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Key Points:

- Spatial separations during conjugate observations are typically within 40° in azimuth and from about 1 to 3 in L shell
- Spacecraft and ground-based intensity ratios demonstrate an intensity decrease both close to the plasmapause and at low L shells
- Event with a gap and spectral structure change was explained as two immediately following events

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Conjugate Observations of Quasiperiodic Emissions by the Van Allen Probes Spacecraft and Ground-Based Station Kannuslehto

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Abstract Whistler mode waves observed in the Earth's inner magnetosphere at frequencies between about 0.5 and 4 kHz which exhibit a nearly periodic time modulation of the wave intensity are called quasiperiodic (QP) emissions. Conjugate measurements of QP events at several different locations can be used to estimate their spatial extent and spatiotemporal variability. Results obtained using conjugate QP measurements provided by the ground-based station Kannuslehto ($L \approx 5.5$) and the Van Allen Probes spacecraft (L shells between about 1.1 and 6.5) between September 2012 and November 2017 are presented. Altogether, 26 simultaneously detected events were analyzed. The event modulation periods and frequency-time structures were generally the same at all observation points. Spatial separations of the spacecraft and the ground-based station during conjugate observations are typically within about 40° in azimuth and from about 1 to 3 in L shell. RBSP consistently observes events at lower L shells than Kannuslehto, with the event occurrence primarily inside of the plasmasphere. Ratios of Poynting fluxes observed by the spacecraft and on the ground are used to evaluate event intensity variations related to the spacecraft position. It is found that the intensity decreases considerably both at low L shells and outside of the plasmasphere. Finally, an event containing a gap in its frequency-time structure related to a sudden change of its properties is analyzed in detail.

1. Introduction

The intensity of very low frequency (VLF) electromagnetic waves in Earth's inner magnetosphere can sometimes be nearly periodically modulated in the time domain. Such emissions are usually observed in the frequency range between about 0.5 and 4 kHz and are known as quasiperiodic (QP) emissions (Carson et al., 1965; Sato & Kokubun, 1980). The period of the intensity modulation can vary from tens of seconds to several minutes (Helliwell, 1965). For a single event, the modulation period is not strictly constant, but can vary considerably over the event duration (e.g., Manninen et al., 2014). Although QP emissions have been observed for decades (first reports of QP emissions were provided by Carson et al., 1965; Helliwell, 1965), their origin is still not completely understood.

Earlier studies from both ground-based and low-altitude spacecraft measurements shown that QP emissions are primarily a dayside phenomenon (Engebretson et al., 2004; Hayosh et al., 2014; Morrison et al., 1994). However, measurements performed at larger radial distances did not reveal any significant local time preference of the event occurrence (Němec et al., 2018). Early ground-based measurements of QP emissions were classified into two categories (Kitamura et al., 1969; Sato et al., 1974). In the first instance (Type 1), simultaneous ultralow frequency (ULF) magnetic field pulsations with a period comparable to the QP modulation period were observed during the detection of the events. If these pulsations did not occur, or if their period was significantly different from the QP modulation period, the events were classified as QP emissions Type 2.

Spacecraft observations (Hayosh et al., 2016; Němec, Santolík, Parrot, et al., 2013; Titova et al., 2015) as well as multistation ground-based measurements (Gołkowski & Inan, 2008) suggest that the propagation of QP emissions throughout the inner magnetosphere is primarily unducted. Nevertheless, a ducted propagation of QP events has occasionally been observed (Manninen et al., 2014). Moreover, Hayosh et al. (2016) showed

that, when propagating down to low altitudes, QP emissions can be guided by the plasmopause boundary. It is generally believed that QP emissions are generated in the equatorial plane at rather large radial distances close to the plasmopause (Morrison, 1990; Sato & Kokubun, 1980).

