Observations of relativistic electron precipitation from the radiation belts driven by EMIC waves

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[1] For some time theoretical modeling has shown that electromagnetic ion cyclotron (EMIC) waves should play an important role in the loss of relativistic electrons from the radiation belts, through precipitation into the atmosphere. Up to now there has been limited experimental evidence for relativistic electron precipitation driven by EMIC waves. In this paper we present case studies of events showing EMIC waves, observed by ground-based pulsation magnetometers, which are linked to strong responses in a subionospheric precipitation monitor. This response is consistent with precipitation occurring near the plasmapause, where EMIC waves may resonate with relativistic electrons. At the same time there is only a weak response in a co-located riometer chain, as expected for relativistic electron precipitation that penetrates deeply into the atmosphere. **Citation:** Rodger, C. J., T. Raita, M. A. Clilverd, A. Seppälä, S. Dietrich, N. R. Thomson, and T. Ulich (2008), Observations of relativistic electron precipitation from the radiation belts driven by EMIC waves, *Geophys. Res. Lett.*, *35*, L16106, doi:10.1029/2008GL034804.

1. Introduction

[2] Understanding the loss of these relativistic electrons is a key to understanding the dynamics of the energetic radiation belts. A significant loss mechanism is Relativistic Electron Precipitation (REP) into the atmosphere. One form of REP which has been observed in balloon campaigns lasts minutes to hours and was linked to EMIC waves [*Millan et al.*, 2002], although no wave observations were undertaken during that study. The mechanism proposed suggests that relativistic electrons would be rapidly driven into the bounce loss cone through interaction with electromagnetic ion cyclotron (EMIC) waves [*Summers and Thorne*, 2003].

[3] EMIC waves occur in the Pc1-Pc2 frequency range (0.1–5 Hz) and are generated near the magnetic equator by unstable distributions of ring current ions. The waves can propagate away from the generation region roughly along the geomagnetic field lines and can also be observed on the ground [*Erlandson et al.*, 1996]. In practice EMIC waves are generated in the magnetosphere as left-handed waves, but can convert to right-handed polarization during propagation. The observation of left-handed waves on the ground allows assumptions as to the *L*-shell of the source region. For at least 3 decades multiple theoretical studies have demonstrated that EMIC waves should be an effective mechanism for loss of >1 MeV electrons from the radiation belts in regions of increased magnetospheric particle density [*Engebretson et al.*, 2008, and references therein].

[4] To the best of the authors' knowledge, it is only very recently that experimental evidence has been presented that demonstrates the link between EMIC activity and REP. Subionospheric VLF measurements made during a large geomagnetic storm on 21 January 2005 detected a 50 min precipitation event which peaked at the same time as a Pc-1 EMIC wave detected at L = 3.4, probably associated with the location of the eroded plasmapause [*Clilverd et al.*, 2007]. Further evidence comes from satellite observations during a moderate geomagnetic storm in which regions of 30–80 keV proton precipitation were found to be co-located with those of relativistic electrons (>1.5 MeV) [*Sandanger et al.*, 2007], consistent with EMIC-driven precipitation of both low-energy protons and highly energetic electrons.

[5] However, there are reasons to further investigate the strong link between EMIC activity and REP inferred from the studies above. While EMIC waves have been viewed as the driver for the intense REP losses occurring during the main-phase of geomagnetic storms, a superposed epoch analysis of 13 geomagnetic storms found that narrowband Pc1–Pc2 waves and localized proton precipitation were rarely observed on the ground during the main and early recovery phases of magnetic storms [*Engebretson et al.*, 2008]. In this study we combine energetic electron precipitation observations, from subionospheric VLF receivers and riometers, with ground-based pulsation magnetometer data to consider the experimental link between highly energetic particle precipitation and EMIC waves.

