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Key Points:

- Global observations of ionospheric electromagnetic ion cyclotron (EMIC) wave events find more events in connection with stronger and longer-lasting magnetic storms than during weaker
- During the early part of a storm recovery phase EMIC waves occur preferably in the 12–24 MLT sector while during the later part around 00–12 MLT
- Highest EMIC occurrence rates are found at longitudes around the South Atlantic Anomaly region

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Local Time and Longitudinal Differences in the Occurrence Frequency of Ionospheric EMIC Waves During Magnetic Storm Periods

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Abstract The spatial and temporal distributions of ionospheric electromagnetic ion cyclotron (EMIC) waves during magnetic storms from 2014 to 2018 were studied using Swarm observations. Ionospheric EMIC waves preferably occurred during storms and their recovery phases at subauroral regions within an average magnetic latitude of 40–55°. There were more wave events during more intense and longer period storms. However, the correlation between event number and storm duration was not good. This might be due to the effect of heavy oxygen ions on EMIC wave generation and the loss of ring current high-energy ions by the EMIC waves. There are obvious magnetic local time (MLT) differences in the peak occurrence frequency of EMIC waves during storm phases. The enhanced solar wind dynamic pressure was favorable for duskside EMIC waves. With an increased substorm activity, the wave occurrence rate peak shifted from the morning side to the dusk-premidnight sector. During the recovery phase of a storm, EMIC waves in the 12–24 MLT sector appeared preferably in the earlier part than those in the 00–12 MLT sector. This shift in local time is related to the eastward rotation of the plasmaspheric plume toward morning during the late storm recovery phase and its overlap with the ring current. Highest occurrence frequency of the storm time EMIC waves could be found in the South Atlantic Anomaly region, which might be related to the drift shell splitting and the wave propagation effect in the weak magnetic field region.

1. Introduction

Electromagnetic ion cyclotron (EMIC) waves are ultralow-frequency waves within the Pc1 frequency range from 0.2 to 5 Hz. They are typically generated by the interaction of hot anisotropic ions with a cold dense plasma population. The energetic ions provide the free energy required for ion cyclotron instability (Cornwall, 1965), whereas the cold plasma enhances the growth rate of waves (Horne & Thorne, 1993; Zhang et al., 2014). Magnetospheric EMIC waves can propagate to lower altitude areas along the magnetic field lines. Pc1 pulsations (i.e., EMIC waves) in the ionosphere or on the ground are generally believed to originate from magnetospheric sources. EMIC waves are critical for ionospheric ion outflow, ion scattering into the loss cone of the ring current, and relativistic electron pitch angle scattering in the radiation belt (Allison & Shprits, 2020; Bortnik et al., 2010; Jordano et al., 2001; Thorne & Kennel, 1971). Therefore, the spatial distribution of EMIC waves must be investigated in relation to geomagnetic and solar wind conditions.

Based on observations of the Dynamics Explorer 1 satellite (DE1), Combined Release and Radiation Effects Satellites (CRRES), and Van Allen Probes, previous studies have shown that the occurrence frequency of EMIC waves during magnetic storms is 1.6–5 times higher than that during quiet periods (Erlandson & Ukhorskiy, 2001; Halford et al., 2010; Wang et al., 2016). Observations from the Akebono satellite in the range of 1–3 R_E showed that for $K_p > 7$, the occurrence rates of waves were higher (Kasahara et al., 1992). Based on ground observations, Bortnik et al. (2008) illustrated that the occurrence frequency of Pc1 geomagnetic pulsations was 2–3 times higher than that during the quiet period 2–4 days after a moderate magnetic storm and 4–5 times higher 2–7 days following a strong geomagnetic storm. It can be inferred from these studies that during stronger storm periods, the occurrence frequency of EMIC waves is higher. These works are based on observations in the magnetosphere and from the ground. However, related ionospheric studies concerning the relationship between the storm period and intensity and the number of wave events are lacking. The ionospheric EMIC waves originate from the magnetosphere, which means the ionospheric and magnetospheric waves have a close relationship. However, the wave may change its characteristics

during its propagation from the magnetosphere to the ionosphere, such as reflection, cutoff, mode coupling, ducting, etc. (e.g., Johnson & Cheng, 1999; Rauch & Roux, 1982). The ionosphere is an important region in which EMIC waves propagate from the magnetosphere to the ground. Therefore, it is important to understand the relationships between the occurrence frequency of ionospheric EMIC waves and the dependence on intensity and duration of magnetic storms to complete the full picture.

It is still unclear whether EMIC waves occur mainly in the main or recovery phase of a storm. During the main phase of a storm, an increased number of energetic ions, injected from the plasma sheet, can provide more energy for the generation of EMIC waves (Blum et al., 2009; Halford et al., 2010). Erlandson and Anderson (1996) studied the relationship between ionospheric Pc1 waves and storm phases at dawn and at noon using 15-months electric field data from the Dynamics Explorer 2 satellite. It was discovered that Pc1 pulsations occurred after a magnetic storm, but not always during the recovery phase. Simulations showed that EMIC waves occurred mainly during the storm main phase (Jordanova et al., 2001). Halford et al. (2010) analyzed 119 magnetic storms using CRRES satellite magnetic field observations from 350 km to 6.3 R_E . They discovered that 56.3% of EMIC waves occurred during the main phase and only 35.6% occurred during the recovery phase. When the recovery phase was delayed to 4–6 days after the minimum Dst value, the number of EMIC waves increased slightly, but most events still occurred during the main phase.

However, during the recovery phase of a magnetic storm, the overlapping regions between the ring current and expanding plasmasphere as well as the interaction between hot and cold plasma favors the occurrence of EMIC waves (Engebretson et al., 2008; Fraser et al., 2010; Saikin et al., 2016; Sakaguchi et al., 2008; Wang et al., 2016). By studying isolated auroral arcs and geomagnetic pulsations, Sakaguchi et al. (2008) discovered that isolated arcs related to EMIC waves often happened during the late recovery phase of storms. Engebretson et al. (2008) revealed that no EMIC waves occurred during the main and early recovery phases of two magnetic storms based on ground stations and space technology five satellite observations. Ground-based observations showed that Pc1–2 oscillations always tended to occur during the recovery phase of a storm. Based on a statistical study involving 22 magnetic storms ($Dst < -30$ nT) from 1996 to 2003, Fraser et al. (2010) reported that 71% of EMIC waves occurred in the recovery phase. Saikin et al. (2016) studied EMIC waves in relation to geomagnetic conditions based on Van Allen Probes observations. Their results showed that EMIC waves were more likely to appear in the main phase than in the recovery phase of storms. Kim et al. (2018) studied the distribution of ionospheric EMIC waves with respect to the magnetic local time (MLT) and magnetic latitude (MLat), and they investigated the effect of geomagnetic activity (K_p and Dst), using Swarm satellite observations from December 2013 to June 2017. They discovered that ionospheric EMIC waves were more likely to occur at middle latitudes in the storm late recovery phase. Kim et al. (2018) did not consider the local time distribution of EMIC waves during different storm phases, hence, this will be part of the present study.

