphere-ionosphere coupling, solar wind-magnetosphere coupling, EMIC wave, radiation belt, radial diffusion

Edited by:
Charles William Smith, University of New Hampshire, United States

Reviewed by:
Kristoff Paulson, Harvard University, United States

***Correspondence:**
Michael D. Hartinger
mhartinger@spacescience.org

†These authors have contributed equally to this work and share first authorship

Specialty section:
This article was submitted to Space Physics, a section of the journal Frontiers in Astronomy and Space Sciences

Received: *01 February 2022*
Accepted: *28 February 2022*
Published: *14 April 2022*

Citation:
Hartinger MD, Takahashi K, Drozdov AY, Shi X, Usanova ME and Kress B (2022) ULF Wave Modeling, Effects, and Applications: Accomplishments, Recent Advances, and Future. Front. Astron. Space Sci. 9:867394. doi: 10.3389/fspas.2022.867394

1 INTRODUCTION TO ULF WAVES

Ultra Low Frequency (ULF) waves are the lowest frequency plasma waves in the Earth’s magnetosphere, with frequencies from 0.001–5 Hz (Jacobs et al., 1964). At the lower end of the ULF band, waves are often well described using a magnetohydrodynamic (MHD) approximation and include eigenmodes with wavelengths comparable to the size of the magnetosphere. Higher frequency ULF waves include electromagnetic ion cyclotron (EMIC) waves, and these are better described with other mathematical approximations (e.g., local linear kinetic theory Gary et al., 1995). ULF waves play important roles in magnetosphere-ionosphere (MI) coupling (e.g., Keiling, 2009), ring current/radiation belt dynamics (e.g., Turner et al., 2012; Kress et al., 2013; Murphy et al., 2015), modulation of VLF waves/precipitation (e.g., Li et al., 2011; Brito et al., 2015; Jaynes et al., 2015), geomagnetically induced currents (GIC) (e.g., Heyns et al., 2021), substorms (e.g., Kepko and Kivelson, 1999; Liang et al., 2009; Keiling and Takahashi, 2011), and other areas relevant to space weather prediction. They are an important component of geospace environment models and thus relevant to the Geospace Environment Modeling (GEM) effort, a community driven effort supported by the United States National Science Foundation that seeks to improve our understanding of the geospace environment, including solar wind-magnetosphere-ionosphere coupling via ULF waves.

The GEM "ULF wave modeling, effects, and applications" (UMEA) focus group (FG) formed in 2016 and ran through 2021. This focus group was motivated by (1) unprecedented availability of coordinated, multi-point space and ground-based observations (e.g., Hartinger et al., 2013; Takahashi et al., 2013), (2) high quality particle and field measurements of ULF wave-particle interactions (e.g., Claudepierre et al., 2013), (3) new and improved simulations better able to capture the excitation and dynamics of ULF waves (e.g., Claudepierre et al., 2010; Lysak et al., 2015) and (4) an ongoing effort in the GEM community to improve models of ULF waves. UMEA's goal was to bring modelers and experimentalists together to address the following questions: What excites ULF waves? How do ULF waves couple to the plasmasphere, ring current, and radiation belt populations? What is the role of ULF waves in MI coupling? This mini-review describes the recent advances in ULF wave research discussed in the UMEA FG from 2016 to 2021, including improved abilities to simulate ULF waves. It also discusses future directions in ULF wave research needed to improve the specification of ULF waves in models. Finally, it connects current and future work to the many important contributions from Richard Thorne and Peter Gary to ULF wave research, including EMIC waves, ULF modulation of Very Low Frequency (VLF) waves, and radiation belt wave-particle interactions.

2 WHAT EXCITES ULF WAVES?

Recent work is revealing new information about the manner in which upstream pressure disturbances with different spatial scales and orientations couple to magnetospheric ULF waves. Oliveira et al. (2020) showed how interplanetary shocks with different impact angles drive ULF waves with different properties. Multi-satellite investigations have yielded new insights into the large spatial scales over which upstream pressure disturbances can drive EMIC waves (Engebretson et al., 2018). Numerous studies have been conducted examining the role of ion foreshock disturbances (e.g., Wang et al., 2020a) and magnetosheath jets (e.g., Archer et al., 2019) in driving ULF waves with different properties. However, there remain few statistical studies that make one-to-one comparisons between ion foreshock or magnetosheath disturbances and ULF waves, limiting our understanding of the properties of such waves; more studies are needed that make use of multi-satellite/multi-constellation measurements. UMEA discussions also indicate that more modeling work is needed to determine how the spatial scale and speed of the upstream pressure disturbance affects ULF wave properties; most past modeling work has focused on two extremes—disturbances across the entire magnetopause or infinitesimal disturbances over a very small section of the magnetopause—whereas observations indicate a wide range of possible spatial scales and speeds on the magnetopause. Recently developed 3D ULF wave models indicate that the 3D properties of Alfven resonances depend on the external driver properties, and that standing Alfven waves and field line resonances in 3D geometries have unique properties that can differ from 2D model predictions (Elsden and Wright, 2017; Elsden and Wright, 2018). Finally, north-south and east-west asymmetries in upstream pressure disturbances can profoundly impact ULF wave properties in the magnetosphere (e.g., Shen et al., 2018; Wang et al., 2019; Oliveira et al., 2020), and more models and globally distributed observations are needed to understand how these asymmetries ultimately affect global wave properties and in turn predict what types of wave-particle interactions may occur in the inner magnetosphere. Energetic particle measurements are increasingly being used as an additional tool to remote sense wave mode structure and local time variations in wave properties (e.g., Hao et al., 2020; Zhao et al., 2020).

ULF waves can also be excited by mechanisms internal to the magnetosphere, including the magnetotail where plasma bubbles convecting earthward produce Pi2-band oscillations (Wang C. P. et al., 2020), buoyancy waves are excited (Wolf et al., 2018), and the ring current where high-m poloidal waves (Shi et al., 2018b; Zhai et al., 2021) and compressional Pc5 waves (Soto-Chavez et al., 2019) are excited. Significant advances have been made in spacecraft measurements of the wave mode structure, particle resonances with the waves, and unstable ion phase space density. New information on the global extent and azimuthal wave number has become available using HF radar (e.g., Shi et al., 2018a) and GPS TEC techniques (e.g., Watson et al., 2015). On the theoretical side, models have been developed for poloidal wave mode structures incorporating finite ion pressure (Xia et al., 2017), and a gyrokinetic code has been developed to simulate excitation of poloidal waves in a dipole magnetosphere (Yamakawa et al., 2019). Numerical simulations that combine MHD background and kinetic particle effects might be a logical direction in future studies of internally excited ULF waves.

3 HOW DO ULF WAVES COUPLE TO THE PLASMASPHERE?

Cold plasmapheric plasma can affect ULF wave generation and propagation. In relation to wave propagation, there has been an ongoing debate whether the plasmapause can serve as a barrier to ULF waves, controlling the radial extent of ULF wave power propagation, as previously suggested (e.g., Lee et al., 2002; Hartinger et al., 2010). However, a recent study by Sandhu et al. (2021) demonstrated no clear evidence for a sharp reduction in wave power across the plasmapause. Instead, it uncovered trapping of highly enhanced wave power in plasmaspheric plumes during disturbed geomagnetic conditions, giving a deeper insight into the storm-time ULF wave dynamics and contributing to modelling efforts of ULF wave driven radial diffusion during geomagnetically active periods.