While ground-based data provide us with information about the event durations and their temporal variations (Manninen et al., 2012, 2014; Smith et al., 1998), spacecraft observations are very useful for analyzing spatial variations and source locations (e.g., Němec et al., 2018; Titova et al., 2015). Hence, in an ideal case, an event is simultaneously detected by both a ground-based instrument and a satellite. If a given QP event is observed simultaneously at different locations, the same frequency-time structure and, most importantly, the same modulation period are usually observed (Němec, Santolík, Parrot, et al., 2013; Němec, Santolík, Pickett, et al., 2013; Martinez-Calderon et al., 2020; Titova et al., 2015).

However, individual QP elements measured at different radial distances at comparable azimuths can be observed with time delays on the order of a few seconds (Martinez-Calderon et al., 2016; Němec et al., 2014). This can be explained by unducted wave propagation between the respective measurement points. Moreover, if the measurement locations are substantially separated in azimuth (approximately tens of degrees), the time delays between QP elements observed at these locations can be larger than tens of seconds. Such time delays are too long to be due to the propagation of QP emissions. A possible explanation might be related to the propagation of a ULF compressional wave which is responsible for the formation of a QP event (Němec, Bezděková, et al., 2016; Němec, Hospodarsky, et al., 2016).

Two different generation mechanisms were suggested to explain the formation of QP emissions. According to the first mechanism, the source region and resonance conditions there are periodically modulated by a compressional ULF wave (Chen, 1974; Sato & Fukunishi, 1981). This can lead to the formation of QP emissions, even in the case of rather weak ULF magnetic field pulsations (Kimura, 1974). However, the magnetic field pulsations measured on the ground are usually Alfvénic (i.e., noncompressional). The suggested mechanism requires compressional ULF waves to be present at least close to the equatorial plane, which is a likely location of the source region of QP emissions (Morrison, 1990; Sato & Kokubun, 1980).

The second mechanism was suggested by Besspalov and Trakhtengerts (1976). It is based on a relaxation oscillation regime of the source. This model, which implicitly assumes ducted propagation, was further developed by Trakhtengerts et al. (1986), Demekhov and Trakhtengerts (1994), and Pasmanik et al. (2004). Considering the observed upper-frequency limit of QP emissions, which appears to be related to one half of the equatorial electron cyclotron frequency and thus to ducted propagation (e.g., Němec et al., 2018), the assumption of ducted propagation appears to be supported. Moreover, the model was shown to successfully explain at least some of the QP emission features observed by satellites (Pasmanik et al., 2004; Pasmanik et al., 2019).

The two possible generation mechanisms differ in whether ULF magnetic field pulsations are necessary for the formation of QP emissions or not. Hence, in some sense, these two mechanisms correspond to QP emissions of Type 1 and Type 2 defined above. However, this QP classification was based on ground-based measurements and, as shown by Tixier and Cornilleau-Wehrlin (1986), it is not straightforward to apply to spacecraft observations, rendering it somewhat unclear (Sazhin & Hayakawa, 1994). Additionally, Bezděková et al. (2019) reported that properties of QP emissions with short (~ 20 s) and long (> 20 s) modulation periods react differently to geomagnetic activity, suggesting that they might be generated by different mechanisms.

The present study focuses on simultaneous measurements of QP emissions by a ground-based instrument (Kannuslehto station) and spacecraft (Van Allen Probes). This allows us to estimate the spatial extent of the observed events and the evolution of their intensity and frequency-time structure. The instruments used in this analysis are described in section 2. The results are presented in section 3 and discussed in section 4. A summary of the main results is presented in section 5.