Clear MLT differences exist in the occurrence probability of magnetospheric EMIC waves, owing to different physical processes. EMIC waves from various satellite missions in different domains have been analyzed previously, but different results were obtained. From detections by the Charge Composition Explorer (CCE) of the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission, which included L-shells from 3.5 to 9 R_E , Anderson et al. (1992) discovered for the first time that EMIC waves occurred primarily in the afternoon (12–15 MLT) in the outer magnetosphere ($L > 7$). Fraser et al. (2010) studied the distribution of EMIC waves during magnetic storms based on Geostationary Operational Environmental Satellite (GOES) observations. They disclosed that most hydrogen band (H^+) waves emerged at dawn, whereas H^+ and helium (He^+) bands occurred in the dusk. Usanova et al. (2012) analyzed the dependence of EMIC wave occurrences on activity indices AE and SymH, using the Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellite observations from 3 to 14 R_E . They discovered that the occurrence frequency of the afternoon EMIC waves increased with the increase in AE, while the high occurrence rate in the morning was related to an enhanced solar wind dynamic pressure. They noticed that the wave occurrence was rare in the inner magnetosphere. Using THEMIS data, Min et al. (2012) revealed that the He^+ band had a maximum occurrence at dusk in the outer magnetosphere (8–12 R_E), whereas the H^+ band peaked in the morning in the outer magnetosphere (10–12 R_E). Allen et al. (2015) used Cluster satellite data and showed that EMIC waves occurred throughout the entire daytime in the outer magnetosphere. Park et al. (2016) investigated the distribution of EMIC waves with MLT in a geosynchronous orbit. They discovered that

the waves mainly occurred in the 06–16 MLT sector during a quiet period, and around 15–16 MLT during a magnetically disturbed period. Furthermore, Kim et al. (2016) used GOES data but found that EMIC waves mostly occurred during the daytime, with the maximum recorded near noon.

Harford et al. (2010) used CRRES observations and studied the relationship between EMIC waves and magnetic storm phases in the inner magnetosphere. They found that during the main and recovery phases of storms, the EMIC waves mainly occurred in the dusk sector ($L = 6$). Meredith et al. (2014) further studied EMIC waves in relation to the AE index using CRRES data. They discovered that with the increase in AE, waves occurred more frequently in the afternoon sector. However, the CRRES satellite had no observations at 08–14 MLT. Based on Van Allen Probes observations in the inner magnetosphere, Saikin et al. (2015) performed a statistical study of the different bands of EMIC waves. They found that H^+ band EMIC wave showed two peak occurrence regions in the prenoon (09–12 MLT) and afternoon (15–17 MLT). The dayside occurrence rates of He^+ band EMIC waves were larger than the nightside. The He^+ band waves exhibited the highest wave power in the afternoon sector. Furthermore, Saikin et al. (2016) noticed that EMIC waves mainly occurred at prenoon (08–11 MLT, $L = 5.5$) during the quiet period. With the increase in AE, the high occurrence frequency of the waves gradually shifted to 12–18 MLT ($L = 4$ –6). During a magnetic storm, the EMIC waves mainly clustered in the afternoon ($L = 4$). In contrast to Usanova et al. (2012), Saikin et al. (2016) found that the duskside EMIC waves in the inner magnetosphere were related to the enhanced dynamic pressure of the solar wind. By using the Van Allen Probes and GOES observations, Jun et al. (2019) reported that H^+ band waves predominantly occurred outside the plasmasphere with the peak occurrence at 12–15 MLT at $L = 4$ –6. The He^+ band waves occurred mainly in the plasmasphere, with the peak occurrence of He^+ band waves with energetic ion injections at 14–17 MLT at $L = 5.5$ –6.5, and those without injections at 03–14 MLT and at $L = 4$ –6.5. The He^+ band waves were related to the increased H^+ flux within energies of 1–50 keV, while the H^+ showed less relationship with the H^+ flux increase. Using EMIC wave and plasma observations by the Van Allen Probes, Yue et al. (2019) revealed that near the threshold of the proton anisotropy instability, the wave occurrence rate was highest with left polarization and near the magnetic equator. In addition, they found that the waves were distributed in two local time sectors, and the duskside waves were more intense than the noon sector waves.

Kasahara et al. (1992) observed a peak occurrence of extremely low frequency emissions (above the local cyclotron frequency of He^+ or O^+) due to EMIC waves at 17–20 MLT using Akebono satellite observations (1–3 R_E). Bräysy et al. (1998) investigated storm time EMIC waves on April 8, 1993 using Freja satellite observations (600–1,750 km). They revealed that at the beginning of the magnetic storm, EMIC waves tended to occur at higher latitudes in the afternoon, however, during the main phase of the storm, they tended to occur at lower latitudes at night. Park et al. (2013) first investigated the spatial distribution of ionospheric Pc1 pulsations based on 10 years of CHAMP satellite data. They reported that the maximum occurrence rate of Pc1 waves occurred in the early morning. However, they discovered that the magnetic activity could not control the Pc1 occurrence rate. Kim et al. (2018) used Swarm satellite data to study the spatial distribution of EMIC waves during quiet periods. They discovered that EMIC waves appeared mainly in the morning (3–7 MLT). These studies showed that the occurrence rates of the EMIC waves varied with the L values, MLT, and geomagnetic activity. The spatial distribution and propagation characteristics of EMIC waves are yet to be elucidated.

The present work aims to statistically study the local time differences of the occurrence rate of ionospheric EMIC waves during magnetic storms, which can be considered as complementary to the magnetospheric studies. This will contribute to our understanding of the spatial distribution of EMIC wave and their propagation characteristics during storm periods.

The Swarm satellites provide a valuable opportunity to investigate the characteristics of ionospheric EMIC waves during magnetic storms. Swarms can cover most of the magnetic latitudes in a short time range. The satellites cover all magnetic local times during the different storm periods under investigation. This provides a good opportunity to study the local time distribution of EMIC waves in relation to storm phases. In this work, the occurrence rate and duration of EMIC waves and their relationship with storm phases, AL index and solar wind dynamic pressure are studied using Swarm satellite high-precision magnetic field data from 2014 to 2018. To our knowledge, such a comprehensive analysis of ionospheric EMIC waves during storm periods has not been performed previously.

Figure 1. The wave power spectral density plotted vs. time from 05:58 UT to 06:25 UT on March 24, 2015. Two EMIC wave events can be identified centered around 06:00 UT and 06:21 UT. The MLT and MLat values are given along the abscissa together with the UT time. EMIC, electromagnetic ion cyclotron; MLT, magnetic local time; MLat, magnetic latitude.

This article is organized in the following. Section 2 describe the satellite mission and the method of data procession. The statistical results of EMIC waves are presented in Section 3 during magnetic storms. The discussion and final conclusions are presented in Sections 4 and 5.

2. Data Processing Method

The Swarm satellites were launched on November 22, 2013. The orbital inclination was 87.5° and the orbital period was ~ 93 min. The final orbit constellation was reached on April 15, 2014. The longitudinal separation between Swarm A and Swarm C was 1.4° and the altitude was about 460 km. Swarm B flies at ~ 520 km and has a larger inclination. In this work, the 50 Hz vector magnetic field data from both Swarm A and B satellites were utilized with an accuracy of 0.01 nT.

The Savitzky-Golay smoothing filter (1,500 data points as a moving window) was used to filter the 50 Hz magnetic field data to determine the background magnetic field. This method was also utilized by Wang et al. (2019). After the subtraction of the background magnetic field from the original magnetic field data, the wavefield can be determined. Then the wavefield was transformed into the magnetic field-aligned coordinate system. Through the fast Fourier transform, we can derive the ellipticity, normal angle, and power of waves (Allen et al., 2015). Every descending and ascending orbit of Swarm is checked, and the EMIC waves have been identified by eyes. The minimum wave power spectral density is 10^{-7} nT²/Hz. The most probable value of the wave power spectral density of these wave events is within 10^{-4} – 10^{-3} nT²/Hz. The duration of selected EMIC wave events must be longer than 1 min in UT (corresponding to a latitudinal extend of 4°). Because of intense aurorae and field-aligned currents, a wave identification in the auroral regions was impossible. At low-latitude regions the wave signature was associated with plasma bubbles (Lühr et al., 2015). Thus, we identified EMIC waves in the subauroral regions of both hemispheres (from 30° to 60° MLat in the Northern Hemisphere and from -30° to -60° MLat in the Southern Hemisphere, within $L = 1.3$ – 4). For more details about the data processing method one can refer to Wang et al. (2019). Figure 1 shows, as