2. Instrumentation

[6] The effects of changing ionization conditions in the mesosphere, due to energetic particle precipitation, can be observed along the propagation path between a VLF transmitter and a receiver. We use narrow band subionospheric VLF/LF data spanning 20–40 kHz received at Sodankylä (SGO), Finland (67.4°N, 26.4°E, L = 5.3). This site is part of the Antarctic-Arctic Radiation-belt Dynamic Deposition VLF Atmospheric Research Konsortia (AARDDVARK) (M. A. Clilverd et al., Remote sensing space weather events: The AARDDVARK network, submitted to *Space Weather*, 2008; see also the description of the array at www.physics.otago.ac.nz/space/AARDDVARK_homepage.htm). The VLF radio wave technique has an advantage for studying REP in that it is most sensitive to ionization caused by electron precipitation with high energies, typically

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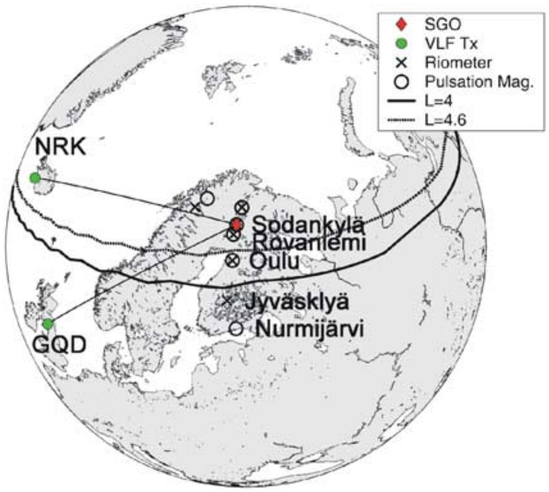

Figure 1. The experimental instrumentation used in this study. The lines show the subionospheric propagation paths from the VLF communications transmitters (circles) to the AARDDVARK receiver in Sodankylä, Finland (diamond). The pulsation magnetometer locations are indicated by open circles, and riometers by a cross.

>100 keV, as these energies ionize the neutral atmosphere in the Earth-ionosphere waveguide i.e., at altitudes below ~70 km. For this study we consider observations of transmitters with callsigns GQD (54.9° N, 3.3° W, L = 2.7; Anthorn, UK; 22.1 kHz), and NRK (64.2° N, 21.9° W, L = 5.6; Keflavik, Iceland; 37.5 kHz). The path from GQD to SGO provides observations across the plasmapause where we expect EMIC-driven precipitation to be present, while the NRK to SGO path monitors precipitation from higher latitudes, and particularly the outer radiation belt.

[7] Additional precipitation observations are provided by the Finnish riometer chain, operated by SGO and ranging from L = 3.9–6.2. The riometers are widebeam, 30–32.4 MHz, vertical pointing parallel dipole systems. The dominant altitude of riometer absorption is typically in the range 70–100 km i.e., biased towards relatively soft particle energies (~30 keV electrons). In this study, we will particularly focus upon the Oulu riometer located at 65.1°N, 25.9°E (L = 4.6), which is near to the expected plasmapause location for moderate (Kp = 4) storms, where EMIC waves may be resonant with relativistic radiation belt electrons [*Meredith et al.*, 2003].

[8] Here EMIC wave observations are provided by a north–south chain of Finnish pulsation magnetometers, operated by SGO, and ranging from L = 3.4–6.1, with a time resolution of 0.025 s. Again, we will principally make use of the observations from Oulu (L = 4.6), focusing upon the frequency range of 0.1–4 Hz, in which Pc1-Pc2 and IPDP (intervals of pulsations of diminishing periods) EMIC waves are known to occur.

[9] Figure 1 shows the location of the radio wave receiver site (diamonds), and the transmitter-receiver paths that are studied during the event period. In some cases the riometer and pulsation magnetometers are co-located (e.g., Oulu), and the diamond marking the AARDDVARK receiver at Sodankylä obscures the markers for both a riometer and a pulsation magnetometer.