2. Data Set

The spacecraft measurements used in this study were obtained by the Van Allen Probes spacecraft (further abbreviated as RBSP according to their original name Radiation Belt Storm Probes). This mission consists of two satellites operating on nearly identical elliptical orbits close to the equatorial plane (geomagnetic latitudes λ lower than about 20°). Their orbits cover a full range of magnetic local times (MLT) and geomagnetic

longitudes. Radial distances r range from about $1.1 R_E$ to $5.8 R_E$. Hence, considering a dipole magnetic field and $L = r/\cos^2 \lambda$, L shells between about 1.1 and 6.5 are covered. The wave instrument onboard (Electric and Magnetic Field Instrument Suite and Integrated Science, EMFISIS) provides multicomponent measurements in the frequency range 10 Hz–12 kHz (Kletzing et al., 2013). In the survey mode data used in the present study, this frequency interval is divided into 64 quasi-logarithmically organized channels. These are based on a 0.468 s long waveform sampled at 35 kHz captured every 6 s (using fast Fourier transform with a length of 16,384 points and a subsequent averaging in frequency). The instrument provides measurements of three magnetic and three electric field components. Wave propagation parameters (planarity, ellipticity, wave, and Poynting vectors) are routinely calculated via singular value decomposition (Santolik et al., 2001, 2003, 2010). Additionally, tracing of the upper hybrid frequency from the data obtained by the high-frequency receiver of the instrument allows one for the determination of the local plasma number density (Kurth et al., 2015). This value can be further used to estimate the location of plasmopause (L_{pp}), which is loosely defined here as the innermost position where the plasma number density falls below 100 cm^{-3} . A plasmopause location determined as the nearest L_{pp} (in time domain) can be thus assigned to each RBSP measurement.

The ground-based VLF measurements were provided by the Kannuslehto station managed by Sodankylä Geophysical Observatory (SGO), Sodankylä, Finland. The station is located in northern Finland, 67.74°N ; 26.27°E ; $L \approx 5.5$. The measurements in the frequency range 0.239 kHz are performed by two orthogonal vertical magnetic loop antennas oriented in the north–south and east–west directions. The sizes of both loops are $10 \times 10 \text{ m}$, have 10 turns, and their effective areas thus reach 1000 m^2 . The measured data are band-pass filtered and sampled at a rate of 78,125 Hz. The advantage of these receivers is a wide dynamic range (up to 120 dB) and an extraordinary sensitivity ($\approx 0.1 \text{ fT}$). The station operates during campaigns, which usually last several months. The magnetic field measurements are calibrated to physical units by a technique recently used by Němec, Bezděková, et al. (2016).

The present study uses measurements from September 2012 to November 2017. During this period, nine observation campaigns at the Kannuslehto station were performed, covering about 550 days of measurements. Altogether, there were 26 time intervals during which QP events were observed simultaneously by RBSP and Kannuslehto identified within this time interval.

Let us describe the process of the event identification in detail. In order to find the conjugate QP measurements, the Kannuslehto VLF measurements were manually inspected. Only Kannuslehto measurement time intervals corresponding to the QP events formerly identified in the RBSP data (Němec et al., 2018) were investigated. The measurement of a QP event was evaluated as simultaneous in the case when at least one of the spacecraft and the Kannuslehto station detected QP emissions. Altogether, 28 such events were identified. The QP emissions were further considered as *same* when the frequency-time structure observed by the given instruments was identical. Altogether, 26 such simultaneously detected events were identified during the analyzed time period. Note that in some cases, the QP emissions were measured by one of the instruments (typically Kannuslehto) for a longer time interval than by the other instrument. In such cases, the QP emissions were analyzed only in the time interval corresponding to the simultaneous measurements. Consequently, a single continuous long-lasting event observed by Kannuslehto could be classified as several conjugate events with respect to the RBSP observations.

In one case, all three instruments (i.e., both RBSP spacecraft and the Kannuslehto station) observed QP emissions at the same time. This event is shown in Figure 1. The event occurred on 19 November 2015 between 16:18 and 16:50 UT in the frequency range between about 1,200 and 2,400 Hz. It can be seen that the intensity modulations correspond to each other at all three locations and also the frequency-time structure of individual QP elements is the same. Note that there is an apparent gap between the QP elements around 16:36 UT, after which the period between the consecutive elements increases. This remarkable feature of the event is discussed in section 3.3. Again, the depicted time interval corresponds to the time of simultaneous observations by all instruments, while the Kannuslehto station also observed the QP emissions before this time period.