Table 1

Characteristic Parameters of EMIC Waves in Four Local Time Sectors During the Storm Main and Recovery Phases, as Observed by Swarm A and B in Both Hemispheres

	MLT (HH)	Main phase				Recovery phase			
		Wave no. of events	MLat (°)	Freq. (Hz)	Power density (log nT ² /Hz)	Wave no. of events	MLat (°)	Freq. (Hz)	Power density (log nT ² /Hz)
NH	03–09	6	52.2	1.59	−3.94	82	50.9	1.53	−3.44
	09–15	3	42.6	1.80	−2.42	49	50.1	1.61	−3.41
	15–21	23	47.9	1.69	−3.76	60	50.0	1.19	−3.32
	21–03	20	47.1	1.66	−3.89	70	49.0	1.71	−3.74
SH	03–09	12	−51.2	1.34	−3.88	101	−52.8	1.39	−3.14
	09–15	8	−49.5	0.96	−3.23	76	−49.7	1.37	−3.56
	15–21	37	−46.8	1.63	−3.91	76	−49.4	0.94	−3.29
	21–03	14	−47.2	1.65	−3.73	92	−50.2	1.55	−3.62

The left to right columns show the number of wave events, averaged magnetic latitude, and mean wave frequency corresponding to the peak power density.

an example, the EMIC wave power spectral density as a function of frequency and time from 05:58 to 06:25 UT on March 24, 2015. Swarm A was flying from the northern subauroral region to the southern subauroral region in the dawn sector (about 6.9 MLT). Two EMIC wave events could be identified, which occurred during the storm recovery phase ($Dst_{min} = -222$ nT).

In total, 71 magnetic storms were identified during 2014–2018 satisfying the criteria that the minimum Dst index must fall below -50 nT. Three phases were determined according to the following criteria: The minimum Dst was selected and then stepped backward until the Dst reached a value greater than zero. This interval was defined as the main phase. The preonset phase was defined as 3 h before the onset of the main phase. The recovery phase commences when the Dst starts to recover and lasts until Dst recovered to 10% of the minimum. During the magnetic storms, Swarm A and B observed 753 wave events in total in the subauroral region, of which 317 (436) occurred in the Northern Hemisphere (Southern Hemisphere). There are 52 (71) events occurring in the main phase, and 261 (345) in the recovery phase in the Northern Hemisphere (Southern Hemisphere). Since the main phase is much shorter than the recovery phase, the number of events in the main phase is expected to be smaller. To remove the time difference between the storm main and recovery phase, we have divided the wave time by the observation time to calculate the occurrence rates of the waves during storm main and recovery phases. The UT, MLat, and MLT corresponding to the maximum power density of waves were recorded for every event. Then a statistical analysis of the wave features was performed.

The satellite orbits generally covered all the magnetic local times during the different storm phases. The EMIC wave events were divided into four local time sectors: dawn (03–09 MLT, 52 magnetic storm events), noon (9–15 MLT, 53 storm events), afternoon (15–21 MLT, 55 storm events), and midnight (21–03 MLT, 58 storm events). It can be seen that the number of magnetic storm events in each local time sector is quite comparable. The number of EMIC wave events, average wave frequency, average spectrum power density, and mean magnetic latitude corresponding to the peak power density in these local time sectors during the storm main phase and the recovery phase are listed in Table 1. The number of wave events during the storm main phase is significantly lower than that from the recovery phase. More EMIC wave events occur in 15–21 MLT during the main phase, and the local time sector with the most events is 03–09 MLT during the recovery phase.

The storm time EMIC waves are mostly located at subauroral regions below 55° MLat. Park et al. (2013) calculated the average latitude of Pc1 pulsations under normal condition, as roughly at 55° – 60° MLat, based on CHAMP satellite observations. Using 10 years of CHAMP data, Xiong et al. (2014) found that on the nightside the aurora oval during storms ($Kp > 4$) could extend below 60° MLat. Consistent with this, the storm time wave events in this study are found at lower latitudes. From Table 1, it can be seen that EMIC

Figure 2. The number of EMIC wave events vs. the intensity (left) and duration (right) of magnetic storms in the two hemispheres. The correlation coefficients are given in the upper left corner of the figure. EMIC, electromagnetic ion cyclotron.

waves are located at lower latitudes during the storm main phase, and at higher latitudes during the recovery phase, except for the dawn sector in the Northern Hemisphere. This trend is consistent with the fact that the aurora oval expands equatorward during the storm main phase and shrinks poleward during the recovery phase. The change is also consistent with a contraction of the ring current and enhanced overlap with plasmasphere during the storm period.

If the other factors are constant, one would expect a higher wave frequencies at lower invariant latitudes, corresponding with a stronger geomagnetic field closer to the Earth. Conversely, lower frequencies are expected at higher invariant latitudes. It is found, using observations from ground magnetic stations, that Pc1 oscillations occur at lower latitudes with frequencies higher than those at higher latitudes (Sakaguchi et al., 2008). Consistent with the above theory, the frequency of EMIC waves during the recovery phase is lower than that during the main phase in most of the MLT sectors, except for 21–03 MLT of the Northern Hemisphere, and 03–09, 09–15 MLT of the Southern Hemisphere (see Table 1). The average power density is within 10^{-4} – 10^{-2} nT²/Hz. The power density is larger during the recovery phase than the main phase, except for the 09–15 MLT in the two hemispheres.

3. Statistical Results

3.1. Effect of Storm Intensity and Duration

The minimum in Dst is used to define the storm intensity, and the storm duration is specified as the period from the storm onset to the end of the recovery phase. Figure 2 presents the change of the event number of EMIC waves for each considered storm with the corresponding intensity and duration. The Northern and Southern Hemisphere results are shown in black and red, respectively. The correlation coefficient (R) is given in the upper left corner of the figure. It can be seen that the number of events in the two hemispheres increases with the increasing storm intensity and the correlation is good. This indicates that more EMIC waves occur during stronger storm periods. With the increase of the magnetic storm intensity, the ring current ion energy becomes higher, which is more favorable for the EMIC waves to occur. This result is essentially consistent with magnetospheric and ground-based observations. Erlandson and Anderson (1996) studied the relationship between the monthly occurrence rate of ionospheric Pc1 waves and Dst by using nine months of DE two satellite electric field data. They found more wave events during the months of larger magnetic storms. Erlandson and Ukhorskiy (2001), using a 10-years magnetic field data set from the DE1 satellite, found that EMIC waves in the magnetic equatorial plane occurred 5 times more frequently during a magnetic storm than during quiet periods. When studying low-latitude Pc1 perturbations by using Parkfield ground station observations, Bortnik et al. (2008) report that the total number of waves increased with the increase of the magnetic storm intensity.

Figure 3. The distribution of satellite dwell times in both hemispheres within the magnetic latitude and magnetic local time ranges during the main and recovery phases of storms. The maximum and minimum dwell times are listed in the lower left corner of each subfigure. The inner, middle, and outer circles represent 70°, 50°, and 30° MLat, respectively. The top is at 12 MLT, the bottom is at 00 MLT, the left is at 18 MLT, and the right is at 06 MLT. MP denotes the main phase of a magnetic storm and RP the recovery phase. MLat, magnetic latitude; MLT, magnetic local time.