3. Precipitation During EMIC Events

[10] In this letter we report on a small number of isolated events demonstrating highly energetic electron precipitation observed during the occurrence of EMIC wave activity. All the events occur during quiet to weakly disturbed geomagnetic conditions, leading to very clear linkages between the wave activity and precipitation. A larger statistical search of the complete experimental database is currently underway, and will be reported in a future journal paper. The top and middle plots of Figure 2 present two hours of pulsation magnetometer observations from the Oulu site on 7 February 2007. Strong EMIC waves were detected in the frequency range 0.35–1.2 Hz from 19:31 UT, lasting until 19:50 UT, and peaking at 19:38 UT. We classify this EMIC wave activity as IPDP, which is characterized by Pc1 pulsations that rise in frequency over the duration of the event. Such events are generally more intense than Pc1s and thus may be more efficient for particle scattering. At the top of the plot we show the mean EMIC wave power in the band 0.5–3 Hz. The top plot of Figure 2 follows the format of *Clilverd et al.* [2007], who reported on particle precipitation and EMIC events during the main pressure pulse of an interplanetary coronal mass ejection hitting the Earth's magnetosphere. The peak power of the EMIC wave activity in Figure 2 was observed at Oulu, where the polarization of the wave at this station was predominantly left handed, again confirming the nature of the wave as EMIC. This also indicates that the source is near the L-shell of Oulu. The wave activity was also visible in all the pulsation magnetometer data from Sodankylä south (Figure 1), including the southern-most magnetometer station (Nurmijärvi), but all at lower power

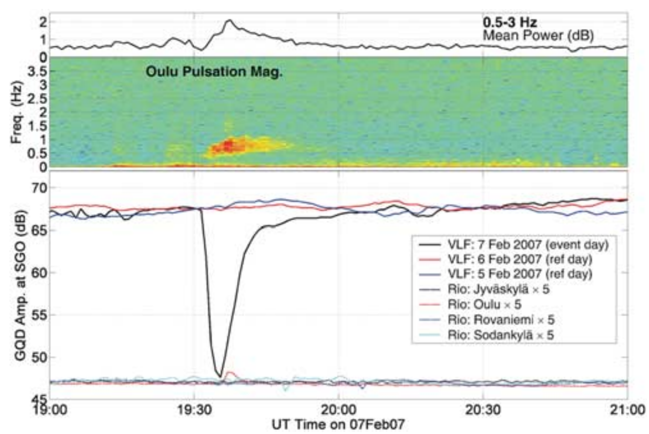

Figure 2. (top and middle) Oulu (L = 4.6) pulsation magnetometer data from 19–21 UT on 7 February 2007 indicating the presence of IPDP EMIC activity occurring during a minor geomagnetic disturbance (Kp = 3.7, D_{st} = −12 nT). (bottom) Contrast between the subionospheric precipitation monitor amplitude of GQD for 3 days centered on the event day (solid lines) and the absorption data from the Finnish riometer chain (dotted lines) on 7 February 2007. The riometer absorptions have been multiplied by 5 and shifted so as to appear on this plot.

Table 1. Summary of Observed Events, Geophysical Conditions, and the Responses of the Instruments[a]

Date	Time (UT)	EMIC Type	VLF ΔA (dB)	Rio ΔAbs (dB)	Kp	D_{st} (nT)	Lpp
8 Dec 2006	18:30–19:10	IPDP	−13	0	3.7	−9	4.6
7 Feb 2007	19:35–19:50	IPDP	−20	0.3	3.7	−12	4.6
20 Nov 2007	13:10–13:50	IPDP	−7	0.3	5.3	−47	4.0
22 Nov 2007	16:30–17:00	Pc1	−6	0	3.7	−21	4.6
Average			−12	0.15	4	−22	4.5

[a]The riometer observations are provided by Oulu (L = 4.6), and the VLF path is GQD-SGO. See the text for further details.

levels and with less clearly left-hand polarization. This suggests that the EMIC activity was generated on a field line near Oulu ($L = 4.6$), and propagated in the ionosphere to the nearby sites poleward (260 km from Oulu) and equatorward (510 km from Oulu). As the EMIC activity was not observed at the two pulsation magnetometer sites polewards of Sodankylä (locations which are 392 km and 491 km north of Oulu), the EMIC-source is likely to have been somewhat equatorward of Oulu, to be consistent with a symmetric wave amplitude pattern. This would place the source approximately 1° equatorward (111 km) of Oulu at L = 4.2.