Figure 1. Example of a QP event measured by (a) the Kannuslehto station, (b) RBSP A, and (c) RBSP B on 19 November 2015 between 16:18 and 16:50 UT. The event was observed in a frequency range between about 1,200 and 2,400 Hz. The plotted time interval corresponds to the simultaneous measurements of the event by all three instruments.

3. Results

3.1. Spatial Extent

Field-aligned projections of the RBSP A and RBSP B orbits on the ground during the times of the identified conjugate events are depicted in Figure 2 by the thick red and blue curves, respectively. The thin curves show the RBSP projections at the times when only one instrument (typically Kannuslehto station) observed the events. Since some of the events lasted for several hours and drawing the projections for the entire event duration would make the plot rather confusing, these projections are limited to within 30 min from the time intervals of conjugate observations. These were calculated by the International Geomagnetic Reference Field model (IGRF, Thébault et al., 2015) combined with the T89 magnetic field (Tsyanenko, 1989) model.

Figure 2. Field-aligned projections of RBSP A (red curves) and RBSP B (blue curves) spacecraft on the ground during the times of observations by at least one instrument (thin curves) and during simultaneous observations of QP emissions by the spacecraft and the Kannuslehto station (thick curves). The map is drawn in geomagnetic coordinates. The location of Kannuslehto station is 119.8° geomagnetic longitude and 64.4° geomagnetic latitude (black cross).

The plot is in geomagnetic coordinates. The position of the Kannuslehto station, marked by the black cross, is 119.8° geomagnetic longitude and 64.4° geomagnetic latitude. The map shows that most of the events were observed within 40° of geomagnetic longitude from the Kannuslehto location and they were mostly detected by RBSP A. There are also rare isolated events which were observed simultaneously although the spatial separation of the instruments was more than 100° in geomagnetic longitude.

Figure 3 allows the visualization of the spatial separation of the detected events in a more illustrative and quantitative way. It shows the distribution of MLT and L shell differences during the measurement times and conjugate event detections. Figure 3a depicts the distribution of relative distances for all Kannuslehto measurement times irrespective of whether QP emissions were detected or not. Figure 3b uses the same format to depict a distribution of spatial separations at the times of the conjugate QP event observations. It can be seen that the integral time of conjugate observations was the longest at $L_{\text{RBSP}} - L_{\text{KAN}}$ between -3 and -1 , whereas in the $|\Delta \text{MLT}|$ domain it principally holds that the lower the difference is, the longer is the integral time of conjugate observations. The dependence of the occurrence rate of simultaneously detected QP emissions (i.e., the ratio of simultaneous and total measurement durations) on the spatial separation of the instruments is depicted in Figure 3c. It confirms the substantial dependence on the L shell difference and the preference for the events to be simultaneously observed when $|\Delta \text{MLT}|$ is small. Note that the preferred negative $L_{\text{RBSP}} - L_{\text{KAN}}$ differences correspond to the situation when RBSP L shell is lower than the Kannuslehto L shell. This is probably due to a comparatively large L_{KAN} (≈ 5.5), which is usually well outside the plasmasphere (e.g., Kwon et al., 2015), while QP emissions observed by RBSP are typically located inside the plasmasphere (Němec et al., 2018).

3.2. Intensity Variations

As argued by Němec, Bezděková, et al. (2016), simultaneous observations of the same event by spacecraft and ground-based instrumentation allow us to conveniently analyze intensity variations related to the spacecraft location. Considering that a ground-based instrument can be (neglecting the Earth's rotation) regarded as a static observer, event intensity variations observed on the ground can be in the first approximation attributed to temporal variations of the source. On the other hand, a moving spacecraft sees a combination of both the source evolution and propagation effects. Normalizing the intensities measured by spacecraft by the intensities measured by a ground-based instrument thus accounts for possible temporal variations of the source, and the remaining intensity variations can be related to the varying spacecraft location.