In Figure 2 (right side), it can be seen that the number of wave events increases with the storm period, as the correlation coefficient is positive. It is generally believed that when magnetic storms last for a long time, the chances of satellites observations of the EMIC waves increase. However, it is also noted that the correlation between the storm duration and the number of wave events is not high. It is important to consider that the period of the magnetic storm depends primarily on the length of the recovery phase. When the magnetic storm recovery phase is longer, the loss of oxygen ions slows down, which inhibits the propagation of the H^+ and He^+ band waves to a lower altitude along the magnetic line (Kozyra et al., 1984). Therefore, it is not conducive to the observation of EMIC waves in the ionosphere. Another important reason for the longer recovery phase can be due to the substorm effect, which supplies fresh particles into the ring current, thus slowing down the recovery of the storm. By using DE1 satellite observations ($3.5 < L < 5$), Erlandson and Ukhorskiy (2001) found that EMIC waves were an important source of the energetic ion loss in the ring current. The strong EMIC waves, produced in the main and early recovery phase, could cause a rapid decrease of the ring current. These factors might be responsible for the fair correlation between the number of EMIC wave events and the duration of the magnetic storm.

Most of the EMIC waves in the two hemispheres occurred within storm main phases (around 16% of the total events) or during recovery phases (around 80% of the total events). Figure 3 shows the distribution of the orbital dwell time of the satellites within MLat and MLT bins during the main phase (MP) and recovery phase (RP) of the storms. Each bin represents 2° in MLat and 2 h in MLT. The area above 70° MLat is not shown. The satellite measurements are roughly equally distributed in MLT, with a dwell time in each MLT-MLat bin higher than 180 min. The orbital dwell time within the recovery phase of a storm is on average 5 times larger than that of the main phase, because the recovery phase lasts significantly longer than the main phase.

Figure 4 shows the distribution of the occurrence frequency of EMIC waves within the MLat and MLT space during the main phase and recovery phase of magnetic storms. The occurrence frequency of waves is defined as the ratio of the total observation time of EMIC wave to the total dwell time spent by Swarm in

Figure 4. The distribution of EMIC wave occurrence frequency (%) in two hemispheres within the magnetic latitude and magnetic local time bins. Bins without events are blank. The peak occurrence rates are listed in the lower left corner of each subfigure. The inner, middle, and outer circles represent 70°, 50°, and 30° MLat, respectively. The top is at 12 MLT, the bottom is at 00 MLT, the left is at 18 MLT, and the right is at 06 MLT. MP denotes the main phase of a magnetic storm and RP the recovery phase. EMIC, electromagnetic ion cyclotron; MLat, magnetic latitude; MLT, magnetic local time.

that bin. During the storm main phase, the EMIC waves are mostly distributed around 18–24 MLT, with a peak rate of about 5% at 18–20 MLT. During the recovery phase, the occurrence rate of EMIC waves in the 18–24 MLT get reduced while in the 00–12 MLT the occurrence rate become enhanced. The highest rates are located in the morning sector (08–10 MLT, about 3%). We further classified the recovery phase into two even parts. During the first half of the recovery phase, the peak occurrence frequency of the EMIC waves tends to occur in the 12–24 MLT sector and in the later recovering phase events prefer to occur around 00–12 MLT. Based on the above feature, it could be concluded that with the temporal evolution of the magnetic storm, there is a trend of westward drift of the peak occurrence rate of EMIC waves, firstly appearing near pre-midnight, then near dusk, and finally on the morning side. In summary, the EMIC waves in the 12–24 MLT sector occur earlier than those around 00–12 MLT. The evolution of preferred local time sectors for EMIC waves during the different storm phases is discussed in Section 4.

3.2. Substorm Effect on EMIC Wave Occurrence

Substorms occur frequently during magnetic storms. In this study, the AE index is used to characterize the intensity of substorm activity to examine the effect of substorms on EMIC waves during magnetic storms. The intensity of a substorm is divided into two ranges: weak substorms ($AE < 200$ nT) and strong substorms ($AE \geq 200$ nT). Figure 5 shows satellite data coverage with respect to the substorm activity. As the AE increases, the amount of dwell time decreases. The orbital time of satellites within each MLT-MLat bin is longer than 400 min.

Figure 6 shows the occurrence frequency of EMIC waves with respect to the substorm activity. As shown in Figure 6, when substorms are relatively weak, the EMIC waves mainly appear on the morning side (02–10 MLT, with a peak incidence of about 4%). As the intensity of the substorm increases, the peak occurrence rate appears before midnight (18–24 MLT, peak incidence about 3%). It can be seen that with enhanced substorm activity the occurrence of EMIC waves shifts from the morning to the dusk-premidnight sector (12–24 MLT).

Figure 5. Same format as Figure 3 but showing the dwell times of the Swarm satellites within a bin under weak and intense magnetic activity conditions in the two hemispheres. The maximum and minimum dwell times are listed in the lower left corner of each subfigure.

Figure 6. Same format as Figure 4 but showing the distribution of EMIC wave occurrence frequency (%) during weak and strong auroral activity in the two hemispheres within the magnetic latitude and magnetic local time bins. The peak occurrence rates are listed in the lower left corner. EMIC, electromagnetic ion cyclotron.

Figure 7. Geographic latitudinal and longitudinal distribution of the occurrence frequency of the storm time EMIC waves in the ionosphere as observed by Swarm. Dashed line at 40° and 60° MLat are added for guiding the eyes. EMIC, electromagnetic ion cyclotron; MLat, magnetic latitude.

It should be noted that in the above analysis, we did not really search for substorms, as it is difficult to classify the satellite dwell time for substorm and nonsubstorm periods. In addition, we separated the wave events into substorm and nonsubstorm periods. The number of events in the four local sectors are divided by the total number of events to calculate the percentage of occurrence. There are 20% (38%) events occurring in 03–09 MLT, 15% (20%) in 09–15 MLT, 37% (21%) in 15–21 MLT, and 28% (21%) in 21–03 MLT during substorm (nonsubstorm) periods. It can be seen that during substorm period, there are more events occurring in the 15–21 MLT, while during nonsubstorm period, there are more events occurring in the 03–09 MLT. This is consistent with the AE-based results.

3.3. Longitudinal Variation of EMIC Waves

The occurrence frequency of EMIC waves during magnetic storms exhibits variations with geographic longitude (GLon) and latitude (GLat), as shown in Figure 7. The results are presented in 30° GLon vs. 2° GLat bins. The storm-time EMIC waves in the two hemispheres are roughly distributed along the midlatitude geomagnetic latitude zone, mainly in the subaurora region. This feature is consistent with the results of Park et al. (2013). In the Northern Hemisphere, waves in the western part are mainly located at lower geographic latitudes, while in the eastern hemisphere they appear at higher geographic latitudes. In the Southern Hemisphere, the opposite trend is found. Both bands follow closely magnetic latitude variations, as indicated by the dashed lines. The longitudinal distribution of EMIC waves in the Northern Hemisphere is relatively uniform, but slightly higher rates are found near East Asia. The longitudinal variation in the Southern Hemisphere differs significantly from that of the Northern Hemisphere, and the EMIC waves are mainly concentrated in the South Atlantic Anomaly (SAA) region (around -30° GLon). By using the CHAMP satellite magnetic field data, Park et al. (2013) studied the variation of the occurrence frequency of Pc1 waves with the geographic longitude during quiet time. They found that the Pc1 waves occurred most frequently at -60° GLon in both hemispheres, and recorded more events in the Northern Hemisphere than

in the Southern Hemisphere. Based on 3.5 years of Swarm observations, Kim et al. (2018) found that the longitudinal difference of EMIC waves was most significant in the Southern Hemisphere at 45° GLon under normal conditions, while it was not significant in the Northern Hemisphere. The results of the present work show that the storm time EMIC waves occur most frequently in the -30 – 30° GLon sector in the Southern Hemisphere (peak rate of 3%). The hemispheric and longitudinal differences among these studies may be related to different activity levels and different periods. Park et al. (2013) and Kim et al. (2018) used the data during the solar cycle 23 and 24, respectively. This paper focuses on magnetic storms periods during the solar cycle 24. The possible causes for longitudinal differences in EMIC wave activity are discussed further in the next section.