In turn, ULF waves can have an effect on cold plasma. Plasmaspheric electrons and ions were found heated and their fluxes modulated by ULF waves. It was suggested that ~1 eV ions can be energized by 10–100 times by ULF wave electric fields due to betatron acceleration (Yue et al., 2016) and E × B drift (Zhang S. et al., 2019). Zong et al. (2012) presented observations of simultaneous plasmaspheric O+ ion enhancements and ULF waves, suggesting ULF waves can interact with oxygen torus ions. In addition, more recent studies (e.g., Ren et al., 2019, and references therein) reported acceleration of cold plasmaspheric electrons by ULF waves through drift-bounce resonance. Overall, this intermediate energy population (a few eV to hundreds of eV) also known as warm plasma cloak (Chappell et al., 2008) has been actively investigated over the past few years (Borovsky and Valdivia, 2018; Delzanno et al., 2021).

Interactions between cold plasma and EMIC waves were also actively discussed in the UMEA FG, with much of the work motivated by the many significant contributions of Peter Gary and Richard Thorne to EMIC wave research, including the factors controlling their generation (plasma temperature, temperature anisotropy, ion composition), storm time evolution, and effect on a wide range of ion and electron populations (Gary, 1992; Gary et al., 1994, 1995; Thorne and Horne, 1992, 1997). EMIC 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. They can couple energy and momentum between magnetospheric plasma in a wide energy range, from a few eV to several MeV. Similarly to ULF waves, there is a two-way relationship between EMIC waves and cold plasma. Plasmaspheric plasma density and ion composition controls EMIC wave growth and propagation, as well as the energy of energetic particles in resonance with EMIC waves (e.g., Usanova et al., 2016; Usanova and Mann, 2016; Blum and Breneman, 2020). Nosé et al. (2020) found a close relationship between EMIC wave occurrence and the structure of the oxygen torus. EMIC waves can heat plasmaspheric ions, as predicted earlier by theory and simulations and confirmed by state-of-the-art MMS satellite measurements (Kitamura et al., 2018; Abid et al., 2021). These new findings point to the importance of cold ion composition measurements for new satellite missions (Lee et al., 2021). Recent studies have also emphasized the role of nonlinear processes in EMIC wave-particle interactions and the potential to include those in global magnetospheric models which will be a next crucial step towards predictive modeling (Usanova, 2021, and references therein).

4 HOW DO ULF WAVES COUPLE TO THE RING CURRENT?

ULF waves also play an important role in the dynamics of higher energy ring current particles. This includes storm time intervals through interaction with ring current ions via drift-bounce resonance. However, the energy transfer between magnetospheric particles and ULF waves through wave-particle interactions has been mostly excluded from models of ring current dynamics. Based on drift-kinetic simulations, Yamakawa et al. (2019) and Yamakawa et al. (2020) showed that high-m Pc3-5 ULF waves can be excited through the drift-bounce resonance by ring current ions associated with the injection from the magnetotail. Oimatsu et al. (2018) showed in a Van Allen Probes case study that energy transfer from the ring current protons to the poloidal Pc4 wave via the drift-bounce resonance contributes up to 85% of the increase in the Dst* index, where Dst* is the solar wind pressure-corrected Dst index. Recent studies have shown that ULF waves can interact with relativistic electrons and ring current ions at the same time (e.g., Yang et al., 2010; Ren et al., 2016). Multiple drift and/or drift-bounce resonances can occur with different plasma species or the same species at different energies simultaneously (Rankin et al., 2020). Since ULF waves can interact with various magnetospheric particle populations (sometimes simultaneously), including the plasmaspheric electrons, ring current ions, and radiation belt energetic electrons, it is still a question if and how ULF waves mediate coupling between different particle populations (Zong, 2021). The incorporation of ULF wave-particle interactions into ring current models is therefore an important target for future studies, and improved energy budgets are needed to quantify the impact of these waves on the ring current.

Higher frequency EMIC waves are also related to ring current dynamics. Anisotropic ring current proton distributions with Tperp>Tpara (with respect to the background magnetic field) provide the source of free energy for EMIC instability (Cornwall, 1965; Horne and Thorne, 1993). Energetic He+ and O+ ring current species, abundant in the magnetosphere during geomagnetically active times, can absorb the wave energy and split the EMIC wave spectrum into multiple sub-bands. The wave growth rates and cut-off frequencies of each sub-band are determined by the hot ion temperature anisotropy, ion composition, and cold plasma density (Kozyra et al., 1984). As the EMIC wave instability evolves, the initially unstable proton distribution isotropizes due to pitch-angle scattering and loss of protons into the atmosphere (e.g., Usanova et al., 2010; Søraas et al., 2013; Yahnin et al., 2021). This process is incorporated in global ring current models (Jordanova et al., 2012) which showed its contribution to a gradual recovery of magnetic storms. The relationship between EMIC waves and the ring current is an ongoing and active area of research.

5 HOW DO ULF WAVES COUPLE TO THE RADIATION BELTS?

ULF waves play a major role in the dynamics of higher energy radiation belt particles through radial transport. ULF wave-particle interactions can lead to rapid dropouts (e.g., Turner et al., 2012; Zou et al., 2020; Olifer et al., 2021) as well as significant energization of electrons (e.g., Kanekal et al., 2016; Jaynes et al., 2018). Thorne et al. (2007) discussed how both ULF waves and local wave-particle interaction can contribute to the acceleration of relativistic electrons. ULF waves can accelerate electrons up to relativistic energies (e.g., Elkington et al., 2003), and plasma density depletions can create preferential conditions for local diffusive acceleration of electrons from ~hundreds of keV to several MeV (Thorne et al., 2013; Allison et al., 2021).

While significant progress has been achieved and many derived parameterizations have been applied in the simulations (e.g., Ozeke et al., 2014; Drozdov et al., 2021), the role of ULF waves in the electron dynamics remains an open question. For example, with sparse measurements it is challenging to determine the azimuthal mode number of ULF waves (Barani et al., 2019), which necessitates assumptions in the estimation of radial diffusion coefficients. Other challenges arise from the sparse distribution of ULF wave measurements. One approach to supplement sparse measurements is the use of realistic, validated global MHD simulations (Elkington et al., 2012); this is one motivation for the UMEA objective of improving such simulations. The effect of ULF waves can be included in simulations via radial diffusion parameterizations (Lejosne and Kollmann, 2020).

ULF waves can also modulate higher-frequency, EMIC and VLF wave growth (e.g., Li et al., 2011; Gamayunov and Engebretson, 2021; Shang et al., 2021), transferring energy from large to small scales. Concerning EMIC waves, the pioneering work by Lyons and Thorne (1972) demonstrated that these waves can play a critical role in the dynamics of multi-MeV electrons. They are highly effective in scattering electrons in the vicinity of the loss cone, can produce localized precipitation (e.g., Blum et al., 2015) and lead to the formation of bite-outs in electron pitch-angle distributions (Usanova et al., 2014) and minima in phase space density profiles (Shprits et al., 2017). A few examples of recent advances in EMIC wave research include significantly improved data coverage and statistics (e.g., Allen et al., 2016; Sigsbee et al., 2016, 2020; Wang et al., 2017; Engebretson et al., 2018; Lee et al., 2019; Vines et al., 2019, 2021; Grison et al., 2021; Jun et al., 2021), investigation of the association of the EMIC waves with injections (e.g., Remya et al., 2018; Jun et al., 2019; Kim et al., 2021), improved understanding of EMIC wave generation (e.g., Lee et al., 2021), exploration of the possibility of sub-MeV electron scattering (e.g., Zhang X. J. et al., 2019; Capannolo et al., 2019; Denton et al., 2019) and quantifying their effect in modeling (e.g., Ma et al., 2016; Drozdov et al., 2017; Cervantes et al., 2020; Wang D. et al., 2020; Drozdov et al., 2020).