The frequency-time spectrograms were thus divided into individual frequency bands corresponding to the survey mode of the RBSP EMFISIS instrument and the power spectral density was analyzed in each of them separately. The time dependences of the wave intensity in the frequency range 1,676–1,882 Hz obtained for the conjugate event from Figure 1 are shown in Figure 4. The black curve and the intensity scale on the left-hand side correspond to the data measured by the Kannuslehto station, while the red curve and the intensity scale on right-hand side correspond to the data measured by RBSP A. It can be seen that the QP structure measured by both instruments is quite well conserved. Also, the gap between QP elements at about 16:36 UT and subsequent increase of the modulation period are observed in each data set (for further details see below).

Figure 3. Distribution of relative distances between the RBSP spacecraft and the Kannuslehto station. (a) Total time duration of the Kannuslehto campaign measurements in given ΔL - $|\Delta MLT|$ bins is color coded according to the color scale on the right-hand side. (b) The same as (a) but for the total time duration of simultaneously detected QP emissions. (c) Occurrence rate of simultaneously detected QP emissions as a function of the L shell separation (abscissa) and MLT separation (ordinate).

In order to evaluate the intensity of individual QP elements, it was necessary to determine their initial and final times. These were defined as the times of local intensity minima between local intensity maxima corresponding to consecutive QP elements. Given that the signal can be rather noisy at these times, the number and approximate times of the QP elements were determined manually. The respective local intensity minima and maxima were then found automatically. The resulting times obtained for the Kannuslehto and RBSP A data are marked in Figure 4 by black crosses and red diamonds, respectively.

Figure 4. Power spectral density of magnetic field fluctuations measured by the Kannuslehto station (black) and RBSP A (red) during the example event from Figure 1 in the frequency range 1,676–1,882 Hz. The black (left-hand side) ordinate corresponds to the Kannuslehto measurements, while the red (right-hand side) ordinate corresponds to the RBSP A measurements. The red diamonds and black crosses show the respective local intensity minima and maxima.

Having identified the initial and final times of a given QP element in a given frequency range, its intensity can be evaluated as an integral of the power spectral density over the respective time interval. In order to account for the variations of the B/E ratio due to a change of the refractive index or wave normal angle, we analyzed the Poynting flux spectral density rather than the power spectral density of magnetic/electric field fluctuations. In the case of RBSP measurements, the Poynting flux is obtained from the combined electric and magnetic field components of the spectral matrices, whereas in the case of the Kannuslehto station, it can be easily calculated considering that the propagation takes place in the air with a refractive index close to 1.

Having calculated the total Poynting flux of individual QP elements in appropriate frequency ranges and time intervals, the QP element intensities observed by RBSP (S_{RBSP}) and by the Kannuslehto station (S_{KAN}) can be compared. This is done in Figure 5, which shows the dependence of their ratio ($S_{\text{RBSP}}/S_{\text{KAN}}$) on the RBSP location with respect to the plasmapause ($L_{\text{RBSP}} - L_{\text{pp}}$). Each point in the figure corresponds to one QP element in a given frequency band where the event was detected and the analysis described above was performed. The red lines denote the median values in given $L_{\text{RBSP}} - L_{\text{pp}}$ intervals. The intensity ratios do not exhibit any clear trend apart from decreasing at low RBSP L shells and for RBSP locations well outside the plasmasphere.