4. Discussion

The Swarm satellites provide excellent data coverage of all MLT sectors during the magnetic storm periods within the years from 2014 to 2018. The vast amount of in situ measurements provides an unprecedented opportunity for the study of the local time distribution of EMIC waves during storm phases. Statistical analyses of ionospheric EMIC waves during magnetic storms are relatively rare in the literature. This study shows that most midlatitude EMIC waves in the ionosphere occur during the magnetic storm recovery phase, due to its long duration. This conclusion is consistent with previous observations (Engebretson et al., 2008; Frasier et al., 2010; Kim et al., 2018; Saikin et al., 2016; Sakaguchi et al., 2008; Wang et al., 2016). During the recovery phase of a magnetic storm, the plasmaspheric plume overlaps with the inner edge of the ring current (Fraser & Nguyen, 2001). The interaction of hot and cold plasma is favorable for the occurrence of EMIC waves. In this study, the number of wave events during the recovery phase constitutes 80% of the total wave events, which is slightly higher than that of previous statistical studies owing to our definition of the recovery phase. Fraser et al. (2010) studied 22 magnetic storms ($Dst < -30$ nT) during time period 1996–2003 and found that 71% of EMIC waves in geosynchronous orbits occurred during the recovery phase. Saikin et al. (2016) and Wang et al. (2016) used Van Allen Probes data and found that $\sim 64\%$ of EMIC waves occurred in the recovery phase in the inner magnetosphere. The difference between this study and previous statistical studies might be due to the different definitions of the storm recovery phase. In our work, the recovery phase ended when Dst recovered 90% of the minimum, whereas in previous studies, the recovery phase ended when Dst recovered 80% of the minimum.

Another point we want to address is that, as outlined above, previous works focused on the comparison of the number of wave events between the storm main phase and recovery phase (e.g., Fraser et al., 2010; Halford et al., 2010; Wang et al., 2016). Saikin et al. (2016) calculated the occurrence rate of waves by dividing the total time of waves in the main phase or recovery phase by the total time of waves during the whole storm. Such comparison might be biased because the main phase of the storm is shorter than the recovery phase. From the wave occurrence frequency shown in Figure 4, it can be seen that the peak occurrence rate in the main phase is indeed higher than during the recovery phase. This implies that, in general, EMIC waves occur more frequently in the main phase.

4.1. Local Time Distribution of EMIC Waves

We have analyzed the distribution of ionospheric EMIC waves over local time during different storm phases. It is discovered that during the storm main phase, most EMIC waves occur from premidnight to dusk, with peaks at 18–20 MLT in the two hemispheres. To our best knowledge, this is the first study that investigates the local time distribution of ionospheric EMIC waves during storm periods, although many similar studies have been conducted regarding the magnetosphere.

Previous observations from outer magnetosphere satellites indicated that EMIC waves tend to occur in the afternoon during magnetic storms, whereas EMIC waves rarely occur near midnight. Using data from the GOES spacecraft, Fraser et al. (2010) discovered that EMIC waves occurred frequently during magnetic storms in the afternoon, and that these waves were related to high-energy ion injections from the plasmasheet during substorms and storms. Based on CRRES satellite observations of 119 magnetic storms, Halford et al. (2010) found that the average position of EMIC waves was $L = 5.89$ and $MLT = 15.5$ h, and that few wave events occurred in the morning and at midnight. It is noteworthy that the CRRES orbit could

not collect data from dawn to noon. Keika et al. (2013) studied EMIC waves in the magnetosphere using AMPTE/CCE satellite data from August 1984 to January 1989 (4.5 years), and they discovered that the wave occurrence in the afternoon ($L > 7$) was the highest, irrespective of the magnetic activity. The waves in the inner magnetosphere were extremely weak but increased in intensity during the magnetic storm periods. They discovered that the occurrence of waves at night in both the inner and outer magnetospheres was extremely low. Using THEMIS satellite observations, Usanova et al. (2010) studied 26 magnetic storms with $Dst \leq -50$ nT, and demonstrated that the occurrence frequency of EMIC waves in the inner magnetosphere was lower than 10%. Hence, they doubted the ability of EMIC waves in affecting the dynamics of energetic particles during storm periods.

Satellite observations in the inner magnetosphere, however, indicated a slight increase in the nighttime EMIC wave activity during magnetic storms. Based on Van Allen Probes observations (September 2012 to June 2014), Saikin et al. (2016) showed that under disturbed conditions, the peak occurrence rate (25%) of EMIC waves was in the afternoon at $L = 4$ –6, and the waves occurrence increased at midnight compared to quiet periods. Wang et al. (2016) discovered that 30% of EMIC waves mainly occurred from noon to dusk at higher L-shell regions, and that 15% appeared from night to dawn on lower L-shells. In the storm recovery phase, EMIC waves occurred at nearly at all local times. The differences in wave occurrence peaks during magnetic storms can be partially explained by the satellite orbit heights.

Statistical results in the ionosphere indicate that EMIC waves are dominated from midnight to dusk during the main phase of a magnetic storms. These EMIC waves are located on average at 45° – 55° MLat (see Table 1). When projected along magnetic lines to the magnetic equatorial plane the region is approximately in the range of 2–3 R_E . This result is supported by previous typical case studies involving the ionosphere. Bräysy et al. (1998) studied a geomagnetic storm from April 2–8, 1993 based on electric field observations from the low-altitude ionospheric Freja satellite. They discovered that EMIC waves were primarily located at 12–18 MLT in the preonset phase of the magnetic storm. The high occurrence rate of EMIC waves during the main phase of the magnetic storm shifted to the dusk-premidnight sector (18–24 MLT). During the recovery phase, the EMIC waves mainly occurred near midnight and in the early morning. Kasahara et al. (1992) revealed that both He^+ and H^+ gyroscopic waves were frequently observed at night based on the Akebono satellite observations over a height range of 3,000–5,500 km. Furthermore, EMIC or Pc1–2 waves observed by satellites and ground instruments under normal conditions varied with the L value. At $L = 2$, the occurrence of Pc1 maximized at 01–06 MLT, at $L = 4$, it maximized at 02–10 MLT, whereas at $L = 5.6$, the peak occurred in the afternoon (Campbell & Stiltner, 1965; Heacock & Hessler, 1962).

The present study discovers that EMIC waves occur primarily in the morning during the late recovery phase of storms. This is consistent with the simulation study of Jordanova et al. (1996). A modeling of the temporal variation of the energetic distribution function demonstrated that the particle distribution during the later recovery phase favored the generation of Pc1 pulsations in the morning sector (Jordanova et al., 1996).

Previous studies showed that EMIC waves occurred more frequently in the morning during geomagnetic quiet periods, which was assumed to be related to the increased solar wind pressure. For example, Park et al. (2016) discovered that during quiet periods, the dynamic pressure significantly affected the appearance of EMIC waves at geosynchronous orbit, particularly in the morning, which exhibited a dawn-dusk asymmetry. Using THEMIS satellite observations, Usanova et al. (2012) revealed that the occurrence of EMIC waves in the morning increased with the dynamic pressure. Based on Van Allen Probes observations, Wang et al. (2016) disclosed that EMIC waves peaked immediately before noon (08–11 MLT) during quiet periods. Saikin et al. (2016) reported that EMIC waves under quiet conditions ($AE < 100$ nT) occurred mainly before noon (08–11 MLT), and at $L = 5.5$, however, in their opinion, the dawn EMIC waves were related to increased solar wind dynamic pressure. Lee et al. (2014) proposed an alternative explanation for the occurrence of EMIC waves at dawn. They speculated that dawn waves were generated outside the magnetic equator and that the polarization can be altered when the wave propagated through a warm plasma cloak. The warm plasma cloak comprises heavy ions and typically occurs at dawn (e.g., Chappell et al., 2008). It is noteworthy that the magnetic activity indices (AL, Kp, etc.) can vary significantly during the storm recovery phase. Hence, the recovery phase does not necessarily correspond to the period of geomagnetic quiet time described by the AE or Kp. Halford et al. (2016) carefully investigated the characteristics of the occurrence of waves that varied with the storm phases, as well as the AE, and Kp indices. They demonstrated that

Table 2
Occurrence Probability of EMIC Waves During Solar Wind Pressure Enhancements Over Different Local Time Sectors and Over Different Magnetic Storm Phases

	MLT (hh)				Storm phase		
	03–09	09–15	15–21	21–03	Prestorm	Main phase	Recovery phase
Occ. Freq. (%)	21	27	44	31	76	68	21

the ability of storm phases in controlling waves was much better than that of geomagnetic indices. The temperature anisotropy and changes in the free energy available for wave excitation are reflected more clearly by the magnetic storm phases rather than by specific values of geomagnetic indices.