6 WHAT IS THE ROLE OF ULF WAVES IN MAGNETOSPHERE-IONOSPHERE COUPLING?

ULF waves can carry significant energy to the ionosphere and play important roles in M-I coupling. They can cause modulation and enhancement of several ionospheric parameters (e.g., electron density and ionospheric conductance) and provide ion frictional heating in the ionosphere-thermosphere (I-T) system. When propagating to the ground, ULF waves can couple to geomagnetic/geoelectric field perturbations (e.g., Hartinger et al., 2020) and potentially drive GICs that may damage technological infrastructures (Heyns et al., 2021; Yagova et al., 2021). Recent studies have shown that ULF wave-related precipitation of energetic electrons can affect ionospheric conductivities and modulate Hall and Pedersen conductances by a factor of 7–10 (e.g., Wang et al., 2020d). These large conductivity modulations in turn affect M-I coupling processes and I-T heating rates (Verkhoglyadova et al., 2018). Watson et al. (2015, 2016) reported TEC variations related to Pc4 and Pc5-6 ULF waves, with the Pc5-6 waves showing peak-to-peak amplitudes as large as 7 TECU.

More work is needed in ULF wave models to incorporate more realistic, event-specific conductivity. Though several mechanisms linking ULF waves to TEC perturbations have been proposed by Pilipenko et al. (2014), most work has focused on event studies. Comprehensive statistical studies are thus need to identify the favored conditions and mechanisms for significant TEC perturbations related to ULF waves. While many previous statistical studies used 1-min resolution data to characterize geomagnetic perturbations for GIC hazard analysis, it has been shown by recent studies that higher sampling rate data (<1 min) are needed to capture more transient and shorter-period wave events such as those associated with SSCs (e.g., Trichtchenko, 2021).

7 ULF WAVE MODELING AND THE GEM ULF WAVE MODELING CHALLENGE

ULF waves in the magnetosphere are studied using coupled global magnetospheric models (e.g., Claudepierre et al., 2008; Hartinger et al., 2014; Claudepierre et al., 2016; Komar et al., 2017) and in simplified field geometries to isolate and better understand underlying physics (Xia et al., 2017; Denton, 2018; Elsden and Wright, 2020; Lysak et al., 2020). Examples of simulations of ULF waves in the magnetosphere presented at GEM UMEA sessions include studies of: global magnetospheric ULF wave modes (Claudepierre et al., 2010; Elsden et al., 2016; Elsden and Wright, 2017, 2020; Xia et al., 2017; Lysak et al., 2020), magnetospheric ULF wave propagation (Degeling et al., 2018), growth and propagation of EMIC waves (Denton et al., 2014), magnetopause surface waves (Lin et al., 2017; Archer et al., 2021), and interaction of ULF waves with ring current and radiation belt particle populations (Komar et al., 2017; Denton et al., 2019; Patel et al., 2019).

In a previous GEM challenge, the Metrics and Validation Focus Group compared ULF wave output of several global MHD simulation codes using idealized driving conditions, finding substantial differences. A few global MHD simulation studies have shown how, for example, grid resolution can profoundly affect wave properties using grid convergence tests and other calculations (e.g., Claudepierre et al., 2010; Hartinger et al., 2014). More model-model (different grid, different simulation code, different boundary condition) and model-data (event specific or idealized simulations compared to statistical results) comparisons are needed to improve the specification of ULF waves in global MHD simulations, and this approach needs to be extended beyond global MHD simulations. The earlier GEM ULF wave modeling challenge was continued by UMEA in order to better understand potential sources of model-model and model-data discrepancies—in particular, to discriminate between numerical effects and missing physics.

Over a series of sessions, the UMEA FG discussed data-model and model-model comparisons during idealized and realistic driving conditions. A project webpage describing this effort is at https://ccmc.gsfc.nasa.gov/challenges/ULF/, including a project summary, links to publications and simulation runs at the NASA GSFC Community Coordinated Modeling Center (CCMC).

8 SUMMARY

The 2016–2021 UMEA effort brought together researchers in different research areas that shared common interests related to ULF waves. This led to fruitful discussions that connected different research areas and GEM focus groups. Many of these discussions, such as the generation mechanisms of EMIC waves and the relative importance of radial transport and local acceleration, were motivated by the pioneering work of Richard Thorne and Peter Gary. Work related to these FG discussions has yielded new insights on the current state of the field and prospects for future research directions. A recurring theme across all 6 years of the FG: ULF waves are discussed in various contexts in virtually every area of geospace research (and every GEM FG) due to the wide variety of ways they can affect geospace system dynamics. In the future, continued coordination across research areas is needed to improve models of ULF waves and better capture their effect on solar wind-magnetosphere-ionosphere coupling and inner magnetosphere dynamics.

AUTHOR CONTRIBUTIONS

MH led the manuscript effort and provided text for **Sections 1**, **8**, and other sections. KT provided text for **Section 2**. MU provided text for **Section 3**, **4**. XS provided text for **Sections 4**, **6**. AD provided text for **Section 5**. BK provided text for **Section 7**.

FUNDING

MH was supported by NASA grants 80NSSC19K0127 and 80NSSC19K0907, and the International Space Sciences Institute (ISSI) international teams program (3D Alfvén resonances). XS was supported by NASA grants 80NSSC19K0907 and 80NSSC21K1677. KT was supported by NASA grants NNX17AD34G and 80NSSC19K0259. MU is thankful for support from the ISSI international teams program and NASA Award 80 NSSC19K0265.

ACKNOWLEDGMENTS

We thank all who participated in the UMEA focus group discussions from 2016 to 2021, but especially Seth Claudepierre and Scot Elkington who provided significant help in planning the UMEA effort and generated many of the ideas that led to the FG proposal.

REFERENCES

Abid, A. A., Lu, Q., Gao, X. L., Alotaibi, B. M., Ali, S., Qureshi, M. N. S., et al. (2021). Energization of Cold Ions by Electromagnetic Ion Cyclotron Waves: Magnetospheric Multiscale (MMS) Observations. *Phys. Plasmas* 28, 072901. doi:10.1063/5.0046764

Allen, R. C., Zhang, J.-C., Kistler, L. M., Spence, H. E., Lin, R.-L., Klecker, B., et al. (2016). A Statistical Study of EMIC Waves Observed by Cluster: 2. Associated Plasma Conditions. *J. Geophys. Res. Space Phys.* 121, 6458–6479. doi:10.1002/2016JA022541

Allison, H. J., Shprits, Y. Y., Zhelavskaya, I. S., Wang, D., and Smirnov, A. G. (2021). Gyroresonant Wave-Particle Interactions with Chorus Waves during Extreme Depletions of Plasma Density in the Van allen Radiation Belts. *Sci. Adv.* 7. doi:10.1126/sciadv.abc0380

Archer, M. O., Hartinger, M. D., Plaschke, F., Southwood, D. J., and Rastaetter, L. (2021). Magnetopause Ripples Going against the Flow Form Azimuthally Stationary Surface Waves. *Nat. Commun.* 12, 5697. doi:10.1038/s41467-021-25923-7

Archer, M. O., Hietala, H., Hartinger, M. D., Plaschke, F., and Angelopoulos, V. (2019). Direct Observations of a Surface Eigenmode of the Dayside Magnetopause. *Nat. Commun.* 10, 615. doi:10.1038/s41467-018-08134-5

Barani, M., Tu, W., Sarris, T., Pham, K., and Redmon, R. J. (2019). Estimating the Azimuthal Mode Structure of ULF Waves Based on Multiple GOES Satellite Observations. *J. Geophys. Res. Space Phys.* 124, 5009–5026. doi:10.1029/2019JA026927

Blum, L. W., and Breneman, A. W. (2020). "Observations of Radiation belt Losses Due to Cyclotron Wave-Particle Interactions," in *The Dynamic Loss of Earth's Radiation Belts*. Editors Jaynes, A. N., and Usanova, M. E. (Cambridge, MA: Elsevier), 49–98. doi:10.1016/B978-0-12-813371-2.00003-2