3.3. Case Study Analysis

An interesting point about the example event depicted in Figure 1 is the apparent gap between 16:33 and 16:38 UT, after which the event seems to recommence with a larger modulation period. The origin of this gap is unclear. Given that it is an exceptionally well-pronounced event observed simultaneously by all the three instruments, we attempt to perform a more detailed analysis with the aim of speculating about a possible origin of the gap. Figures 6a–6d show a frequency-time spectrogram of power spectral density of magnetic field fluctuations and frequency-time plots of planarity of magnetic field fluctuations, wave normal angle, and the angle between Poynting vector direction and the ambient magnetic field, respectively, from RBSP A. Only the frequency-time intervals where the power spectral density of magnetic field fluctuations is larger than $10^{-7.6} \text{ nT}^2 \text{ Hz}^{-1}$ are plotted. The spacecraft geomagnetic longitudes during the event observations varied between about 75° and 100° and the spacecraft L shells varied between about 2.3 and 3.4. Figures 6e–6h use the same format to show the results obtained using the RBSP B data. Due to the lower background levels observed by RBSP B, the threshold of power spectral density of magnetic field fluctuations for frequency-time intervals to be plotted in this case is $10^{-8.1} \text{ nT}^2 \text{ Hz}^{-1}$. The spacecraft geomagnetic longitudes varied between about 60° and 75° and the spacecraft L shells varied between about 2.9 and 4.0.

Figure 5. Ratios of the Poynting fluxes of individual QP elements obtained by RBSP and Kannuslehto as a function of the RBSP location with respect to the plasmopause. Each point corresponds to a single QP element in a given frequency band where QP emissions were observed. The red lines mark the median values of Poynting flux ratios in given $L_{\text{RBSP}} - L_{\text{pp}}$ intervals.

It can be seen that the event intensity measured by RBSP B is lower than the intensity measured by RBSP A (Figures 6a and 6e). Furthermore, the wave properties as measured by RBSP B remain almost the same over the entire event duration. The only exception is the planarity which is at first close to 0.5 and it decreases significantly after 16:43 UT. This indicates that as the spacecraft moved, it detected waves coming from several different directions simultaneously. The wave measurements performed by RBSP A display somewhat different behavior. Although the magnetic field planarity remains roughly similar and low during the whole event, both wave normal angle and the angle between the Poynting vector and the ambient magnetic field are significantly different after the event interruption around 16:36 UT. Whereas before 16:36 UT the wave normal angle is rather large ($\sim 60^\circ$), it decreases to about 20° at later times, but these changes are inconclusive because of the low planarity values. At the same time, the angle between the Poynting vector and the

19 November 2015

Figure 6. Wave analysis of the event from Figure 1. (a) Frequency-time spectrogram of power spectral density of magnetic field fluctuations measured by RBSP A. (b) Frequency-time plot of planarity of magnetic field fluctuations. (c) Frequency-time plot of wave normal angle. (d) Frequency-time plot of the angle between the Poynting vector and the ambient magnetic field. Only frequency-time intervals with power spectral density of magnetic field fluctuations larger than $10^{-7.6} \text{ nT}^2 \text{ Hz}^{-1}$ are plotted. (e)–(h) Same as (a)–(d) but for RBSP B measurements. Only frequency-time intervals with power spectral density of magnetic field fluctuations larger than $10^{-8.1} \text{ nT}^2 \text{ Hz}^{-1}$ are plotted.

Figure 7. Wave polarization of the event from Figure 1 measured by Kannuslehto. Positive and negative values indicate the right-handed and left-handed polarized waves, respectively. Only frequency-time intervals with power spectral density of magnetic field fluctuations larger than $9 \cdot 10^{-12} \text{ nT}^2 \text{ Hz}^{-1}$ are plotted.

ambient magnetic field varies from about 150° to about 40° . This means that while the waves were coming to the spacecraft predominantly from the north in the beginning of the event, they came predominantly from the south toward the end of the event.

The QP emissions observed by Kannuslehto were right-handed nearly circularly polarized, as shown in Figure 7, and they were coming to the observation point from southwest/northeast (not shown). The exact direction of arrival cannot be resolved, as there is a $\pm 180^\circ$ ambiguity in the analysis. Nevertheless, the wave arrival from the southwest would be consistent with larger Kannuslehto L shell as compared to RBSP L shells during the observation times, as well as with the RBSP locations slightly westward from Kannuslehto. Note that both the event polarization and angle of arrival observed by Kannuslehto remained quite steady during the entire event, with no particular change related to the gap in the QP elements.

4. Discussion

The situation depicted in Figure 1 when all three instruments simultaneously detected a QP event is quite rare (a single event out of the 26 identified). Considering typical separations of the RBSP spacecraft, this suggests a significant limitation of the spatial extent of these events. On the other hand, a comparison of Figures 1b and 1c reveals that although the event intensity measured by RBSP B is substantially lower than the intensity measured by RBSP A, the same frequency-time structure is observed. This indicates that the emissions from a single source can eventually spread over a rather large area, possibly due to unducted propagation.

The analyzed events are usually observed simultaneously when the instrument separation is lower than about 40° of geomagnetic longitude (about 3 hr in MLT). This corresponds to the results obtained by Němec et al. (2018) reporting the analysis of QP events observed simultaneously by both RBSP spacecraft. On the other hand, the same QP modulation is occasionally observed at azimuthal separations as large as 100° . Considering that the unducted propagation tends to be limited to the vicinity of a given magnetic meridian (see, e.g., Hayakawa, 1987, and references therein), it seems difficult to explain such observations purely by off-meridional unducted propagation. Such observations thus strongly indicate that the source of QP emissions can at times extend over a wide range of geomagnetic longitudes.

RBSP L shells during the simultaneous observations of QP events are typically lower than Kannuslehto L shells. An analysis of the wave arrival directions at Kannuslehto (not shown) revealed that the events were usually coming to the station from the south/north (there is a $\pm 180^\circ$ ambiguity when detecting the direction). This is consistent with the event origin in the equatorial plane and their subsequent propagation within the plasmasphere (Němec et al., 2018) and eventual ducting by the plasmopause when propagating to low altitudes (Hayosh et al., 2016). Note that most of the detected events were indeed observed inside the plasmasphere (not shown) explaining why the obtained L shell differences are typically negative.

As RBSP were located close to the equatorial plane, the obtained L shell separations help to estimate the radial extent of the events. The obtained values of about $2 R_E$ can likely be explained by unducted wave propagation (Martinez-Calderon et al., 2016; Němec et al., 2014). Note that in such a case the QP elements

at different locations would be observed with a time delay corresponding to the wave propagation from the source region. However, due to the relatively low time resolution of the survey mode RBSP measurements (6 s), which is comparable to/larger than the expected time delays, such precise timing analysis was not possible in the present study.

The intensity of detected events can vary significantly over a relatively small range of geomagnetic longitudes/MLTs. A quantitative comparison of event Poynting flux values measured by RBSP and Kannuslehto is difficult, as they can significantly vary due to many different effects. The propagation direction analysis performed by Hayosh et al. (2016) at low altitudes reveals often a rather oblique wave propagation. One might thus expect that part of the wave energy does not propagate down to the ground, but it rather gets ionospherically reflected and propagates back to larger radial distances (Hanzelka et al., 2017). Additionally, in particular during the day, the waves are significantly attenuated when penetrating through the ionosphere (Němec et al., 2008). Finally, they likely propagate at least some distance in the Earth-ionosphere waveguide before reaching the Kannuslehto station, which further decreases their intensity both due to the attenuation in the waveguide and due to the spreading of the wave energy in a wide range of directions. All these effects should result in Poynting flux values detected on the ground being lower than those detected at larger distances. However, the wave intensity measured on the ground is sometimes larger than that measured by the spacecraft. This can likely be explained by the wave propagation and damping, suggesting that at those times the spacecraft was not favorably located to observe the emissions. Specifically, the RBSP Poynting fluxes normalized by the Kannuslehto Poynting fluxes decrease significantly both at small and large L shell differences. The intensity decrease at low RBSP L shells corresponds well to a lower geomagnetic latitude limit on the QP event occurrence in low-altitude spacecraft data (Hayosh et al., 2014). Considering that the event frequencies are generally higher than the local lower hybrid frequencies in the expected source region locations (Němec, Santolík, Parrot, et al., 2013), and assuming an unducted wave propagation (Němec et al., 2014, 2018), a possible explanation might stem from the lower hybrid frequency variation along the wave propagation path. As the lower hybrid frequency increases with decreasing L shell, a wave eventually enters a region where the wave frequency meets the lower hybrid frequency and gets magnetospherically reflected (e.g., Vavilov et al., 2013). It is thus difficult to achieve an effective unducted propagation of QP emissions down to low L shells.

It is interesting to note that the Poynting flux ratios appear to decrease close to the inner plasmapause boundary, which might be a preferred source location. Considering that the RBSP spacecraft are located close to the equatorial plane, this might suggest a latitudinally extended source. Alternatively, as the determination of the plasmapause location is clearly somewhat inaccurate, part of the data points evaluated as just inside the plasmasphere could have actually occurred in the plasma trough, where the emissions are expected to weaken/disappear.

The presented example event is interesting as it was simultaneously observed by all three instruments and, additionally, it contains a pronounced gap after which the event apparently continues with a longer modulation period. In order to find the origin of the gap and the source of the modulation period change, several possibilities were investigated. Alfvénic magnetic field pulsations measured by ground magnetometers close to the respective field-line projections did not show any specific variation at the time of the gap, nor a periodicity related to the QP modulation period. Ambient magnetic field measured in situ by flux-gate magnetometers onboard RBSP did not exhibit any fluctuations with a periodicity comparable to the QP modulation period nor any sudden change at the time of the gap either. Furthermore, the RBSP energetic particle and plasma number density measurements did not reveal any sudden change at the time of the gap. This can likely be explained by the spacecraft not being located in the source region at the time of the observations. However, the gap occurrence and the frequency-time structure change observed at the three locations simultaneously clearly show that they are related to changes of the source itself rather than to propagation effects.

The values of magnetic field planarity observed by RBSP are about 0.5, suggesting a complicated propagation pattern with the waves coming to the spacecraft simultaneously from several directions. However, the wave propagation analysis indicates that the predominant Poynting vector direction of detected QP emissions changes significantly right after the gap. This, along with the sudden increase of the modulation period, might suggest that after the gap another QP event was generated at a different location. The observed situation would effectively correspond to two different QP events. However, their close consecutive

occurrence can hardly be a coincidence. Instead, assuming the flow cyclotron maser generation mechanism (Trakhtengerts et al., 1986), they might possibly be related to two different electron populations drifting through a density structure favorable for the generation of QP emissions.

Note that there was no sudden significant change of polarization or angle of arrival related to the gap observed by Kannuslehto. This may be possibly explained by Kannuslehto being located too far from the source region, with the observed wave parameters being governed by the entire wave propagation path rather than by modest variations of the source itself.

5. Conclusions

An analysis of simultaneous measurements of QP emissions by the Van Allen Probes spacecraft and the Kannuslehto station was presented. Altogether, 26 events were analyzed. Generally, the same frequency-time structure is observed at all locations where an event is detected. It was shown that the spatial separations of the instruments at the times of conjugate event measurements are typically within 40° of geomagnetic longitude and between about 1 and 3 in L shells. RBSP L shells at the times of event detections are typically lower than Kannuslehto L shells, consistent with the events occurring primarily inside the plasmasphere.

The analysis of Poynting flux ratios allowed us to account for possible spatiotemporal variations of the source and analyze the QP intensity as a function of the spacecraft location. It revealed that the QP intensity decreases significantly both at low L shells and outside the plasmasphere.

Finally, a QP event with a gap in its structure followed by a sudden change of the modulation period was analyzed in detail. Considering the accompanying change of the wave propagation direction, we speculated that it might actually be formed by two closely related events.

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