To investigate the local time effect of the solar wind dynamic pressure, we analyze the time range within 50% of the peak of an enhanced dynamic pressure interval. The enhancement in the solar wind dynamic pressure during such an interval should be greater than 0.5 nPa. The number of EMIC wave events that occur during the dynamic pressure enhancement periods is divided by the total number of events for calculating the occurrence rate. Table 2 lists the occurrence rate due to the enhanced solar wind dynamic pressure during different phases of a storm and at different local times. It is clear, that the dynamic pressure is most effective during the preonset phase and in the afternoon. During the preonset period ~76% of the EMIC waves occur owing to an enhanced pressure. This result is comparable to the results of Wang et al. (2016) where 80% of the EMIC waves within the early stage of a magnetic storm were associated with increased dynamic pressure based on Van Allen Probes observations. Our work indicates that waves in the afternoon are more related to the enhanced dynamic pressure. This is consistent with the observations of Saikin et al. (2016). Saikin et al. (2016) discovered that with an increase in solar wind dynamic pressure ($P_{\text{dyn}} > 3$ nPa), EMIC waves in the inner magnetosphere mainly occurred in the afternoon. The intensity of the effect of solar wind dynamic pressure on wave occurrences in the outer or inner magnetosphere seems to be different. The effect of the dynamic pressure is observed during the entire dayside in the outer magnetosphere (e.g., Anderson et al., 1992a; Usanova et al., 2012), but the influence on the inner magnetosphere is most effective in the afternoon. Under an enhanced dynamic pressure condition, the splitting of drift shells and the Shabansky mechanism provide ion anisotropies that contribute to the generation of EMIC waves (Usanova et al., 2012).

4.2. Storm Phase Dependent EMIC Wave Occurrences in Different Local Time Sectors

In this study, when analyzing the occurrence rates of EMIC waves during different storm phases, it is found that most of the waves during the main phase occur within 12–24 MLT, and the peak occurrence rate of EMIC waves during the recovery phase appears near dawn. This indicates that the waves in the 12–24 MLT sector occur earlier than those within 00–12 MLT. For checking the evolution during the recovery, we take

Figure 8. Relative timing of EMIC waves during the recovery phase within the 00–12 MLT vs. the 12–24 MLT sector. The relative time is defined as the ratio of the time difference between the EMIC wave after the minimum Dst divided by the full storm recovery period. EMIC, electromagnetic ion cyclotron; MLT, magnetic local time.

the time difference from the Dst minimum (Δt) to the EMIC wave, and divide it by the full recovery period (T_{rec}). The ratio ($\Delta t/T_{\text{rec}}$) is defined as the relative time of wave occurrence. In Figure 8, the relative time distributions of recovery phase EMIC waves in the two local time sectors (00–12 MLT and 12–24 MLT) is presented. The red symbols represent events in the Northern Hemisphere, and blue in the Southern Hemisphere. The diagonal dashed line marks the identical relative times in both local time sectors. Clearly, most points in the figure are above the dashed line, indicating that wave events in the 12–24 MLT sector occur preferably in the earlier part of the recovery phase than those within 00–12 MLT. Our statistical results are consistent with those from the case study by Wang et al. (2019). Wang et al. (2019) investigated the storm time EMIC waves during June 21–29, 2015, and found that the waves in the premidnight sector occurred earlier than those around prenoon during the recovery period in response to the substorm.

The effects of substorms are most effective in the premidnight sector (as shown in Figure 6) and during the storm main phase (figure not shown). Substorms can provide a large amount of particle energies for the enhancement of the ring current, which in turn offer energies for the generation of EMIC waves. Substorms mainly commence in the premidnight

Figure 9. Longitudinal variation of the total magnetic field strength at the mean locations of high EMIC wave occurrence rates, separately for the two hemispheres. EMIC, electromagnetic ion cyclotron.

sector, which can account for the high appearance of EMIC waves in the premidnight sector. A possible explanation for EMIC local time evolution could be, it takes time for the energetic ions to drift from the premidnight sector to the early morning sector due to the combined role of magnetic field gradient and curvature. In addition, the drift paths of these high-energy ions are further away from the Earth in the morning sector. Another possibly, Goldstein and Sandel (2005) found that during the early storm recovery phase the plasmaspheric plume was well developed on the evening side, and it rotated within the later recovery phase past midnight to the morning side. The resulting overlap area of the plasmasphere in the morning sector with the high-energy ions of the ring current are favorable for wave excitation. These factors may be responsible for the appearance of EMIC waves on the morning side at a later time than those in the dusk sector.

4.3. Longitudinal Variation of EMIC Waves

In this study, we examine the variation of the occurrence frequency of EMIC waves within geographic longitude and latitude during storm periods in the two hemispheres. The results of this work show that the storm

time EMIC waves occur most frequently between -30° – 30° GLon in the Southern Hemisphere. Figure 9 shows the variation of the geomagnetic field strength over geographic longitude at latitudes where EMIC waves prefer to occur. As shown in the figure, the abnormally low geomagnetic field in the SAA region corresponds to the peak in occurrence rate of the waves, which indicates that with the weaker magnetic field, the EMIC waves are more likely to occur. Possible reasons might be related to the drift shell splitting. Particles with larger pitch angle drift along the fixed value of magnetic field contour, while particles with lower pitch angle follow a round path of drift. Consequently, those particles with larger pitch angle will move more inward at SAA region than those with lower pitch angle. The anisotropic distribution of the energetic ions with different pitch angles favor the generation of EMIC waves. This suggestion is further supported by the following result as shown in Figure 10. We have studied the longitudinal distribution of the wave occurrence during the storm main and recovery phases, separately. It shows that the event concentration around 0° GLon is obvious in both hemispheres during the main phase, and it becomes weaker in the Northern Hemisphere during the recovery phase. When the ring current comes closer to the Earth during the main phase, the anomalous field distribution in the SAA becomes more prominent along the drift shells. Another possible reason might be associated with the wave propagation under a weakened magnetic field. The Alfvén velocity gets decreased within the SAA region, which suppresses wave leakage to the ground. Thus, EMICs can be more easily observed by Swarm satellite in the ionosphere. In the Northern Hemisphere, the longitudinal variation of magnetic field intensity is not so obvious as it is in the Southern Hemisphere. This corresponds to the relatively small longitudinal difference in the occurrence rate of EMIC waves in the Northern Hemisphere, further confirming the important role of the geomagnetic field strength in the propagation of EMIC waves.

5. Summary

Based on the high-precision vector magnetic field data from Swarm satellites, we conduct a statistical study on the spatial distribution of ionospheric electromagnetic ion cyclotron (EMIC) waves during storm periods of the years 2014–2018. The focus is on the magnetic local time (MLT) variation of the occurrence probability of EMIC waves in relation to the different storm phases. The global distribution of the storm time EMIC waves is also analyzed. A number of interesting results are found. These may be summaries as follows:

1. With the increase of intensity and duration of magnetic storms, more EMIC events are observed. However, the correlation coefficient between the storm durations and the numbers of EMIC waves is not good
2. Larger numbers of EMIC wave events are observed during the recovery phase, while the occurrence rate is higher in the main phase. During the main phase the EMIC waves preferably appear in the dusk to premidnight sector, while more events occur at dawn in the late recovery phase

Figure 10. Geographic latitudinal and longitudinal distribution of the occurrence frequency of the storm time EMIC waves in the ionosphere as observed by Swarm. Top is in the Northern Hemisphere and bottom is in the Southern Hemisphere. Left is in the main phase and right is in the recovery phase. EMIC, electromagnetic ion cyclotron.

3. The solar wind dynamic pressure has an important effect on the duskside EMIC waves during the quiet time before storm onset. With the enhancement of the substorm activity, the peak occurrence rate of EMIC waves moves from the morning side to the duskside
4. In the storm recovery phase the EMIC waves in the 12–24 MLT occur earlier than those in the 00–12 MLT sector
5. The South Atlantic Anomaly region exhibits higher ionospheric EMIC wave occurrences, which might be related to the drift shell splitting in the weak magnetic field region

Data Availability Statement

The 50-Hz magnetic field data from Swarm satellite are retrieved at <http://swarm-diss.eo.esa.int>. The solar wind and interplanetary magnetic field data are available at NASA/GSFC'S Space Physics Data Facility's OMNIWeb (<https://omniweb.gsfc.nasa.gov>). The availability of data from these websites to the public is appreciated.

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References

- Allen, R. C., Zhang, J.-C., Kistler, L. M., Spence, H. E., Lin, R.-L., Klecker, B., et al. (2015). A statistical study of EMIC waves observed by cluster: 1. Wave properties. *Journal of Geophysical Research: Space Physics*, 120, 5574–5592. <https://doi.org/10.1002/2015JA021333>
- Allison, H. J., & Shprits, Y. Y. (2020). Local heating of radiation belt electrons to ultra-relativistic energies. *Nature Communications*, 11, 4533. <https://doi.org/10.1038/s41467-020-18053-z>
- Anderson, B. J., Erlandson, R. E., & Zanetti, L. J. (1992). A statistical study of Pc 1–2 magnetic pulsations in the equatorial magnetosphere: 1. Equatorial occurrence distributions. *Journal of Geophysical Research*, 97(A3), 3075–3088. <https://doi.org/10.1029/91JA02706>
- Blum, L. W., MacDonald, E. A., Gary, S. P., Thomsen, M. F., & Spence, H. E. (2009). Ion observations from geosynchronous orbit as a proxy for ion cyclotron wave growth during storm times. *Journal of Geophysical Research*, 114, A10214. <https://doi.org/10.1029/2009JA014396>

- Bortnik, J., Cutler, J. W., Dunson, C., Bleier, T. E., & McPherron, R. L. (2008). Characteristics of low-latitude Pc1 pulsations during geomagnetic storms. *Journal of Geophysical Research*, 113, A04201. <https://doi.org/10.1029/2007ja012867>
- Bortnik, J., & Thorne, R. M. (2010). Transit time scattering of energetic electrons due to equatorially confined magnetosonic waves. *Journal of Geophysical Research*, 115, A07213. <https://doi.org/10.1029/2010JA015283>
- Bräysy, T., Mursula, K., & Marklund, G. (1998). Ion cyclotron waves during a great magnetic storm observed by Freja double-probe electric field instrument. *Journal of Geophysical Research*, 103(A3), 4145–4155. <https://doi.org/10.1029/97JA02820>
- Campbell, W. H., & Stiltner, E. C. (1965). Some characteristics of geomagnetic pulsations at frequencies near 1 c/s. *Journal of Research of the National Bureau of Standards Section D Radio Science*, 69D(8), 1117–1132. <https://doi.org/10.6028/jres.069D.119>
- Chappell, C. R., Huddleston, M. M., Moore, T. E., Giles, B. L., & Delcourt, D. C. (2008). Observations of the warm plasma cloak and an explanation of its formation in the magnetosphere. *Journal of Geophysical Research*, 113, A09206. <https://doi.org/10.1029/2007JA012945>
- Cornwall, J. M. (1965). Cyclotron instabilities and electromagnetic emission in the ultralow frequency and very low frequency ranges. *Journal of Geophysical Research*, 70(1), 61–69. <https://doi.org/10.1029/JZ070i001p00061>
- Engelbreton, M. J., Lessard, M. R., Bortnik, J., Green, J. C., Horne, R. B., Detrick, D. L., et al. (2008). Pc1-Pc2 waves and energetic particle precipitation during and after magnetic storms: Superposed epoch analysis and case studies. *Journal of Geophysical Research*, 113, A01211. <https://doi.org/10.1029/2007JA012362>
- Erlandson, R. E., & Anderson, B. J. (1996). Pc 1 waves in the ionosphere: A statistical study. *Journal of Geophysical Research*, 101(A4), 7843–7857. <https://doi.org/10.1029/96JA00082>
- Erlandson, R. E., & Ukhorskiy, A. J. (2001). Observations of electromagnetic ion cyclotron waves during geomagnetic storms: Wave occurrence and pitch angle scattering. *Journal of Geophysical Research*, 106(A3), 3883–3895. <https://doi.org/10.1029/2000ja000083>
- Fraser, B. J., Grew, R. S., Morley, S. K., Green, J. C., Singer, H. J., Loto'aniu, T. M., & Thomsen, M. F. (2010). Storm time observations of electromagnetic ion cyclotron waves at geosynchronous orbit: GOES results. *Journal of Geophysical Research*, 115, A05208. <https://doi.org/10.1029/2009JA014516>
- Fraser, B. J., & Nguyen, T. S. (2001). Is the plasmapause a preferred source region of electromagnetic ion cyclotron waves in the magnetosphere? *Journal of Atmospheric and Solar-Terrestrial Physics*, 63(11), 1225–1247. [https://doi.org/10.1016/S1364-6826\(00\)00225-X](https://doi.org/10.1016/S1364-6826(00)00225-X)
- Goldstein, J., & Sandel, B. (2005). The global pattern of evolution of plasmaspheric drainage plumes. *Geophysical Monograph*, AGU, 159, 1.
- Halford, A. J., Fraser, B. J., & Morley, S. K. (2010). EMIC wave activity during geomagnetic storm and nonstorm periods: CRRES results. *Journal of Geophysical Research*, 115, A12248. <https://doi.org/10.1029/2010JA015716>
- Halford, A. J., Fraser, B. J., Morley, S. K., Elkington, S. R., & Chan, A. A. (2016). Dependence of EMIC wave parameters during quiet, geomagnetic storm, and geomagnetic storm phase times. *Journal of Geophysical Research: Space Physics*, 121, 6277–6291. <https://doi.org/10.1002/2016JA022694>
- Heacock, R. R., & Hessler, V. P. (1962). Pearl-type telluric current micropulsations at College. *Journal of Geophysical Research*, 67(10), 3985–3995. <https://doi.org/10.1029/JZ067i010p03985>
- Horne, R. B., & Thorne, R. M. (1993). On the preferred source location for the convective amplification of ion cyclotron waves. *Journal of Geophysical Research*, 98(A6), 9233–9247. <https://doi.org/10.1029/92JA02972>
- Johnson, J. R., & Cheng, C. Z. (1999). Can ion cyclotron waves propagate to the ground? *Geophysical Research Letters*, 26(6), 671–674. <https://doi.org/10.1029/1999GL900074>
- Jordanova, V. K., Farrugia, C. J., Thorne, R. M., Khazanov, G. V., Reeves, G. D., & Thomsen, M. F. (2001). Modeling ring current proton precipitation by electromagnetic ion cyclotron waves during the May 14–16, 1997, storm. *Journal of Geophysical Research*, 106(A1), 7–22. <https://doi.org/10.1029/2000JA002008>
- Jordanova, V. K., Kozyra, J. U., & Nagy, A. F. (1996). Effects of heavy ions on the quasi-linear diffusion coefficients from resonant interactions with electromagnetic ion cyclotron waves. *Journal of Geophysical Research*, 101(A9), 19771–19778. <https://doi.org/10.1029/96JA01641>
- Jun, C.-W., Yue, C., Bortnik, J., Lyons, L. R., Nishimura, Y. T., Kletzing, C. A., et al. (2019). A statistical study of EMIC waves associated with and without energetic particle injection from the magnetotail. *Journal of Geophysical Research: Space Physics*, 124, 433–450. <https://doi.org/10.1029/2018JA025886>
- Kasahara, Y., Sawada, A., Yamamoto, M., Kimura, I., Kokubun, S., & Hayashi, K. (1992). Ion cyclotron emissions observed by the satellite Akebono in the vicinity of the magnetic equator. *Radio Science*, 27(2), 347–362. <https://doi.org/10.1029/91RS01872>
- Keika, K., Takahashi, K., Ukhorskiy, A. Y., & Miyoshi, Y. (2013). Global characteristics of electromagnetic ion cyclotron waves: Occurrence rate and its storm dependence. *Journal of Geophysical Research: Space Physics*, 118, 4135–4150. <https://doi.org/10.1002/jgra.50385>
- Kim, K. H., Omura, Y., Jin, H., & Hwang, J. (2016). A case study of EMIC waves associated with sudden geosynchronous magnetic field changes. *JGR*, 122, 3322–3341. <https://doi.org/10.1002/2016JA023391>
- Kim, H., Hwang, J., Park, J., Bortnik, J., & Lee, J. (2018). Global characteristics of electromagnetic ion cyclotron waves deduced from Swarm satellites. *Journal of Geophysical Research: Space Physics*, 123, 1325–1336. <https://doi.org/10.1002/2017JA024888>
- Kozyra, J. U., Cravens, T. E., Nagy, A. F., Fonthelm, E. G., & Ong, R. S. B. (1984). Effects of energetic heavy ions on electromagnetic ion cyclotron wave generation in the plasmapause region. *Journal of Geophysical Research*, 89(A4), 2217–2233. <https://doi.org/10.1029/JA089iA04p02217>
- Lee, J. H., & Angelopoulos, V. (2014). Observations and modeling of EMIC wave properties in the presence of multiple ion species as function of magnetic local time. *Journal of Geophysical Research: Space Physics*, 119, 8942–8970. <https://doi.org/10.1002/2014JA020469>
- Lühr, H., Park, J., Gjerloev, J. W., Rauberg, J., Michaelis, I., Merayo, G. J. M., & Brauer, P. (2015). Field-aligned currents' scale analysis performed with the Swarm constellation. *Geophysical Research Letters*, 42, 1–8. <https://doi.org/10.1002/2014GL062453>
- Meredith, N. P., Horne, R. B., Kersten, T., Fraser, B. J., & Grew, R. S. (2014). Global morphology and spectral properties of EMIC waves derived from CRRES observations. *Journal of Geophysical Research: Space Physics*, 119, 5328–5342. <https://doi.org/10.1002/2014JA020064>
- Min, K., Lee, J., Keika, K., & Li, W. (2012). Global distribution of EMIC waves derived from THEMIS observations. *Journal of Geophysical Research*, 117, A05219. <https://doi.org/10.1029/2012JA017515>
- Park, J., Lühr, H., & Rauberg, J. (2013). Global characteristics of Pc1 magnetic pulsations during solar cycle 23 deduced from CHAMP data. *Annales Geophysicae*, 31, 1507–1520. <https://doi.org/10.5194/angeo-31-1507-2013>
- Park, J. S., Kim, K. H., Shiokawa, K., Lee, D.-H., Lee, E., Kwon, H. J., et al. (2016). EMIC waves observed at geosynchronous orbit under quiet geomagnetic conditions ($K_p \leq 1$). *Journal of Geophysical Research: Space Physics*, 121, 1377–1390. <https://doi.org/10.1002/2015JA021968>
- Rauch, J. L., & Roux, A. (1982). Ray tracing of ULF waves in a multicomponent magnetospheric plasma—Consequences for the generation mechanism of ion cyclotron waves. *Journal of Geophysical Research*, 87(A10), 8191–8198. <https://doi.org/10.1029/JA087iA10p08191>
- Saikin, A. A., Zhang, J.-C., Allen, R. C., Smith, C. W., Kistler, L. M., Spence, H. E., et al. (2015). The occurrence and wave properties of H^+ , He^+ , and O^+ -band EMIC waves observed by the Van Allen Probes. *Journal of Geophysical Research: Space Physics*, 120, 7477–7492. <https://doi.org/10.1002/2015JA021358>

