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Whistler Mode Quasiperiodic Emissions: Contrasting Van Allen Probes and DEMETER Occurrence Rates

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Key Points:

- Van Allen Probes observe the quasiperiodic events at all local times and longitudes, but more often during spring and autumn seasons
- DEMETER observes the events nearly exclusively during the day, with a significant longitudinal variation and minimum occurrence in July
- The difference is explained by nondipolar Earth's magnetic field and by background wave intensities complicating DEMETER observations

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Abstract Quasiperiodic emissions are magnetospheric whistler mode waves at frequencies between about 0.5 and 4 kHz which exhibit a nearly periodic time modulation of the wave intensity. We use large data sets of events observed by the Van Allen Probes in the equatorial region at larger radial distances and by the low-altitude DEMETER spacecraft. While Van Allen Probes observe the events at all local times and longitudes, DEMETER observations are limited nearly exclusively to the daytime and significantly less frequent at the longitudes of the South Atlantic Anomaly. Further, while the events observed by Van Allen Probes are smoothly distributed over seasons with only mild maxima in spring/autumn, DEMETER occurrence rate has a single pronounced minimum in July. The apparent inconsistency is explained by considering a nondipolar Earth's magnetic field and significant background wave intensities which in these cases prevent the quasiperiodic events from being identified in DEMETER data.

1. Introduction

Quasiperiodic (QP) emissions are magnetospheric whistler mode electromagnetic waves whose intensity exhibits a nearly periodic temporal modulation. The events are typically observed at frequencies between about 0.5 and 4 kHz, and their modulation periods may range from some tens of seconds up to a few minutes (Carson et al., 1965; Hayosh et al., 2014; Němec et al., 2018). The emissions are believed to be generated in the equatorial region at larger radial distances, possibly close to the plasmapause (Němec et al., 2018; Sato & Kokubun, 1980; Morrison, 1990). Historically, the events were classified using ground-based observations as "Type 1" and "Type 2", depending on whether or not magnetic field pulsations corresponding to the QP modulation were simultaneously observed (Kitamura et al., 1969; Sato et al., 1974; Sato & Kokubun, 1981). It was suggested that QP emissions of Type 1 might be formed due to a source modulation by ultralow frequency (ULF) waves (Chen, 1974; Kimura, 1974; Sazhin, 1987). An alternative generation mechanism due to an autooscillation regime of the wave generation based on the flow cyclotron maser (Demekhov & Trakhtengerts, 1994; Pasmanik et al., 2004) is able to explain the QP modulation without the presence of modulating ULF waves (QP Type 2). We note, however, that the QP Type 1 and QP Type 2 classification becomes questionable when spacecraft observations are used (Sazhin & Hayakawa, 1994; Tixier & Cornilleau-Wehrlin, 1986). Furthermore, the ULF pulsations observed on the ground along with QP emissions Type 1 do not have to be related to the QP generation itself, as they may be eventually generated in the ionosphere (Sato & Matsudo, 1986) due to energetic electrons periodically precipitated by the emissions (Gołkowski & Inan, 2008; Hayosh et al., 2013).

Multicomponent satellite measurements (Martinez-Calderon et al., 2016; Němec et al., 2013, 2014; Titova et al., 2015) indicate that the emissions propagate unducted, with plasmapause guiding (Hayosh et al., 2016) and ionospheric reflection (Hanzelka et al., 2017; Xia et al., 2019) possibly important for their propagation down to low altitudes. This seems to be consistent with a large spatial extent of the emissions revealed by multipoint observations (Němec et al., 2013, 2016; Němec, Hospodarsky et al., 2016; Titova et al., 2015). Ground-based observations, on the other hand, enable observations of a given event for an extensive period of time and an analysis of its temporal variations (Manninen et al., 2012). This was used to demonstrate variations of QP modulation periods possibly related to substorms (Manninen et al., 2013, 2014a, 2014b).

While according to both ground-based (Engebretson et al., 2004; Morrison et al., 1994; Smith et al., 1998) and low-altitude satellite (Hayosh et al., 2014) surveys the emissions appear to be primarily daytime phenomenon, satellite surveys at larger radial distances (Němec et al., 2013, 2018) revealed the emissions at principally all local times, with a slight preference for the dusk sector. In the present study, we contrast the occurrence rates of QP emissions as observed by the Van Allen Probes at large radial distances and the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) spacecraft at low radial distances, and we attempt to explain the obtained discrepancies. The data set is introduced in section 2. The obtained results are presented in section 3. They are discussed and briefly summarized in section 4.