Blum, L. W., Halford, A., Millan, R., Bonnell, J. W., Goldstein, J., Usanova, M., et al. (2015). Observations of Coincident EMIC Wave Activity and Duskside Energetic Electron Precipitation on 18-19 January 2013. *Geophys. Res. Lett.* 42, 5727–5735. doi:10.1002/2015GL065245

Borovsky, J. E., and Valdivia, J. A. (2018). The Earth's Magnetosphere: A Systems Science Overview and Assessment. *Surv. Geophys.* 39, 817–859. doi:10.1007/s10712-018-9487-x

Brito, T., Hudson, M. K., Kress, B., Paral, J., Halford, A., Millan, R., et al. (2015). Simulation of ULF Wave-Modulated Radiation belt Electron Precipitation during the 17 March 2013 Storm. *J. Geophys. Res. Space Phys.* 120, 3444–3461. doi:10.1002/2014JA020838

Capannolo, L., Li, W., Ma, Q., Chen, L., Shen, X. C., Spence, H. E., et al. (2019). Direct Observation of Subrelativistic Electron Precipitation Potentially Driven by EMIC Waves. *Geophys. Res. Lett.* 46, 12711–12721. doi:10.1029/2019GL084202

Cervantes, S., Shprits, Y. Y., Aseev, N. A., and Allison, H. J. (2020). Quantifying the Effects of EMIC Wave Scattering and Magnetopause Shadowing in the Outer Electron Radiation Belt by Means of Data Assimilation. *J. Geophys. Res. Space Phys.* 125. doi:10.1029/2020JA028208

Chappell, C. R., Huddleston, M. M., Moore, T. E., Giles, B. L., and Delcourt, D. C. (2008). Observations of the Warm Plasma Cloak and an Explanation of its Formation in the Magnetosphere. *J. Geophys. Res.* 113, a–n. doi:10.1029/2007JA012945

Claudepierre, S. G., Elkington, S. R., and Wiltberger, M. (2008). Solar Wind Driving of Magnetospheric ULF Waves: Pulsations Driven by Velocity Shear at the Magnetopause. *J. Geophys. Res.* 113, a–n. doi:10.1029/2007JA012890

Claudepierre, S. G., Hudson, M. K., Lotko, W., Lyon, J. G., and Denton, R. E. (2010). Solar Wind Driving of Magnetospheric Ulf Waves: Field Line Resonances Driven by Dynamic Pressure Fluctuations. *J. Geophys. Res. Space Phys.* 115. doi:10.1029/2010ja015399

Claudepierre, S. G., Mann, I. R., Takahashi, K., Fennell, J. F., Hudson, M. K., Blake, J. B., et al. (2013). Van Allen Probes Observation of Localized Drift Resonance between Poloidal Mode Ultra-low Frequency Waves and 60 keV Electrons. *Geophys. Res. Lett.* 40, 4491–4497. doi:10.1002/grl.50901

Claudepierre, S. G., Toffoletto, F. R., and Wiltberger, M. (2016). Global Mhd Modeling of Resonant Ulf Waves: Simulations with and without a Plasmasphere. *J. Geophys. Res. Space Phys.* 121, 227–244. doi:10.1002/2015JA022048

Cornwall, J. M. (1965). Cyclotron Instabilities and Electromagnetic Emission in the Ultra Low Frequency and Very Low Frequency Ranges. *J. Geophys. Res.* 70, 61–69. doi:10.1029/JZ070i001p00061

Degeling, A. W., Rae, I. J., Watt, C. E. J., Shi, Q. Q., Rankin, R., and Zong, Q.-G. (2018). Control of Ulf Wave Accessibility to the Inner Magnetosphere by the Convection of Plasma Density. *J. Geophys. Res. Space Phys.* 123, 1086–1099. doi:10.1002/2017JA024874

Delzanno, G. L., Borovsky, J. E., Henderson, M. G., Resendiz Lira, P. A., Roytershteyn, V., and Welling, D. T. (2021). The Impact of Cold Electrons and Cold Ions in Magnetospheric Physics. *J. Atmos. Solar-Terrestrial Phys.* 220, 105599. doi:10.1016/j.jastp.2021.105599

Denton, R. E. (2018). Electromagnetic Ion Cyclotron Wavefields in a Realistic Dipole Field. *J. Geophys. Res. Space Phys.* 123, 1208–1223. doi:10.1002/2017JA024886

Denton, R. E., Jordanova, V. K., and Fraser, B. J. (2014). Effect of Spatial Density Variation and O+ Concentration on the Growth and Evolution of Electromagnetic Ion Cyclotron Waves. *J. Geophys. Res. Space Phys.* 119, 8372–8395. doi:10.1002/2014JA020384

Denton, R. E., Ofman, L., Shprits, Y. Y., Bortnik, J., Millan, R. M., Rodger, C. J., et al. (2019). Pitch Angle Scattering of Sub-MeV Relativistic Electrons by Electromagnetic Ion Cyclotron Waves. *J. Geophys. Res. Space Phys.* 124, 5610–5626. doi:10.1029/2018JA026384

Drozdov, A. Y., Allison, H. J., Shprits, Y. Y., Elkington, S. R., and Aseev, N. A. (2021). A Comparison of Radial Diffusion Coefficients in 1-D and 3-D Long-Term Radiation Belt Simulations. *JGR Space Physics]* 126. doi:10.1029/2020ja028707

Drozdov, A. Y., Shprits, Y. Y., Usanova, M. E., Aseev, N. A., Kellerman, A. C., and Zhu, H. (2017). EMIC Wave Parameterization in the Long-Term VERB Code Simulation. *J. Geophys. Res. Space Phys.* 122, 8488–8501. doi:10.1002/2017JA024389

Drozdov, A. Y., Usanova, M. E., Hudson, M. K., Allison, H. J., and Shprits, Y. Y. (2020). The Role of Hiss, Chorus, and EMIC Waves in the Modeling of the Dynamics of the Multi-MeV Radiation Belt Electrons. *J. Geophys. Res. Space Phys.* 125, 2628. doi:10.1029/2020JA028282

Elkington, S. R., Chan, A. A., and Wiltberger, M. (2012). *Global Structure of ULF Waves during the 24–26 September 1998 Geomagnetic Storm*. American Geophysical Union AGU, 127–138. doi:10.1029/2012GM001348

Elkington, S. R., Hudson, M. K., and Chan, A. A. (2003). Resonant Acceleration and Diffusion of Outer Zone Electrons in an Asymmetric Geomagnetic Field. *J. Geophys. Res.* 108. doi:10.1029/2001JA009202

Elsden, T., and Wright, A. (2020). Evolution of High- M Poloidal Alfvén Waves in a Dipole Magnetic Field. *J. Geophys. Res. Space Phys.* 125. doi:10.1029/2020JA028187

Elsden, T., Wright, A. N., and Hartinger, M. D. (2016). Deciphering Satellite Observations of Compressional Ulf Waveguide Modes. *J. Geophys. Res. Space Phys.* 121, 3381–3394. doi:10.1002/2016JA022351

Elsden, T., and Wright, A. N. (2018). The Broadband Excitation of 3-D Alfvén Resonances in a MHD Waveguide. *J. Geophys. Res. Space Phys.* 123, 530–547. doi:10.1002/2017JA025018

Elsden, T., and Wright, A. N. (2017). The Theoretical Foundation of 3-D Alfvén Resonances: Time-dependent Solutions. *J. Geophys. Res. Space Phys.* 122, 3247–3261. doi:10.1002/2016JA023811