- Saikin, A. A., Zhang, J. C., Smith, C. W., Spence, H. E., Torbert, R. B., & Kletzing, C. A. (2016). The dependence on geomagnetic conditions and solar wind dynamic pressure of the spatial distributions of EMIC waves observed by the Van Allen Probes. *Journal of Geophysical Research: Space Physics*, 121, 4362–4377. <https://doi.org/10.1002/2016JA022523>
- Sakaguchi, K., Shiokawa, K., Miyoshi, Y., Otsuka, Y., Ogawa, T., Asamura, K., & Connors, M. (2008). Simultaneous appearance of isolated auroral arcs and Pc 1 geomagnetic pulsations at subauroral latitudes. *Journal of Geophysical Research*, 113, A05201. <https://doi.org/10.1029/2007JA012888>
- Thorne, R. M., & Kennel, C. F. (1971). Relativistic electron precipitation during magnetic storm main phase. *Journal of Geophysical Research*, 76(19), 4446–4453. <https://doi.org/10.1029/JA076i019p04446>
- Usanova, M. E., Mann, I. R., Bortnik, J., Shao, L., & Angelopoulos, V. (2012). THEMIS observations of electromagnetic ion cyclotron wave occurrence: Dependence on AE, SYMH, and solar wind dynamic pressure. *Journal of Geophysical Research*, 117, A10218. <https://doi.org/10.1029/2012JA018049>
- Wang, D., Yuan, Z., Yu, X., Huang, S., Deng, X., Zhou, M., & Li, H. (2016). Geomagnetic storms and EMIC waves: Van Allen Probe observations. *Journal of Geophysical Research: Space Physics*, 121, 6444–6457. <https://doi.org/10.1002/2015JA022318>
- Wang, H., He, Y., Lühr, H., Kistler, L., Saikin, A., Lund, E., & Ma, S. (2019). Storm time EMIC waves observed by Swarm and Van Allen Probe satellites. *Journal of Geophysical Research: Space Physics*, 124, 293–312. <https://doi.org/10.1029/2018JA026299>
- Xiong, C., Lühr, H., Wang, H., & Johnsen, M. G. (2014). Determining the boundaries of the auroral oval from CHAMP field-aligned current signatures. *Annales Geophysicae*, 32(6), 609–622. <https://doi.org/10.5194/angeo-32-609-2014>
- Yue, C., Jun, C.-W., Bortnik, J., An, X., Ma, Q., Reeves, G. D., et al. (2019). The relationship between EMIC wave properties and proton distributions based on Van Allen probes observations. *Geophysical Research Letters*, 46, 4070–4078. <https://doi.org/10.1029/2019GL082633>
- Zhang, J. C., Saikin, A. A., Kistler, L. M., Smith, C. W., Spence, H. E., Mouikis, C. G., et al. (2014). Excitation of EMIC waves detected by the Van Allen Probes on 28 April 2013. *Geophysical Research Letters*, 41, 4101–4108. <https://doi.org/10.1002/2014GL060621>