[11] The bottom plot of Figure 2 compares the subionospheric and riometer precipitation monitors during this time. The solid lines show the 1 min resolution amplitude of the VLF transmitter GQD as received at Sodankylä for 7 February 2007 (black line), and the two previous days (red and blue lines) to provide an indication of typical subionospheric propagation conditions. At the time of the Oulu-observed EMIC wave activity, a large decrease in the subionospheric amplitude is observed, reaching −20 dB at ~19:36 UT, and recovering over the following ~30 min. There is no response on the path from NRK to Sodankylä (L = 5–6), indicating that the ionospheric changes are only occurring equatorward of these L-shells. The magnitude of this decrease is dramatic, and larger than the changes observed during intense precipitation events in large geomagnetic storms (e.g., 21 January 2005) (Clilverd et al., submitted manuscript, 2008). Such a large change strongly suggests that precipitation striking a region at about 1400 km from the transmitter (at L = 4.3) could be modifying the location of the modal minimum (i.e., a null in the transmitter signal strength) that normally lies close to SGO. Changes at this location have been identified, through our modeling, as being capable of producing large amplitude variations at SGO. This region is at a very similar L-shell to that determined using the EMIC wave observations.

[12] The dotted lines in bottom plot of Figure 2 indicate the 1-min resolution cosmic noise absorptions measured by the southern elements in the Finnish riometer chain from south (Jyväskylä) to north (Sodankylä). The absorption values have been multiplied by 5 and shifted upwards to emphasize the variation. Only the Oulu riometer (dotted red line) responds during the time-period of the EMIC wave activity, with a very small increase in absorption of 0.3 dB at 19:37:45 UT. This is very close to the time of the peak power in the Oulu EMIC wave activity (~19:38 UT) but slightly after the peak subionospheric amplitude perturbation (19:34:30–19:36:00 UT). The riometer response possibly indicates a softening in the precipitation spectra at this time, or a slight change in the precipitation location during the activity period to cover the viewing region of the Oulu-based riometer.

[13] Table 1 summarizes the observations from 7 February 2007, which is coincident with a substorm onset. This event was found through an examination of the daily subionospheric and pulsation magnetometer plots. Three other events are listed in Table 1, which were found in the same search. Subsequent analysis showed that these events share similar characteristics. They occur during quiet to weak geomagnetic disturbances, show EMIC wave activity with power that peaks at Oulu, and have very similar timing relative to subionospherically detected precipitation occurring on the path from GQD to Sodankylä. At these times no signature is seen in the high-latitude paths, confirming that the precipitation is limited to L-shells lower than $L \sim 5$. During these events the riometer chain either does not respond, or shows very little additional absorption. For example, the Oulu riometer absorption increased by only ~0.3 dB during the EMIC activity of 20 November 2007, while the other study periods show no riometer response within the measurement uncertainty. All 4 precipitation events occur during isolated IDPD/Pc1 activity "bursts" generated under differing geomagnetic conditions; 8 December 2006 and 7 February 2007 are at substorm onsets, 20 November 2007 is during a storm main phase, while the isolated Pc1 burst at ~16:40 UT on 22 November 2007 are most likely to be compression-related as part of a source which lasts throughout the day.

[14] The observation of large changes in VLF propagation conditions but little or no riometer absorption during the EMIC event confirms that EMIC waves cause precipitation of relativistic electrons from the radiation belts during geomagnetic storms. The timing agreement between the pulsation magnetometers and the subionospheric observations confirms that EMIC waves drive precipitation over at least 12° longitude difference (~1 hr MLT). All the events in Table 1 have left-hand polarized EMIC waves at Oulu, except 20 November 2007, where the waves are more clearly left-handed at the next magnetometer station polewards (Rovaniemi, L = 5.1).