Engebretson, M. J., Posch, J. L., Capman, N. S. S., Campuzano, N. G., Bělik, P., Allen, R. C., et al. (2018). MMS, Van Allen Probes, GOES 13, and Ground-Based Magnetometer Observations of EMIC Wave Events before, during, and after a Modest Interplanetary Shock. *J. Geophys. Res. Space Phys.* 123, 8331–8357. doi:10.1029/2018JA025984

Gamayunov, K. V., and Engebretson, M. J. (2021). Low Frequency ULF Waves in the Earth's Inner Magnetosphere: Statistics during Coronal Mass Ejections and Seeding of EMIC Waves. *JGR Space Phys.* 126. doi:10.1029/2021ja029247

Gary, S. P., Moldwin, M. B., Thomsen, M. F., Winske, D., and McComas, D. J. (1994). Hot Proton Anisotropies and Cool Proton Temperatures in the Outer Magnetosphere. *J. Geophys. Res.* 99, 23603–23616. doi:10.1029/94JA02069

Gary, S. P. (1992). The Mirror and Ion Cyclotron Anisotropy Instabilities. *J. Geophys. Res.* 97, 8519–8529. doi:10.1029/92JA00299

Gary, S. P., Thomsen, M. F., Yin, L., and Winske, D. (1995). Electromagnetic Proton Cyclotron Instability: Interactions with Magnetospheric Protons. *J. Geophys. Res.* 100, 21961–21972. doi:10.1029/95JA01403

Grison, B., Santolík, O., Lukačevič, J., and Usanova, M. E. (2021). Occurrence of EMIC Waves in the Magnetosphere According to Their Distance to the Magnetopause. *Geophys. Res. Lett.* 48. doi:10.1029/2020GL090921

Hao, Y. X., Zhao, X. X., Zong, Q. G., Zhou, X. Z., Rankin, R., Chen, X. R., et al. (2020). Simultaneous Observations of Localized and Global Drift Resonance. *Geophys. Res. Lett.* 47, e88019. doi:10.1029/2020GL088019

Hartinger, M. D., Angelopoulos, V., Moldwin, M. B., Takahashi, K., and Clausen, L. B. N. (2013). Statistical Study of Global Modes outside the Plasmasphere. *J. Geophys. Res. Space Phys.* 118, 804–822. doi:10.1002/jgra.50140

Hartinger, M. D., Shi, X., Lucas, G. M., Murphy, B. S., Kelbert, A., Baker, J. B. H., et al. (2020). Simultaneous Observations of Geoelectric and Geomagnetic fields Produced by Magnetospheric Ulf Waves. *Geophys. Res. Lett.* 47, e2020GL089441. doi:10.1029/2020GL089441

Hartinger, M. D., Welling, D., Viall, N. M., Moldwin, M. B., and Ridley, A. (2014). The Effect of Magnetopause Motion on Fast Mode Resonance. *J. Geophys. Res. Space Phys.* 119, 8212–8227. doi:10.1002/2014JA020401

Hartinger, M., Moldwin, M. B., Angelopoulos, V., Takahashi, K., Singer, H. J., Anderson, R. R., et al. (2010). Pc5 Wave Power in the Quiet-Time Plasmasphere and Trough: CRRES Observations. *Geophys. Res. Lett.* 37, a–n. doi:10.1029/2010GL042475

Heyns, M. J., Lotz, S. I., and Gaunt, C. T. (2021). Geomagnetic Pulsations Driving Geomagnetically Induced Currents. *Space Weather* 19, e2020SW002557. doi:10.1029/2020SW002557

Horne, R. B., and Thorne, R. M. (1993). On the Preferred Source Location for the Convective Amplification of Ion Cyclotron Waves. *J. Geophys. Res.* 98, 9233–9248. doi:10.1029/92JA02972

Jacobs, J. A., Kato, Y., Matsushita, S., and Troitskaya, V. A. (1964). Classification of Geomagnetic Micropulsations. *J. Geophys. Res.* 69, 180–181. doi:10.1029/JZ069i001p00180

Jaynes, A. N., Ali, A. F., Elkington, S. R., Malaspina, D. M., Baker, D. N., Li, X., et al. (2018). Fast Diffusion of Ultrarelativistic Electrons in the Outer Radiation belt: 17 March 2015 Storm Event. *Geophys. Res. Lett.* 45, 10874–10882. doi:10.1029/2018GL079786

Jaynes, A. N., Lessard, M. R., Takahashi, K., Ali, A. F., Malaspina, D. M., Michell, R. G., et al. (2015). Correlated Pc4-5 ULF Waves, Whistler-mode Chorus, and Pulsating aurora Observed by the Van Allen Probes and Ground-based Systems. *J. Geophys. Res. Space Phys.* 120, 8749–8761. doi:10.1002/2015JA021380

Jordanova, V. K., Welling, D. T., Zaharia, S. G., Chen, L., and Thorne, R. M. (2012). Modeling Ring Current Ion and Electron Dynamics and Plasma Instabilities during a High-Speed Stream Driven Storm. *J. Geophys. Res.* 117, a–n. doi:10.1029/2011JA017433

Jun, C. W., Miyoshi, Y., Kurita, S., Yue, C., Bortnik, J., Lyons, L., et al. (2021). The Characteristics of EMIC Waves in the Magnetosphere Based on the Van Allen Probes and Arase Observations. *J. Geophys. Res. Space Phys.* 126. doi:10.1029/2020JA029001

Jun, C. W., Yue, C., Bortnik, J., Lyons, L. R., Nishimura, Y., and Kletzing, C. (2019). EMIC Wave Properties Associated with and without Injections in the Inner Magnetosphere. *J. Geophys. Res. Space Phys.* 124, 2029–2045. doi:10.1029/2018JA026279

Kanekal, S. G., Baker, D. N., Fennell, J. F., Jones, A., Schiller, Q., Richardson, I. G., et al. (2016). Prompt Acceleration of Magnetospheric Electrons to Ultrarelativistic Energies by the 17 March 2015 Interplanetary Shock. *J. Geophys. Res. Space Phys.* 121, 7622–7635. doi:10.1002/2016JA022596

Keiling, A. (2009). Alfvén Waves and Their Roles in the Dynamics of the Earth's Magnetotail: A Review. *Space Sci. Rev.* 142, 73–156. doi:10.1007/s11214-008-9463-8

Keiling, A., and Takahashi, K. (2011). Review of Pi2 Models. *Space Sci. Rev.* 161, 63–148. doi:10.1007/s11214-011-9818-4

Kepko, L., and Kivelson, M. (1999). Generation of Pi2 Pulsations by Bursty Bulk Flows. *J. Geophys. Res.* 104, 25021–25034. doi:10.1029/1999JA900361

Kim, H., Schiller, Q., Engebretson, M. J., Noh, S., Kuzichev, I., Lanzerotti, L. J., et al. (2021). Observations of Particle Loss Due to Injection-Associated Electromagnetic Ion Cyclotron Waves. *J. Geophys. Res. Space Phys.* 126. doi:10.1029/2020JA028503

Kitamura, N., Kitahara, M., Shoji, M., Miyoshi, Y., Hasegawa, H., Nakamura, S., et al. (2018). Direct Measurements of Two-Way Wave-Particle Energy Transfer in a Collisionless Space Plasma. *Science* 361, 1000–1003. doi:10.1126/science.aap8730

Komar, C. M., Glocer, A., Hartinger, M. D., Murphy, K. R., Fok, M.-C., and Kang, S.-B. (2017). Electron Drift Resonance in the Mhd-Coupled Comprehensive Inner

Magnetosphere-Ionosphere Model. *J. Geophys. Res. Space Phys.* 122, 006–012. doi:10.1002/2017JA024163