2. Data Set

We use large data sets of QP events compiled in former studies. Specifically, we use a set of 768 QP events identified in 5 years of the Van Allen Probes data by Němec et al. (2018) and a set of 2,264 QP events identified in 6.5 years of the DEMETER spacecraft data by Hayosh et al. (2014). Both these data sets were manually compiled by visually identifying the emissions in frequency-time spectrograms of wave intensities measured by the respective spacecraft. For each of the identified events, its beginning and ending times are marked, which serve as a starting point for the present analysis.

The Van Allen Probes mission consists of a pair of identical spacecraft following each other on highly elliptical orbits close to the equatorial plane with the perigee altitude of about 600 km and the apogee altitude of about 32,000 km. Power spectral densities of magnetic field fluctuations in the frequency range between 2 Hz and 12 kHz (64 logarithmically spaced frequency channels) are measured with a time resolution of 6 s by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) Waves instrument in its survey mode (Kletzing et al., 2013). The orbit of DEMETER had an altitude of about 660 km and it was quasi Sun-synchronous, so that the measurements were always performed at local times close to either 10:30 or 22:30 hours. Power spectral densities of electric field fluctuations in the frequency range between 20 Hz and 20 kHz (1,024 linearly spaced frequency channels) measured by the Instrument Champ Electrique (ICE) instrument (Berthelier et al., 2006) at geomagnetic latitudes lower than 65° with a time resolution of about 2 s were used.

Note that although there is only about 1.5 year difference between the time spans of the analyzed Van Allen Probes and DEMETER spacecraft data, the number of events identified in the DEMETER data is almost 3 times higher than the number of events identified in the Van Allen Probes data. This can be partly attributed to better frequency and time resolution of the DEMETER wave measurements, but for the most part it can be explained by different spacecraft orbits. While DEMETER at its low altitude quickly samples different longitudes and L shells, the Van Allen Probes change their location considerably slower. Additionally, a single long-lasting spatially extended event can be eventually counted as several events in DEMETER observations, as the gaps in observations in the polar regions are by definition interpreted as the event ends in the Hayosh et al. (2014) event list. Consequently, DEMETER tends to see more short-lasting events, while Van Allen Probes observe less events, but with longer durations.

Examples of frequency-time spectrograms of QP events observed by these spacecraft are shown in Figure 1. Figure 1a shows a frequency-time spectrogram of power spectral density of magnetic field fluctuations measured by the Van Allen Probe A on 4 October 2017 close to the equatorial plane. The event consisting of several quasiperiodically occurring elements at frequencies between about 1 and 2.5 kHz can be clearly identified. Figure 1b shows a frequency-time spectrogram of power spectral density of electric field fluctuations measured by the DEMETER spacecraft on 13 August 2010 during a daytime half orbit. The data were measured during a daytime half orbit, when the spacecraft moved from the North to the South. A QP event at frequencies between about 0.5 and 1.5 kHz is observed at larger geomagnetic latitudes in both hemispheres, with the intensity gradually fading toward the geomagnetic equator.

3. Results

The large data sets of QP events identified in the Van Allen Probes and DEMETER spacecraft data allow us to calculate and compare respective occurrence rates as a function of various parameters. For this purpose, we define the occurrence rate for a given parameter range as the total time duration of QP events normalized by the total time duration of the investigated wave measurements performed during given parameter values.

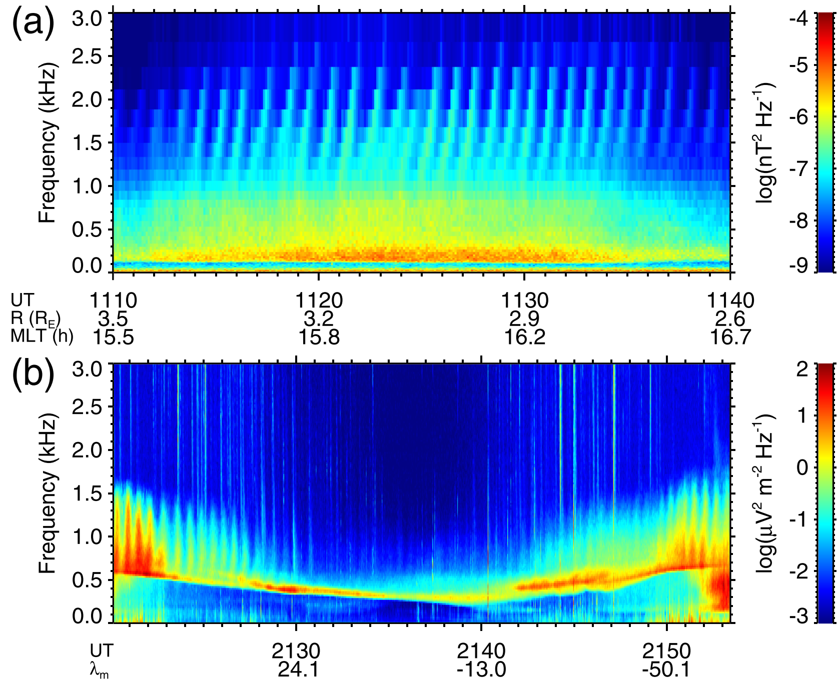

Figure 1. (a) Frequency-time spectrogram of power spectral density of magnetic field fluctuations measured by the Van Allen Probe A spacecraft on 4 October 2017 close to the equatorial plane. Several quasiperiodically occurring elements at frequencies between about 1 and 2.5 kHz can be identified. (b) Frequency-time spectrogram of power spectral density of electric field fluctuations measured by the DEMETER spacecraft on 13 August 2010 during a daytime half orbit. The spacecraft moved from the north to the south. Quasiperiodically occurring elements at frequencies between about 0.5 and 1.5 kHz can be observed at larger geomagnetic latitudes in both hemispheres, with the intensity fading toward the geomagnetic equator.

The principal results concerning the QP occurrence rates are shown in Figure 2. The results obtained for the Van Allen Probes spacecraft are shown by the red lines, while the results obtained for the DEMETER spacecraft are shown by the black lines. Figure 2a shows the QP occurrence rates as a function of the magnetic local time. The Van Allen Probes spacecraft observe the events principally at all MLTs, with a rather broad maximum in the dusk sector. On the other hand, the events are observed by the DEMETER spacecraft nearly exclusively during the daytime half orbits. Note that the DEMETER measurements are limited to solely two magnetic local time bins due to its Sun-synchronous orbit and DEMETER QP observations take place primarily at L shells larger than about 3 (Hayosh et al., 2014).

Figure 2b shows the occurrence rate of the emissions as a function of the geomagnetic longitude. The Van Allen Probes spacecraft observe the events quite equally at all geomagnetic latitudes, with possible shallow minima at geomagnetic longitudes of about 90° and 240°. On the other hand, the occurrence rate as observed by DEMETER exhibits a significant longitudinal variation. The rather shallow minimum at about 240° seems to roughly correspond to the minimum observed by the Van Allen Probes. Additionally, the occurrence rate is significantly lower at geomagnetic longitudes of about 0°, roughly corresponding to the longitudes of the South Atlantic Anomaly.

Figure 2c shows the occurrence rate of the emissions as a function of the month of the year. It can be seen that the occurrence rate obtained by the Van Allen Probes tends to peak during the Spring and Autumn. On the other hand, the occurrence rate obtained by DEMETER peaks during the northern winter, and it has a well pronounced minimum during the northern summer. Otherwise, the occurrence rate values are remarkably similar for the two missions, in particular during spring and fall seasons.

4. Discussion and Conclusions

The occurrence rate dependences obtained by the Van Allen Probes and DEMETER spacecraft are strikingly different. It seems reasonable to try to relate this difference to different spacecraft orbits. The Van Allen

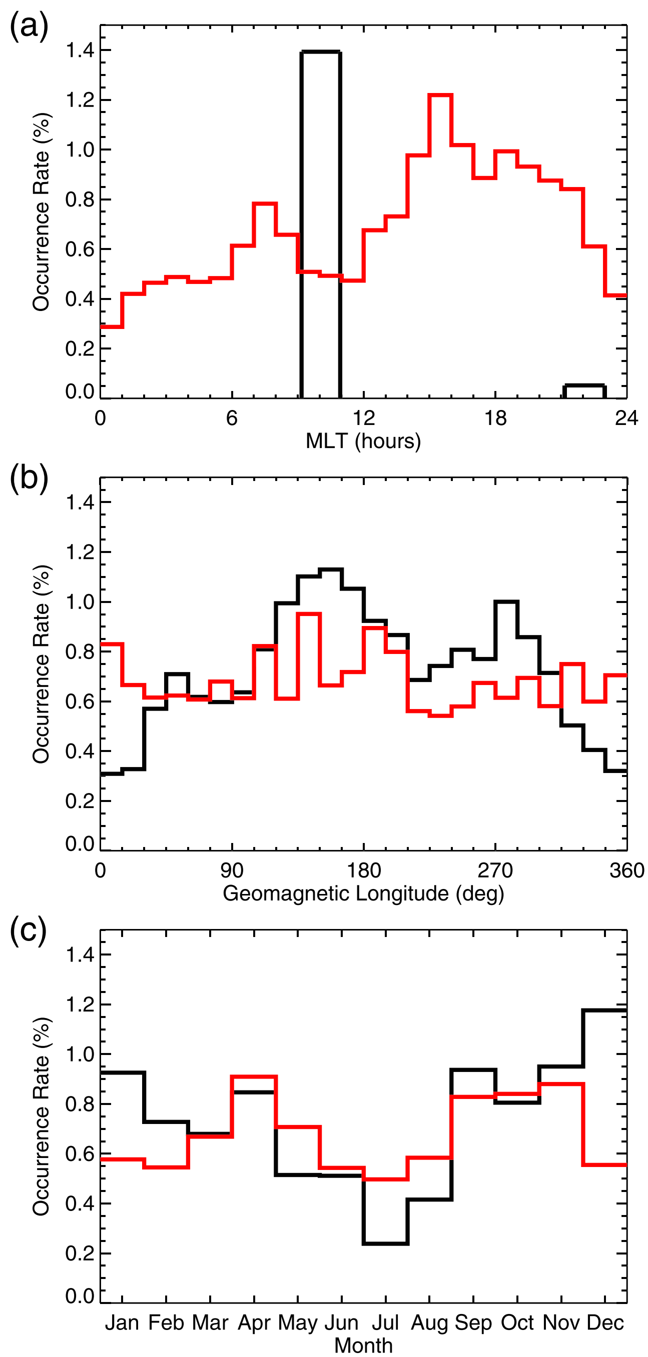

Figure 2. (a) Occurrence rate of quasiperiodic emissions as a function of the magnetic local time. The results obtained by the Van Allen Probes are shown by the red line, while the results obtained by the DEMETER spacecraft are shown by the black line. The occurrence rate is calculated as the time duration of quasiperiodic emissions divided by the total measurement duration in a given magnetic local time interval. (b) The same as (a) but for the occurrence rate as a function of the geomagnetic longitude. (c) The same as (a), but for the occurrence rate as a function of the month of the year.

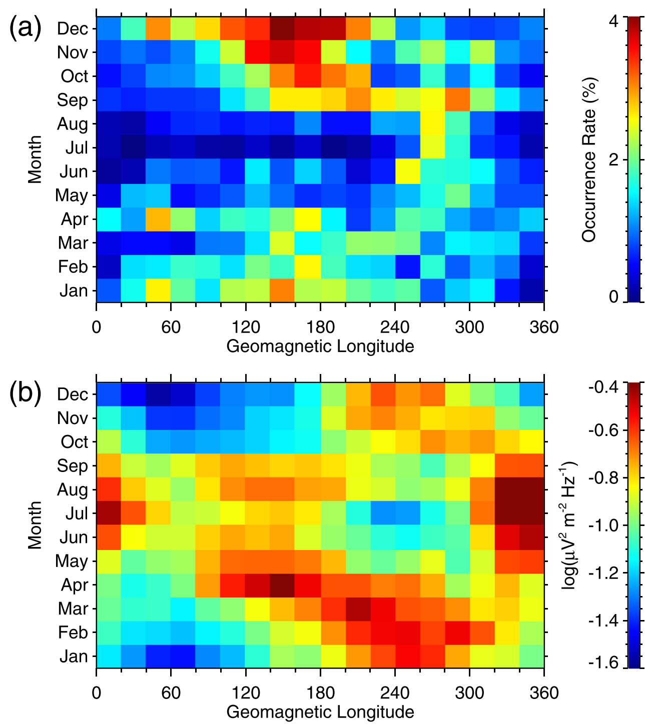

Figure 3. (a) Daytime occurrence rate of quasiperiodic emissions observed by the DEMETER spacecraft as a function of the geomagnetic longitude (abscissa) and month (ordinate) is color coded according to the color scale on the right. (b) Average power spectral density of electric field fluctuations at frequencies between 0.75 and 2 kHz and geomagnetic latitudes between 35° and 60° measured by the DEMETER spacecraft during the daytime is color coded according to the color scale on the right as a function of the geomagnetic longitude (abscissa) and month (ordinate).

Probes measure most of the time close to the equatorial plane at larger radial distances. Given that—when observed—QP emissions occur over a quite large portion of the inner magnetosphere (Němec et al.,2013, 2014; Titova et al., 2015), QP events are typically observed by the Van Allen Probes continuously for quite long periods of time (tens of minutes). On the other hand, a single DEMETER half orbit lasts about 35 min, with QP events being generally observed at absolute geomagnetic latitudes between about 35° and 60° (Hayosh et al., 2014). Consequently, QP events detected by DEMETER are not too long (about 5 min), but there are more of them. The occurrence rates analyzed in the present paper, however, account reasonably for this different sampling, as demonstrated by the quite comparable overall occurrence rate values.

Another important difference which might affect the event identification and occurrence rate variations is the "background wave intensity," that is, the overall intensity of all emissions other than QP observed by the spacecraft. Most importantly, the wave intensities measured by DEMETER are significantly increased due to terrestrial sources, in particular lightning (Colman & Starks, 2013; Němec et al., 2010; Záhlava et al., 2018). Although this is to some extent the case also at larger radial distances (Green et al., 2005; Meredith et al., 2006), the overall contribution of terrestrial sources to the Van Allen Probe intensities appears to be considerably weaker (Záhlava et al.,2018, 2019). It is thus possible that the background wave intensity measured by DEMETER is at times so large that QP emissions are eventually missed when inspecting individual frequency-time spectrograms for their presence. This explanation is quite appealing, especially considering that the geomagnetic latitude interval where QP emissions can be eventually observed is rather narrow (DEMETER passes through it in about 7 min), and the intensity of QP elements decreases considerably toward lower latitudes.

In order to verify this hypothesis, the daytime QP occurrence rates and background wave intensities observed by DEMETER are compared in Figure 3. Figure 3a shows the color-coded QP occurrence rates as a function of the geomagnetic longitude (abscissa) and month (ordinate), while Figure 3b uses the same format to depict the average power spectral densities of electric field fluctuations. These were calculated over

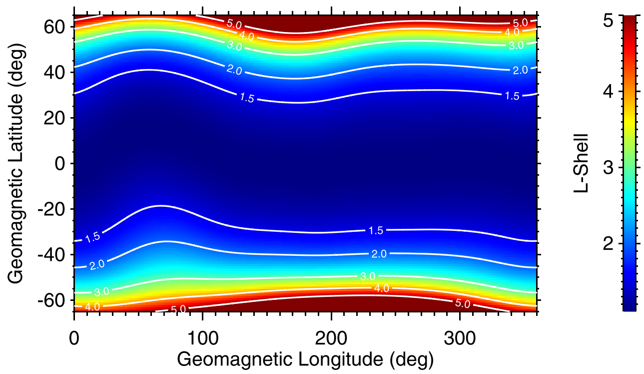

Figure 4. Radial distance of the geomagnetic field lines at the equator is color coded as a function of the geomagnetic longitude (abscissa) and geomagnetic latitude (ordinate) according to the color scale on the right. The white lines mark the isocontours corresponding to 1.5, 2.0, 3.0, 4.0, and 5.0 R_E, respectively.

the frequency range between 0.75 and 2 kHz and the geomagnetic latitude interval between 35° and 60°, corresponding to the intervals where QP emissions are typically detected by DEMETER (Hayosh et al., 2014). Figure 3a shows that the low occurrence rates at geomagnetic longitudes around 0° span over principally all the year. At geomagnetic longitudes approximately between 20° and 220°, the occurrence rates exhibit a well-pronounced seasonal variation, peaking in the northern winter and having a deep minimum in the northern summer, in agreement with the ground-based results reported by Engebretson et al. (2004). Quite oppositely, the occurrence rates at geomagnetic longitudes between about 220° and 320° appear to have a broad maximum in the local summer. Comparing with the average wave intensities depicted in Figure 3b, one can see that at least in some longitude-month intervals the lower QP occurrence rates correspond to larger wave intensities and vice versa. This is particularly clear for geomagnetic longitudes between about 100° and 320°. Considering that typical obtained background wave intensities of about $10^{-0.8}\mu V^2\,m^{-2}\,Hz^{-1}$ are comparable to the peak intensities of individual QP elements (Hayosh et al., 2014), this provides a strong supporting evidence that QP identification in DEMETER data is at times indeed hindered by strong background wave intensities. We note that the same explanation may be likely adopted to explain the lower occurrence rate of magnetospheric line radiation (MLR) events observed by DEMETER during summer (Bezděková et al., 2015) as the frequency-latitudinal intervals where these events are observed by DEMETER are typically similar to those of QP emissions (Hayosh et al., 2014; Němec et al., 2009).

There is, however, a noticeable interval at geomagnetic longitudes between about 0° and 100°, where both the background wave intensities and QP occurrence rate during the northern winter remain low. The low QP occurrence rate obtained by DEMETER in this longitudinal interval (Hayosh et al., 2014) as well as apparently analogous low occurrence rate of MLR events at these longitudes (Němec et al., 2009) was formerly attributed to the precipitation of energetic particles in the drift loss cone and its possible negative effects on the event generation (Bezděková et al., 2015). However, if this was indeed the case, the QP occurrence rate at these longitudes would be lower also on the Van Allen Probes, which is not observed. We thus suggest an alternative explanation based on the nondipolar Earth's magnetic field.

A relevant plot obtained using the International Geomagnetic Reference Field magnetic field model (Thébault et al., 2015) is shown in Figure 4. The International Geomagnetic Reference Field model was evaluated for the central time of the DEMETER mission (1 October 2007). However, as the Earth's internal magnetic field evolves only very slowly, the results are effectively independent of this choice. The figure uses color coding to show the radial distances ("L shells") of geomagnetic field lines at the equator (defined as the location where the radial component of the magnetic field changes sign) as a function of the geomagnetic longitude (abscissa) and geomagnetic latitude (ordinate). The white lines depict the isocontours corresponding to 1.5, 2.0, 3.0, 4.0, and 5.0 R_E, respectively. It can be seen that the largest geomagnetic latitudes covered by the DEMETER spacecraft measurements (±65°) correspond to L shells larger than 5 at geomagnetic longitudes between about 90° and 330°. However, at geomagnetic longitudes between about 0° and 80°, the L shell range covered by the DEMETER spacecraft measurements is significantly lower. We note that magnetic field contributions from external magnetospheric sources (Tsyganenko,1989, 1995) almost do not change this picture. Although their inclusion generally results in somewhat larger L shells, the differences are below about 0.15 L shell.

Considering that QP emissions are observed by DEMETER primarily at L shells larger than about 3 (Hayosh et al., 2014), the interval of geomagnetic latitudes where the events are eventually observable at the longitudes of South Atlantic Anomaly is thus severely limited. While at geomagnetic longitudes of about 170° nearly 25% of measurements are performed at $L > 3$, this is the case for less than 15% of measurements performed at the longitudes of the South Atlantic Anomaly. This may, in turn, directly explain the low QP occurrence rates obtained by DEMETER at these longitudes.

The larger QP occurrence rate observed by Van Allen Probes during the spring/autumn might be possibly linked to geomagnetic activity variations. Specifically, the geomagnetic activity is known to peak during the spring/autumn seasons (Russell & McPherron, 1973), and QP emissions were shown to occur typically after periods of enhanced geomagnetic activity (Hayosh et al., 2014). As for the local time distribution of QP emissions, the near absence of the events in nighttime DEMETER data can be likely at least partly attributed to typically larger nighttime background wave intensities at frequencies above about 2 kHz observed over a wide range of latitudes (Němec et al., 2010; Záhlava et al., 2018). These larger nighttime intensities are a consequence of lower ionospheric attenuation of terrestrial lightning-generated emissions (Cohen & Inan, 2012; Graf et al., 2013; Němec et al., 2008). An additional reason for the lack of QP events observed by DEMETER during the nighttime may be related to the local time dependence of QP emission properties. Specifically, Němec et al. (2018) reported that the QP emissions observed on the dusk side tend to have lower frequencies than QP emissions observed at other local times. Considering that the background emissions are generally more intense at lower frequencies, this would again result in the emissions being more easily obscured by other electromagnetic waves.

In summary, we showed that the occurrence rates of QP emissions as observed by the Van Allen Probes at larger radial distances and by the DEMETER spacecraft at low altitudes are strikingly different. We suggested that this can be likely explained by (i) other natural electromagnetic waves which are at times intense enough to prevent the identification of QP emissions in DEMETER data, and by (ii) nondipolar Earth's magnetic field which, along with limited geomagnetic latitude range covered by DEMETER, results in the emissions at larger L shells not being measured at the longitudes of the South Atlantic Anomaly. We believe that principally the same explanation can be readily used to explain formerly reported variations of the occurrence rate of MLR events observed by DEMETER. Finally, our results demonstrate the problems and the need for caution when analyzing magnetospheric wave phenomena generated at larger radial distances using low-altitude spacecraft and ground-based instruments.

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