4. Modeling

[15] For the purposes of checking the response of our experimental instruments for the events listed in Table 1, we undertake initial modeling based on the average subionospheric and riometer response listed on the last line of Table 1. Here our goal is not to reproduce the exact response of the instruments to every event, but to investigate whether highly relativistic precipitation can lead to very strong subionospheric attenuation while producing little additional riometer absorption. We assume that the precipitation stretches

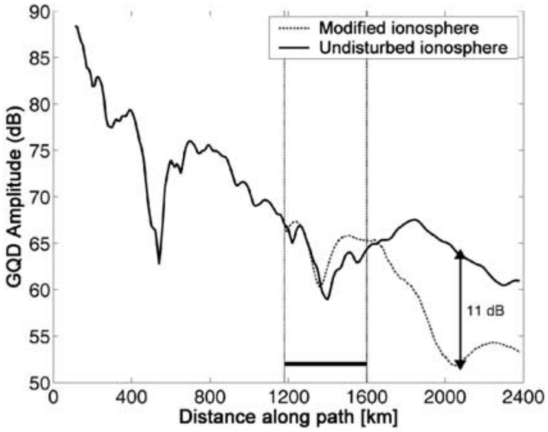

Figure 3. Comparison between the predicted subionospheric amplitudes of GQD with and without a section of precipitation-modified ionosphere. The modified section of the path is shown by the heavy black line and the vertical dashed lines.

from $L = 4.–4.6$ over the longitude range which includes the GQD-SGO great circle path and the Finnish riometer and magnetometer chains. This L-shell range is centered on the GQD-SGO high sensitivity location, covering 420 km of the 2078 km path, and is indicated by the $L = 4.0–4.6$ contours in Figure 1. Modeling shows that ionospheric modifications located around this minimum location produce particularly large changes for a receiver at SGO. The precipitation region covers the Oulu riometer, but is just outside the viewing region of the riometers north and south of Oulu. We follow the approach outlined by *Rodger et al.* [2007], where precipitation occurs along a section of the transmitter-receiver great circle path, the electron number density profile is determined from a simple ionospheric electron recovery model, and the profile is then used as input to a subionospheric propagation model. Through this route we thus model the effect of precipitation on the GQD-received amplitudes at Sodankylä.

[16] Figure 3 shows the propagation model-determined subionospheric amplitudes along the GQD-SGO path. In this case the ionospheric modification is caused by the precipitation of 2 MeV monoenergetic electrons with flux 500 el. $cm^{-2}s^{-1}str^{-1}keV^{-1}$. The ionospheric electron density profile is modified in the 420 km section marked by the heavy black line and the vertical dashed lines, leading to the $\sim$11.3 dB decrease in the Sodankylä received amplitude relative to the undisturbed case, as marked in Figure 3. The resulting absorption on the Oulu riometer is calculated to be only 0.14 dB. Clearly, this combination of a large flux of relativistic electrons can produce a large subionospheric response, but a comparatively small change in riometer absorptions, similar to the pattern for the events listed in Table 1. This large difference in instrument responses is partially due to the precipitation arriving at a highly responsive section on this VLF path, where the subionospheric propagation is particularly sensitive, but also because the electron number density change peaks at $\sim$60 km, well below the altitudes where riometers are most sensitive. Note that while the strong subionospheric/weak riometer response requires highly energetic precipitation, at this stage the specific precipitation energies are not fixed, and significant further modeling is required to incorporate a more realistic energy spectrum for the precipitating flux. Detailed modeling of the events outlined here will be left to a further study.

[17] *Lukkari et al.* [1977] analyzed pulsation magnetometer and riometer data from the Finnish chain and found a close correlation between IPDP events and strong localized riometer absorption (with magnitudes up to $\sim$5 dB), suggesting the absorption events were from relativistic electrons precipitated by the IPDP. Similarly to the events considered in the current study, the IPDP pulsations were generated in the afternoon sector during magnetic disturbances (substorms) and were concentrated at $L = 3.7–4.8$. Our modeling suggests that riometer absorptions of $\sim$5 dB would require 2 MeV precipitating fluxes which are $\sim$50–100 times stronger than considered in this study. