Van Allen Probes observations of unusually low frequency whistler mode waves observed in association with moderate magnetic storms: Statistical study

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Abstract We show the first evidence for locally excited chorus at frequencies below 0.1fₑ (electron cyclotron frequency) in the outer radiation belt. A statistical study of chorus during geomagnetic storms observed by the Van Allen Probes found that frequencies are often dramatically lower than expected. The frequency at peak power suddenly stops tracking the equatorial 0.5fₑ and f₀ decreases rapidly, often to frequencies well below 0.1fₑ (in situ and mapped to equator). These very low frequency waves are observed both when the satellites are close to the equatorial plane and at higher magnetic latitudes. Poynting flux is consistent with generation at the equator. Wave amplitudes can be up to 20 to 40 mV/m and 2 to 4 nT. We conclude that conditions during moderate to large storms can excite unusually low frequency chorus, which is resonant with more energetic electrons than typical chorus, with critical implications for understanding radiation belt evolution.

1. Introduction

Early ground and satellite observations of electromagnetic waves with frequencies below the electron gyrofrequency, fₑ, identified a whistler mode emission that was named chorus [Burtis and Helliwell, 1969, 1976; Russell et al., 1969]. The instability mechanism is widely accepted to be anisotropic electron distributions, assumed to be associated with substorm injections [Kennel and Petschek, 1966; Kennel, 1966; Brice, 1964; Helliwell, 1967, 1969; Tsurutani and Smith, 1974; Curtis, 1978]. The process is most active in the postmidnight sector due to drift paths of injected electrons [Tsurutani and Lakhina, 1997]. Theories and observations of the source locations of chorus have concluded that the waves are typically excited at the magnetic equator and propagate away from this region [Dunkel and Helliwell, 1969; Burton and Holzer, 1974; Tsurutani and Smith, 1977; LeDuc et al., 1998; Santolik and Gurnett, 2003; Breneman et al., 2009; Agapitov et al., 2013; Li et al., 2013, and references therein]. A potential additional location for the instability to operate is within a magnetic minimum away from the equator [Burton and Holzer, 1974; Tsurutani and Smith, 1977], although this mechanism is generally invoked only for high-latitude dayside chorus. The waves often consist of an upper band and lower band, separated by a minimum in power at half the equatorial electron cyclotron frequency [Burtis and Helliwell, 1969] for which a number of explanations have been proposed, including Landau damping [Tsurutani and Smith, 1974] and excitation by different energy electrons and/or different mechanisms [Curtis, 1978; Omura et al., 2009; Liu et al., 2011; Fu et al., 2014]. Other theories proposed include nonlinear damping due to inhomogeneity in the geomagnetic field [Omura et al., 2009] and excitation in regions of enhanced or decreased density [Bell et al., 2009]. The observed frequency-time spectrograms, therefore, usually track 0.5fₑ. Frequently, only the lower band is observed.

The occurrence probability of low-frequency chorus (defined as power between the lower hybrid frequency, f₇₉, and 0.1fₑ) has recently been examined using data from multiple satellites by Meredith et al. [2014]. The study normalized observed wave frequencies to the local electron cyclotron frequency. The authors conclude that waves with low frequencies relative to fₑ have propagated to regions with higher magnetic field than where they were generated. Note that a similar explanation for the low-frequency chorus was proposed by Burtis and Helliwell [1969]. In contrast to most statistical studies of chorus, which bin wave power and/or frequency in magnetic latitude (MLAT)/L/magnetic local time (MLT) and by magnetic activity (either Kp or AE), we examine the time evolution
of the wave frequency at peak power during storms as the Van Allen Probes (or Radiation Belt Storm Probes, RBSP) repeatedly traverse L shells of ~3 to ~6, with an ~9 h period through the development of a storm. This provides a different perspective on the evolution of the frequency composition of chorus during active intervals. This is critical to understanding the energization and loss of electrons in the outer radiation belt during different storm phases. This approach enabled us to identify a phenomenon that we call "cernuous" whistlers (from the Latin for drooping), waves that suddenly no longer track $0.5 f_{ce}$ and that fall well below $0.1 f_{ce}$ at peak power, and their association with storms, solar wind parameters, and magnetic activity.

The data sets utilized in this study are from the Van Allen Probes (RBSP) satellites Electric Fields and Waves (EFW) instruments [Wygant et al., 2013] and the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) waves and fluxgate magnetometer [Kletzing et al., 2012] instruments. In addition, we make use of the T04 magnetic field models [Tsyganenko and Sitnov, 2005] with solar wind parameters provided through the Coordinated Data Analysis Web (CDAWeb).

2. Exemplar Event and Statistics

The moderate geomagnetic storm on 27–30 August 2014 provides the exemplary case of cernuous whistler mode waves. Figure 1 plots the electric field spectra from 20 Hz to 4 kHz from RBSP-A (Figure 1, first panel) and RBSP-B (Figure 1, second panel), and the magnetic latitude (RBSP-A in blue and RBSP-B in red) for approximately one orbit, from 13 to 23 UT. The wave data are over plotted with $f_{ce}/2$, $f_{ce}/10$, and $f_{lh}$ determined from the local field (in black) and the T04 model field (in dashed blue) mapped to the equatorial plane. Regions of cernuous waves are highlighted in pink.

Figure 1. Electric field spectra from 20 Hz to 4 kHz from (first panel) RBSP-A and (second panel) RBSP-B from 13–23 UT on 27 August 2014. The spectra are obtained from the EFW onboard fast Fourier transforms obtained from one spin plane component (E12) and are sampled at every 4 s. (third panel) MLAT and (fourth panel) MLT. Spectra are overplotted with $f_{ce}/2$, $f_{ce}/10$, and $f_{lh}$ determined from the local field (in black) and the T04 model field (in dashed blue) mapped to the equatorial plane. Regions of cernuous waves are highlighted in pink.
and magnetic field waveforms in field-aligned coordinates, the magnetic field spectrum, the wave normal angle spectrum, and the Poynting flux parallel to the magnetic field. In all the intervals, the wave vectors lie within ~20° of the magnetic field. The Poynting flux is along the magnetic field and away from the equatorial plane for the first three intervals (on 27 August 2014) when the satellites are north of the equatorial plane. Examination of the spectra on short time scales shows that chorus elements for RBSP-A intervals are often nearly vertical, which also indicates that the excitation is close to the satellite. During the fourth interval (on 1 November 2012, to be discussed below), the satellite was south of the equatorial plane and the Poynting flux is opposite to the magnetic field, again away from the equatorial plane. During all intervals, the waves are consistent with excitation close to the equatorial plane at unusually low frequencies. There are also examples that include rising and falling tones, as often observed in chorus.

An overview of solar wind conditions, magnetic activity, and the waves seen on the Van Allen Probes during the interval from 02 UT on 27 August 2014 to 24 UT on 29 August 2014 is shown in Figure 3. The storm was initiated by an increase in solar wind pressure and a long interval of large southward interplanetary magnetic field (IMF), as well as large IMF B_y (first dawnward and then duskward). The initial traversals of the outer radiation belt after the solar wind pressure increase, first by RBSP-B and then RBSP-A, were at high latitudes and both show that the chorus tracks the T04 model f_ce/2 mapped to the equatorial plane. The passes with the clearest examples of usual chorus dependence are highlighted in light purple. The second encounters (highlighted in Figure 1) occurred near the minimum in Dst, when AE > 1000. The dramatic decrease in the chorus frequency and onset of the cernuous whistler mode waves (chorus) seen on RBSP-A occurred ~1 h after a brief solar wind pressure pulse. There were three more traversals of the outer belt with cernuous whistler mode waves on RBSP-A, at ~06 UT on 28 August, ~13 UT on 28 August (not tracking f_ce/2, but not below 0.1 f_ce), and ~7 UT on 29 August. The passes with the clearest examples of cernuous waves are highlighted by the pink bands. There was an interval of weak low-frequency chorus over a small L extent on RBSP-B at ~12 UT on 29 August. The other traversals either had very weak whistler mode waves or whistler mode waves tracking f_ce/2.

There are two characteristics, usually occurring together, of unusual whistler mode frequencies with respect to f_ce determined from the model and/or in situ magnetic field. Both can be seen in Figures 1 and 3. The first type (cernuous) occurs when the peak frequency of chorus with respect to f_ce suddenly changes and drops below the usual bands centered on f_ce/2. The usual dependence can be seen both on RBSP-A and RBSP-B during the intervals highlighted in light purple in Figure 3, as well as in many published cases (for example, Kletzing et al., 2012, Figure 2; Meredith et al., 2001, Plate 1). In these cases, the chorus frequency tracks ~0.5 f_ce based on the equatorial magnetic field (either the in situ or mapped model field), with a minimum in power at 0.5 f_ce.

The second property occurs when the peak frequency is below 0.1 f_ce, sometimes as low as f_In. On 27 August 2014, at ~18:30 UT on RBSP-A and ~15 UT on RBSP-B, the waves drop to very low frequencies (~100 Hz), ~f_In, and therefore meet this criterion. On 28 August at ~6 and on 29 August at ~7 on RBSP-A, the peak frequency was ~0.1 f_ce.

Another example of cernuous chorus is shown in Figure 4, which plots data from 00 UT on 1 November to 24 UT on 2 November 2012, in the same format as Figure 3. There was a strong extended solar wind pressure increase with a storm sudden commencement on 31 October, the IMF turned southward at ~4 UT on 1 November 2012 with a large B_y, first duskward and then dawnward by 12 UT, and the storm main phase began at ~6 UT. During the first encounter with the outer belt by both satellites (~7–12 UT on 1 November 2012), the chorus exhibits the usual frequency dependence (highlighted in light purple); however, during the next pass (~15–22 UT), the peak frequency abruptly decreases to below 0.1 f_ce on both satellites. The cernuous waves (indicated by the pink highlighting) occurred near the minimum in Dst after a second pressure pulse. The IMF turned northward near the beginning of 2 November and the AE index was very low throughout the day. Low-amplitude chorus, also not tracking 0.5 f_ce but not as low as 0.1 f_ce, was seen until ~5 UT in association with weak (~150 nT) AE. This event shows very clearly the well-known connection between chorus and substorm injections as indicated by AE [Tsurutani and Smith, 1977; Meredith et al., 2001; Wilson et al., 2011]. Note that Fu et al. [2014] simulated excitation of chorus during the interval on RBSP-A when the chorus had the two-band structure centered on 0.5 f_ce.
Figure 2. Snapshots of waveforms and spectral data for selected intervals. (top left, top right, and bottom left) From 27 August 2014 and are indicated by the arrows in Figure 1. (bottom right) From 1 November 2012 at the time indicated by the arrow in Figure 4. From top to bottom the panels are one perpendicular component of the electric field waveform, one perpendicular component of the magnetic field waveform, the wave vector in each frequency band for which the waves are strongly polarized, and the parallel component of the Poynting flux.
We have examined all 36 storms with peak $Dst < -50$ nT from October 2012 to December 2014. Table 1 summarizes the observations sorted by magnetic local time sector at apogee MLT. Column 2 gives the date of storm onset. Column 3 indicates which satellites had cernuous waves, and column 4 indicates waves below $0.1f_{ce}$ (if A or B is in italics, the waves were weak or the feature was less dramatic). Column 5 indicates the phase of storm where the event occurred; “$Nr$ min” means in the region of minimum $Dst$. Column 6 shows the number of events/number of storms in each MLT sector.

In the local time sectors where chorus occurrence is known to peak (0–6 and 6–12), there were 18 storms and 17 had cernuous waves; 11 had cases with waves down to ~$f_{lh}$. Wave amplitudes can be up to 20 to 40 mV/m and 2 to 4 nT. Of the 10 storms in the dusk sector (18–24 MLT) where chorus occurrence is a minimum, three had cernuous waves and these were weaker and occurred on only the inbound orbit where the MLT was postmidnight. Using the number of outer radiation belt passes in each storm for normalization, the fraction of the time that cernuous and usual chorus are seen can be estimated. During the storms in Table 1 at MLTs of 0–12, the percentage of outer belt passes with cernuous waves (during part of the pass) varies from ~15% to ~30%. Outer belt passes with the usual chorus are slightly more common, ranging from ~15% to ~50%. The remainder of the passes contains either weak chorus (sometimes cernuous) or no chorus. There is no significant difference between the local time dependence of the percentage of passes with cernuous waves and with the usual chorus.

Using the range of plasma densities and magnetic fields typically observed in the events in the 0–12 MLT sector with the observed frequencies and wave normal angles, we can calculate the energy of electrons in cyclotron resonance with the cernuous waves, using the relativistic formulation. The range of $f_ce/f_pe$ is ~0.1 to 0.4. Resonant energies increase as $f/f_{ce}$ decreases. In these regions, the electron cyclotron frequency covers the range from ~2 kHz to 5 kHz, and the wave frequencies are $<100$ Hz to ~$500$ Hz. For wave normal angle and pitch angle of ~15°, $f_{ce}$ of 3 kHz, and density of 2 cm$^{-3}$, the resonant energy varies from ~20 keV to ~60 keV as the wave frequency decreases from 500 Hz to 100 Hz. As the density increases from ~1 cm$^{-3}$ to 5 cm$^{-3}$, resonant energies decrease from ~50 keV to ~15 keV. Note that the resonant energies are lower for Landau resonance and increase with increasing $f/f_{ce}$ (the reverse of the case for cyclotron resonance).

There were eight storms in the postnoon (12–18 MLT) sector. Seven contained intervals with very intermittent whistler mode wave bursts between $f_{lh}$ and ~$0.1f_{ce}$. Waves of this type were almost only seen in this local time sector and occurred during the recovery phase and with low $AE$. Additional studies will be needed to determine the source of these waves and whether they are consistent with chorus.

As shown in Table 1, most of the cernuous events occurred near the minimum in $Dst$. Most cases were associated with high $AE$ (>500 nT). There is no strong correlation between the occurrence of cernuous whistlers and solar wind pressure beyond what might be expected since the events all occur during storms.

3. Discussion and Conclusions

In a survey of all geomagnetic storms with $Dst < -50$ nT observed by the Van Allen Probes satellites from October 2012 to December 2014, we have found that almost all storms in the midnight to noon local time sector have unusually low frequency whistler mode waves, consistent with lower band chorus, during at least one pass through the outer radiation belt. Two different features are seen. The first we have termed cernuous waves down to ~$f_{lh}$. Wave amplitudes can be up to 20 to 40 mV/m and 2 to 4 nT. Of the 10 storms in the dusk sector (18–24 MLT) where chorus occurrence is a minimum, three had cernuous waves and these were weaker and occurred on only the inbound orbit where the MLT was postmidnight. Using the number of outer radiation belt passes in each storm for normalization, the fraction of the time that cernuous and usual chorus are seen can be estimated. During the storms in Table 1 at MLTs of 0–12, the percentage of outer belt passes with cernuous waves (during part of the pass) varies from ~15% to ~30%. Outer belt passes with the usual chorus are slightly more common, ranging from ~15% to ~50%. The remainder of the passes contains either weak chorus (sometimes cernuous) or no chorus. There is no significant difference between the local time dependence of the percentage of passes with cernuous waves and with the usual chorus.

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or when the frequency at peak power suddenly drops below the frequency expected based on either the in situ field or the T04 model field mapped to the conjugate equatorial plane. The second is the occurrence of waves consistent with local excitation at frequencies between ~\( f_{lh} \) and ~0.1\( f_{ce} \). Often both occur together. The wave frequency at peak power relative to the equatorial \( f_{ce} \) evolves with storm phase, \( AE \), and \( L \).

In contrast to the conclusions of Meredith et al. [2014] that low frequencies were due to propagation into regions of higher magnetic field, our results indicate that low-frequency chorus is often locally excited at frequencies below 0.1\( f_{ce} \).

There are four main possibilities that might explain our results: (1) the unstable waves are at lower frequencies because higher-energy electrons have the anisotropy required to drive the waves and/or cold plasma density is larger; (2) the chorus waves were excited at (near) the equatorial plane conjugate to the Van Allen Probes but at much lower frequencies, relative to \( f_{ce} \), due to excitation by a different mechanism than temperature anisotropy; (3) waves were excited off equator in a region of very low magnetic field in the usual range of \( f_{ce} \) or in the equatorial plane deeper in the magnetotail; or (4) the model magnetic field is incorrect and overestimates the equatorial field. Option 3, which is similar to the thesis of Meredith et al. [2014], is not consistent with the Poynting flux measurements. Because the model magnetic field matches the medium- and large-scale features of the observed field both when the Van Allen Probes satellites were at high latitudes and in the equatorial plane, it is not likely that the mapped model equatorial magnetic field is too high (option 4). In addition, errors in the model cannot explain the events observed close to the equatorial plane.

Assuming a density of \( \sim 2 \text{ cm}^{-3} \), the resonant energies for the cernuous regions are \( \sim 20 \) to 100 keV, in contrast to the few to tens of keV for waves at typical frequencies. The role of the cold plasma density in the excitation of cernuous waves may be complicated. Theoretical studies [Gary et al., 2012; Wu et al., 2013] show that increased cold electron density lowers the frequency for peak growth rate (for fixed hot electron anisotropy). Decreasing the frequency relative to \( f_{ce} \) increases the resonant energy; however, keeping other parameters fixed, resonant energy decreases with increasing density. Unraveling the possible role of density will require additional studies.

One interesting and suggestive result is that three storms with cernuous chorus, including the event in Figure 3, have been discussed by Mozer et al. [2013] and Artemyev et al. [2014], as prototypes of events with double layers (or time domain structures). Note that the intervals they show have chorus in the usual frequency range and are during the outer radiation belt traversals preceding the ones with very low frequencies. We have examined the EFW burst time domain data when they are available for the subsequent traversals with cernuous chorus, and there are time domain structures at lower amplitudes. The 27 August 2014 event shown in Figures 1 and 2 also has double layers (Cattell et al., Van Allen Probes observations of unusually low frequency chorus during the August 27, 2014 moderate storm: Wave properties, particle distributions and comparison to theory, in manuscript in preparation, 2015). Although this concurrence may just be due to the fact that both phenomena are associated with storms, it may indicate that the particle distributions necessary for both phenomena require highly distorted magnetic fields or that the double layers provide the acceleration of low-energy electrons to energies that could excite the whistlers [Mozer et al., 2014; Artemyev et al., 2014]. Reineitner et al. [1983] earlier described correlated observations of chorus and broadband electrostatic waves parallel to the magnetic field.
The fact that most events occurred near the minimum in $Dst$ suggests that the conditions (magnetic field structure, plasma density, and particle distributions) needed to excite the cernuous waves develop only after prolonged enhanced convection and the buildup of the ring current. Potential requirements include distorted magnetic field, long intervals of high $AE$ and associated injections, energization of injected electrons, modification of the electron distributions due to drift shell splitting and/or magnetopause shadowing, and enhanced density. The occurrence of magnetopause shadowing for several of the storms in Table 1 has been documented [Hudson et al., 2014, 2015]. Min et al. [2010] concluded that for one storm, the electron anisotropy needed to excite morningside chorus was due to drift shell splitting. Note that studies of cold density versus L shell, MLT, and $Dst$ [Thaller et al., 2015] indicate that enhanced cold density is unlikely in the region where the cernuous waves are seen due to the dramatic erosion of the plasmasphere and sharp magnetopause boundary on the dawnside. Chorus wave properties and comparison to particle distributions for the 27 August 2014 storm are examined in detail in Cattell et al. (manuscript in preparation, 2015). This study includes detailed tests of possible wave excitation mechanisms.

| LT | Date     | $Dst$ | Cernuous | $<1f_{ce}$ | Storm Phase | Comments                  |
|----|----------|-------|----------|-----------|-------------|---------------------------|
| 0–6| 11/1/2012| −63   | A, B     | A, B      | Nr min      |                           |
|    | 11/13/2012| −108  | A, B     | A, B      | Nr min      |                           |
|    | 1/17/2013 | −53   | A, B     | A, B      | Nr min      |                           |
|    | 1/25/2013 | −51   | B        |           | Onset, main |                           |
|    | 3/1/2013  | −55   | A, B     | A         | Nr min      |                           |
|    | 9/12/2014 | −75   | A, B     | A         | Nr min      |                           |
|    | 11/10/2014| −57   | A        |           | Nr min      |                           |
|    | 11/16/2014| −50   | B        |           |             |                           |
|    | 12/22/2014| −51   | A        |           | Nr min      |                           |
| 6–12| 9/30/2012 | −119  | A, B     | B         | Main and min|                           |
|    | 10/7/2012 | −105  | A, B     |           | Nr min      |                           |
|    | 10/12/2012| −79   | B        | A         | Nr min      |                           |
|    | 2/18/2014 | −112  | A, B     | A, B      | Nr min      |                           |
|    | 2/23/2014 | −56   | A, B     | A         | Rec         |                           |
|    | 2/27/2014 | −99   | A, B     |           | Nr min and rec|                           |
|    | 4/11/2014 | −80   | A        | A         | Nr min      |                           |
|    | 4/30/2014 | −67   | A        |           |             |                           |
|    | 8/27/2014 | −80   | A, B     | A, B      | Nr min and rec|                           |
| 12–18| 08/27/2013| −54   | A        |           |             |                           |
|    | 10/2/2013 | −67   | A        |           |             |                           |
|    | 10/9/2013 | −62   | A        |           |             |                           |
|    | 10/30/2013| −50   | A        |           |             |                           |
|    | 11/7/2013 | −50   | A        |           |             |                           |
|    | 11/9/2013 | −61   | A        |           |             |                           |
|    | 11/11/2013| −70   | A        |           |             |                           |
|    | 12/8/2013 | −66   | A        |           |             |                           |
| 18–24| 3/17/2013| −132  | A, B     | B         |             |                           |
|    | 3/28/2013 | −61   | A, B     | B         |             | (ib 0–3)                  |
|    | 5/1/2013  | −67   | A, B     |           | Nr min      |                           |
|    | 5/18/2013 | −57   | A, B     |           |             |                           |
|    | 5/25/2013 | −50   | A, B     |           |             |                           |
|    | 6/1/2013  | −119  | A, B     |           |             |                           |
|    | 6/6/2013  | −73   | A, B     |           | Main        | (ib)                      |
|    | 6/28/2013 | −98   | A, B     |           |             |                           |
|    | 7/6/2013  | −79   | A, B     |           |             |                           |
|    | 7/14/2013 | −73   | A, B     |           |             |                           |
| Total | 36       | 18    | 14       |            |             |                           |
Acknowledgments
The authors thank J.H. King and N. Papatachavili at AdnetSystems and NASA/GSFC for access to the OMNI data through CDAMweb and the World Data Center. We also thank the EFW instrument teams at Space Sciences Lab of UCB and LASP of CU, the EMFISIS suite teams at University of Iowa and UAH, and the APL satellite team. The Van Allen Probes data sets are available from http://www.space.umn.edu/missions/rbspfew-home-university-of-minnesota/ and http://emfisis.physics.uio.edu/data/index. Work at the University of Minnesota was supported by NASA contract NAS5-01072. The research at the University of Iowa was supported by JHU/APL contract 921647 under NASA Prime contract NAS5-01072. The authors thank J.H. King and N. Helliwell, R. A. (1969), Low-frequency waves in the magnetosphere, J. Geophys. Res., 74, 4063–4066, doi:10.1029/JZ074i022p04063.

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By examining the time evolution of chorus through the storms, we have taken an approach that is different from many previously published studies of the peak frequency and/or occurrence probability of chorus. We found that like the usual chorus, cernuous chorus occurred primarily in the postmidnight to noon magnetic local time sector during intervals of high AE. However, cernuous waves were usually observed near or within the minimum in Dst. The explanation for the occurrence of the low-frequency chorus has not yet been determined. Any proposed mechanism must be able to explain both the very low frequencies and the rapid drop in the normalized peak frequency with L. Almost every storm in this MLT sector had at least one period of unusually low and cernuous chorus in the outer radiation belt. This characteristic is significant for the storm time evolution of the outer belt because these waves are resonant with more energetic electrons.

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