Kozyra, J. U., Cravens, T. E., Nagy, A. F., Fontheim, E. G., and Ong, R. S. B. (1984). Effects of Energetic Heavy Ions on Electromagnetic Ion Cyclotron Wave Generation in the Plasmapause Region. *J. Geophys. Res.* 89, 2217–2234. doi:10.1029/JA089iA04p02217

Kress, B. T., Hudson, M. K., Ukhorskiy, A. Y., and Mueller, H.-R. (2013). *Nonlinear Radial Transport in the Earth's Radiation Belts*. (Washington, DC: American Geophysical Union AGU), 151–160. doi:10.1029/2012GM001333

Lee, D.-H., Hudson, M. K., Kim, K., Lysak, R. L., and Song, Y. (2002). Compressional MHD Wave Transport in the Magnetosphere 1. Reflection and Transmission across the Plasmapause. *J. Geophys. Res.* 107. doi:10.1029/2002JA009239

Lee, J. H., Turner, D. L., Toledo-Redondo, S., Vines, S. K., Allen, R. C., Fuselier, S. A., et al. (2019). MMS Measurements and Modeling of Peculiar Electromagnetic Ion Cyclotron Waves. *Geophys. Res. Lett.* 46, 11622–11631. doi:10.1029/2019GL085182

Lee, J. H., Turner, D. L., Vines, S. K., Allen, R. C., Toledo-Redondo, S., Bingham, S. T., et al. (2021). Application of Cold and Hot Plasma Composition Measurements to Investigate Impacts on Dusk-Side Electromagnetic Ion Cyclotron Waves. *J. Geophys. Res. Space Phys.* 126. doi:10.1029/2020JA028650

Lejosne, S., and Kollmann, P. (2020). Radiation Belt Radial Diffusion at Earth and Beyond. *Space Sci. Rev.* 216. doi:10.1007/s11214-020-0642-6

Li, W., Thorne, R. M., Bortnik, J., Nishimura, Y., and Angelopoulos, V. (2011). Modulation of Whistler Mode Chorus Waves: 1. Role of Compressional Pc4-5 Pulsations. *J. Geophys. Res.* 116, a–n. doi:10.1029/2010ja016312

Liang, J., Liu, W. W., Donovan, E. F., and Spanswick, E. (2009). In-situ Observation of ULF Wave Activities Associated with Substorm Expansion Phase Onset and Current Disruption. *Ann. Geophys.* 27, 2191–2204. doi:10.5194/angeo-27-2191-2009

Lin, D., Scales, W. A., and Sen, S. (2017). Flow Curvature Effects on the Kelvin-Helmholtz Instability: Hybrid Simulation. *Radiat. Effects Defects Sol.* 172, 750–753. doi:10.1080/10420150.2017.1398254

Lyons, L. R., and Thorne, R. M. (1972). Parasitic Pitch Angle Diffusion of Radiation belt Particles by Ion Cyclotron Waves. *J. Geophys. Res.* 77, 5608–5616. doi:10.1029/JA077i028p05608

Lysak, R. L., Song, Y., Sciffer, M. D., and Waters, C. L. (2015). Propagation of Pi2 Pulsations in a Dipole Model of the Magnetosphere. *J. Geophys. Res. Space Phys.* 120, 355–367. doi:10.1002/2014JA020625

Lysak, R. L., Song, Y., Waters, C. L., Sciffer, M. D., and Obana, Y. (2020). Numerical Investigations of Interhemispheric Asymmetry Due to Ionospheric Conductance. *J. Geophys. Res. Space Phys.* 125. doi:10.1029/2020JA027866

Ma, Q., Li, W., Thorne, R. M., Nishimura, Y., Zhang, X. J., Reeves, G. D., et al. (2016). Simulation of Energy-dependent Electron Diffusion Processes in the Earth's Outer Radiation belt. *J. Geophys. Res. Space Phys.* 121, 4217–4231. doi:10.1002/2016JA022507

Murphy, K. R., Mann, I. R., and Sibeck, D. G. (2015). On the Dependence of Storm Time ULF Wave Power on Magnetopause Location: Impacts for ULF Wave Radial Diffusion. *Geophys. Res. Lett.* 42, 9676–9684. doi:10.1002/2015GL066592

Nosé, M., Matsuoka, A., Kumamoto, A., Kasahara, Y., Teramoto, M., Kurita, S., et al. (2020). Oxygen Torus and its Coincidence with EMIC Wave in the Deep Inner Magnetosphere: Van Allen Probe B and Arase Observations. *Earth Planets Space* 72, 111. doi:10.1186/s40623-020-01235-w

Oimatsu, S., Nosé, M., Takahashi, K., Yamamoto, K., Keika, K., Kletzing, C. A., et al. (2018). Van allen Probes Observations of Drift-Bounce Resonance and Energy Transfer between Energetic Ring Current Protons and Poloidal Pc4 Wave. *J. Geophys. Res. Space Phys.* 123, 3421–3435. doi:10.1029/2017JA025087

Olifer, L., Mann, I. R., Ozeke, L. G., Claudepierre, S. G., Baker, D. N., and Spence, H. E. (2021). On the Similarity and Repeatability of Fast Radiation belt Loss: Role of the Last Closed Drift Shell. *JGR Space Phys.* 126. doi:10.1029/2021ja029957

Oliveira, D. M., Hartinger, M. D., Xu, Z., Zesta, E., Pilipenko, V. A., Giles, B. L., et al. (2020). Interplanetary Shock Impact Angles Control Magnetospheric ULF Wave Activity: Wave Amplitude, Frequency, and Power Spectra. *Geophys. Res. Lett.* 47. doi:10.1029/2020GL090857

Ozeke, L. G., Mann, I. R., Murphy, K. R., Jonathan Rae, I., and Milling, D. K. (2014). Analytic Expressions for ULF Wave Radiation belt Radial Diffusion Coefficients. *J. Geophys. Res. Space Phys.* 119, 1587–1605. doi:10.1002/2013JA019204

Patel, M., Li, Z., Hudson, M., Claudepierre, S., and Wygant, J. (2019). Simulation of Prompt Acceleration of Radiation belt Electrons during the 16 July 2017 Storm. *Geophys. Res. Lett.* 46, 7222–7229. doi:10.1029/2019GL083257

Pilipenko, V., Belakhovsky, V., Murr, D., Fedorov, E., and Engebretson, M. (2014). Modulation of Total Electron Content by Ulf Pc5 Waves. *J. Geophys. Res. Space Phys.* 119, 4358–4369. doi:10.1002/2013JA019594

Rankin, R., Wang, C. R., Wang, Y. F., Zong, Q., Zhou, X. Z., Degeling, A. W., et al. (2020). *Ultra-Low-Frequency Wave–Particle Interactions in Earth's Outer Radiation Belt*. (Hoboken, NJ: American Geophysical Union AGU), 189–205. chap. 11. doi:10.1002/9781119509592.ch11

Remya, B., Sibeck, D. G., Halford, A. J., Murphy, K. R., Reeves, G. D., Singer, H. J., et al. (2018). Ion Injection Triggered EMIC Waves in the Earth's Magnetosphere. *J. Geophys. Res. Space Phys.* 123, 4921–4938. doi:10.1029/2018JA025354

Ren, J., Zong, Q. G., Zhou, X. Z., Rankin, R., and Wang, Y. F. (2016). Interaction of Ulf Waves with Different Ion Species: Pitch Angle and Phase Space Density Implications. *J. Geophys. Res. Space Phys.* 121, 9459–9472. doi:10.1002/2016JA022995

Ren, J., Zong, Q. G., Zhou, X. Z., Spence, H. E., Funsten, H. O., Wygant, J. R., et al. (2019). Cold Plasmaspheric Electrons Affected by ULF Waves in the Inner Magnetosphere: A Van Allen Probes Statistical Study. *J. Geophys. Res. Space Phys.* 124, 7954–7965. doi:10.1029/2019JA027009

Sandhu, J. K., Rae, I. J., Staples, F. A., Hartley, D. P., Walach, M. T., Elsden, T., et al. (2021). The Roles of the Magnetopause and Plasmapause in Storm-Time ULF Wave Power Enhancements. *J. Geophys. Res. Space Phys.* 126. doi:10.1029/2021JA029337

Shang, X., Liu, S., Chen, L., Gao, Z., Wang, G., He, Q., et al. (2021). ULF-Modulation of Whistler-Mode Waves in the Inner Magnetosphere during Solar Wind Compression. *JGR Space Phys.* 126. doi:10.1029/2021ja029353

Shen, X.-C., Shi, Q., Wang, B., Zhang, H., Hudson, M. K., Nishimura, Y., et al. (2018). Dayside Magnetospheric and Ionospheric Responses to a Foreshock Transient on 25 June 2008: 1. FLR Observed by Satellite and Ground-Based Magnetometers. *J. Geophys. Res. Space Phys.* 123, 6335–6346. doi:10.1029/2018JA025349

Shi, X., Baker, J. B. H., Ruohoniemi, J. M., Hartinger, M. D., Murphy, K. R., Rodriguez, J. V., et al. (2018b). Long-Lasting Poloidal ULF Waves Observed by Multiple Satellites and High-Latitude SuperDARN Radars. *J. Geophys. Res. Space Phys.* 123, 8422–8438. doi:10.1029/2018JA026003

Shi, X., Ruohoniemi, J. M., Baker, J. B. H., Lin, D., Bland, E. C., Hartinger, M. D., et al. (2018a). Survey of Ionospheric Pc3-5 Ulf Wave Signatures in Superdarn High Time Resolution Data. *J. Geophys. Res. Space Phys.* 123, 4215–4231. doi:10.1029/2017JA025033

Shprits, Y. Y., Kellerman, A., Aseev, N., Drozdov, A. Y., and Michaelis, I. (2017). Multi-MeV Electron Loss in the Heart of the Radiation Belts. *Geophys. Res. Lett.* 44, 1204–1209. doi:10.1002/2016GL072258

Sigsbee, K., Kletzing, C. A., Faden, J. B., Jaynes, A. N., Reeves, G. D., and Jahn, J. M. (2020). Simultaneous Observations of Electromagnetic Ion Cyclotron (EMIC) Waves and Pitch Angle Scattering during a Van Allen Probes Conjunction. *J. Geophys. Res. Space Phys.* 125. doi:10.1029/2019JA027424

Sigsbee, K., Kletzing, C. A., Smith, C. W., MacDowall, R., Spence, H., Reeves, G., et al. (2016). Van Allen Probes, THEMIS, GOES, and Cluster Observations of EMIC Waves, ULF Pulsations, and an Electron Flux Dropout. *J. Geophys. Res. Space Phys.* 121, 1990–2008. doi:10.1002/2014JA020877

Søraas, F., Laundal, K. M., and Usanova, M. (2013). Coincident Particle and Optical Observations of Nightside Subauroral Proton Precipitation. *J. Geophys. Res. Space Phys.* 118, 1112–1122. doi:10.1002/jgra.50172

Soto-Chavez, A. R., Lanzerotti, L. J., Manweiler, J. W., Gerrard, A., Cohen, R., Xia, Z., et al. (2019). Observational Evidence of the Drift-Mirror Plasma Instability in Earth's Inner Magnetosphere. *Phys. Plasmas* 26, 042110. doi:10.1063/1.5083629

Takahashi, K., Hartinger, M. D., Angelopoulos, V., Glassmeier, K.-H., and Singer, H. J. (2013). Multispacecraft Observations of Fundamental Poloidal Waves without Ground Magnetic Signatures. *J. Geophys. Res. Space Phys.* 118, 4319–4334. doi:10.1002/jgra.50405

Thorne, R. M., and Horne, R. B. (1997). Modulation of Electromagnetic Ion Cyclotron Instability Due to Interaction with Ring Current O+during Magnetic Storms. *J. Geophys. Res.* 102, 14155–14163. doi:10.1029/96JA04019

Thorne, R. M., and Horne, R. B. (1992). The Contribution of Ion-Cyclotron Waves to Electron Heating and SAR-Arc Excitation Near the Storm-Time Plasmapause. *Geophys. Res. Lett.* 19, 417–420. doi:10.1029/92GL00089

Thorne, R. M., Li, W., Ni, B., Ma, Q., Bortnik, J., Chen, L., et al. (2013). Rapid Local Acceleration of Relativistic Radiation-belt Electrons by Magnetospheric Chorus. *Nature* 504, 411–414. doi:10.1038/nature12889

Thorne, R. M., Shprits, Y. Y., Meredith, N. P., Horne, R. B., Li, W., and Lyons, L. R. (2007). Refilling of the Slot Region between the Inner and Outer Electron Radiation Belts during Geomagnetic Storms. *J. Geophys. Res.* 112, a–n. doi:10.1029/2006JA012176

Trichtchenko, L. (2021). Frequency Considerations in Gic Applications. *Space Weather* 19, e2020SW002694. doi:10.1029/2020SW002694

Turner, D. L., Shprits, Y., Hartinger, M., and Angelopoulos, V. (2012). Explaining Sudden Losses of Outer Radiation belt Electrons during Geomagnetic Storms. *Nat. Phys* 8, 208–212. doi:10.1038/nphys2185

Usanova, M. E., Drozdov, A., Orlova, K., Mann, I. R., Shprits, Y., Robertson, M. T., et al. (2014). Effect of EMIC Waves on Relativistic and Ultrarelativistic Electron Populations: Ground-Based and Van allen Probes Observations. *Geophys. Res. Lett.* 41, 1375–1381. doi:10.1002/2013GL059024

Usanova, M. E. (2021). Energy Exchange between Electromagnetic Ion Cyclotron (EMIC) Waves and Thermal Plasma: From Theory to Observations. *Front. Astron. Space Sci.* 8. doi:10.3389/fspas.2021.744344

Usanova, M. E., Mann, I. R., and Darrouzet, F. (2016). EMIC Waves in the Inner Magnetosphere. *Wash. DC Am. Geophys. Union Geophys. Monogr. Ser.* 216, 65–78. doi:10.1002/9781119055006.ch5

Usanova, M. E., Mann, I. R., Kale, Z. C., Rae, I. J., Sydora, R. D., Sandanger, M., et al. (2010). Conjugate Ground and Multisatellite Observations of Compression-Related EMIC Pc1 Waves and Associated Proton Precipitation. *J. Geophys. Res.* 115, A07208. doi:10.1029/2009JA014935

Usanova, M., and Mann, I. (2016). "Waves, Particles, and Storms in Geospace," in *Waves, Particles and Storms in Geospace* (Hoboken, NJ: Oxford University Press). doi:10.1093/acprof:oso/9780198705246.001.0001

Verkhoglyadova, O. P., Meng, X., Mannucci, A. J., and McGranaghan, R. M. (2018). Semianalytical Estimation of Energy Deposition in the Ionosphere by Monochromatic Alfvén Waves. *J. Geophys. Res. Space Phys.* 123, 5210–5222. doi:10.1029/2017JA025097

Vines, S. K., Allen, R. C., Anderson, B. J., Engebretson, M. J., Fuselier, S. A., Russell, C. T., et al. (2019). EMIC Waves in the Outer Magnetosphere: Observations of an Off-Equator Source Region. *Geophys. Res. Lett.* 46, 5707–5716. doi:10.1029/2019GL082152

Vines, S. K., Anderson, B. J., Allen, R. C., Denton, R. E., Engebretson, M. J., Johnson, J. R., et al. (2021). Determining EMIC Wave Vector Properties through Multi-Point Measurements: The Wave Curl Analysis. *JGR Space Phys.* 126. doi:10.1029/2020JA028922

Wang, B., Liu, T., Nishimura, Y., Zhang, H., Hartinger, M., Shi, X., et al. (2020a). Global Propagation of Magnetospheric Pc5 ULF Waves Driven by Foreshock Transients. *J. Geophys. Res. Space Phys.* 125. doi:10.1029/2020JA028411

Wang, B., Nishimura, Y., Hartinger, M., Sivadas, N., Lyons, L. L., Varney, R. H., et al. (2020d). Ionospheric Modulation by Storm Time Pc5 ULF Pulsations and the Structure Detected by PFISR-THEMIS Conjunction. *Geophys. Res. Lett.* 47, e2020GL089060. doi:10.1029/2020GL089060

Wang, B., Nishimura, Y., Zhang, H., Shen, X. C., Lyons, L., Angelopoulos, V., et al. (2019). The 2-D Structure of Foreshock-Driven Field Line Resonances Observed by THEMIS Satellite and Ground-Based Imager Conjunctions. *J. Geophys. Res. Space Phys.* 124, 6792–6811. doi:10.1029/2019JA026668

Wang, C. P., Xing, X., Bortnik, J., and Chu, X. (2020b). Inward Propagation of Flow-Generated Pi2 Waves from the Plasma Sheet to the Inner Magnetosphere. *J. Geophys. Res. Space Phys.* 125, e27581. doi:10.1029/2019JA027581

Wang, D., Shprits, Y. Y., Zhelavskaya, I. S., Effenberger, F., Castillo, A. M., Drozdov, A. Y., et al. (2020c). The Effect of Plasma Boundaries on the Dynamic Evolution of Relativistic Radiation Belt Electrons. *J. Geophys. Res. Space Phys.* 125. doi:10.1029/2019JA027422

Wang, X. Y., Huang, S. Y., Allen, R. C., Fu, H. S., Deng, X. H., Zhou, M., et al. (2017). The Occurrence and Wave Properties of EMIC Waves Observed by the Magnetospheric Multiscale (MMS) mission. *J. Geophys. Res. Space Phys.* 122, 8228–8240. doi:10.1002/2017JA024237

Watson, C., Jayachandran, P. T., Singer, H. J., Redmon, R. J., and Danskin, D. (2016). Gps Tec Response to Pc4 "Giant Pulsations". *J. Geophys. Res. Space Phys.* 121, 1722–1735. doi:10.1002/2015JA022253

Watson, C., Jayachandran, P. T., Singer, H. J., Redmon, R. J., and Danskin, D. (2015). Large-amplitude GPS TEC Variations Associated with Pc5-6 Magnetic Field Variations Observed on the Ground and at Geosynchronous Orbit. *J. Geophys. Res. Space Phys.* 120, 7798–7821. doi:10.1002/2015JA021517

Wolf, R. A., Toffoletto, F. R., Schutza, A. M., and Yang, J. (2018). Buoyancy Waves in Earth's Magnetosphere: Calculations for a 2-D Wedge Magnetosphere. *J. Geophys. Res. Space Phys.* 123, 3548–3564. doi:10.1029/2017JA025006

Xia, Z., Chen, L., Zheng, L., and Chan, A. A. (2017). Eigenmode Analysis of Compressional Poloidal Modes in a Self-consistent Magnetic Field. *J. Geophys. Res. Space Phys.* 122, 10,369–10,381. doi:10.1002/2017JA024376

Yagova, N. V., Pilipenko, V. A., Sakharov, Y. A., and Selivanov, V. N. (2021). Spatial Scale of Geomagnetic Pc5/Pi3 Pulsations as a Factor of Their Efficiency in Generation of Geomagnetically Induced Currents. *Earth, Planets and Space* 73, 1–13. doi:10.1186/s40623-021-01407-2

Yahnin, A. G., Popova, T. A., Demekhov, A. G., Lubchich, A. A., Matsuoka, A., Asamura, K., et al. (2021). Evening Side EMIC Waves and Related Proton Precipitation Induced by a Substorm. *J. Geophys. Res. Space Phys.* 126, e29091. doi:10.1029/2020JA029091

Yamakawa, T., Seki, K., Amano, T., Takahashi, N., and Miyoshi, Y. (2020). Excitation of Internally Driven ULF Waves by the Drift-Bounce Resonance with Ring Current Ions Based on the Drift-Kinetic Simulation. *J. Geophys. Res. Space Phys.* 125, e2020JA028231. doi:10.1029/2020JA028231

Yamakawa, T., Seki, K., Amano, T., Takahashi, N., and Miyoshi, Y. (2019). Excitation of Storm Time Pc5 ULF Waves by Ring Current Ions Based on the Drift-Kinetic Simulation. *Geophys. Res. Lett.* 46, 1911–1918. doi:10.1029/2018GL081573

Yang, B., Zong, Q.-G., Wang, Y. F., Fu, S. Y., Song, P., Fu, H. S., et al. (2010). Cluster Observations of Simultaneous Resonant Interactions of Ulf Waves with Energetic Electrons and thermal Ion Species in the Inner Magnetosphere. *J. Geophys. Res.* 115, a–n. doi:10.1029/2009JA014542

Yue, C., Li, W., Nishimura, Y., Zong, Q., Ma, Q., Bortnik, J., et al. (2016). Rapid Enhancement of Low-energy (. *J. Geophys. Res. Space Phys.* 121, 6430–6443. doi:10.1002/2016JA022808

Zhai, C., Shi, X., Wang, W., Hartinger, M. D., Yao, Y., Peng, W., et al. (2021). Characterization of High-m ULF Wave Signatures in GPS TEC Data. *Geophys. Res. Lett.* 48. doi:10.1029/2021GL094282

Zhang, S., Tian, A., Degeling, A. W., Shi, Q., Wang, M., Hao, Y., et al. (2019a). Pc4-5 Poloidal ULF Wave Observed in the Dawnside Plasmaspheric Plume. *J. Geophys. Res. Space Phys.* 124, 9986–9998. doi:10.1029/2019JA027319

Zhang, X. J., Mourenas, D., Artemyev, A. V., Angelopoulos, V., and Sauvaud, J. A. (2019b). Precipitation of MeV and Sub-MeV Electrons Due to Combined Effects of EMIC and ULF Waves. *J. Geophys. Res. Space Phys.* 124, 7923–7935. doi:10.1029/2019JA026566

Zhao, X. X., Hao, Y. X., Zong, Q. G., Zhou, X. Z., Yue, C., Chen, X. R., et al. (2020). Origin of Electron Boomerang Stripes: Localized ULF Wave-Particle Interactions. *Geophys. Res. Lett.* 47, e87960. doi:10.1029/2020GL087960

Zong, Q.-G., Wang, Y. F., Zhang, H., Fu, S. Y., Zhang, H., Wang, C. R., et al. (2012). Fast Acceleration of Inner Magnetospheric Hydrogen and Oxygen Ions by Shock Induced ULF Waves. *J. Geophys. Res.* 117, a–n. doi:10.1029/2012JA018024

Zong, Q. (2021). Magnetospheric Response to Solar Wind Forcing: ULF Wave - Particle Interaction Perspective. *Ann. Geophysicae Discuss.* 2021, 1–68. doi:10.5194/angeo-2021-57

Zou, Z., Zuo, P., Ni, B., Gao, Z., Wang, G., Zhao, Z., et al. (2020). Two-step Dropouts of Radiation belt Electron Phase Space Density Induced by a Magnetic Cloud Event. *ApJ* 895, L24. doi:10.3847/2041-8213/ab9179

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.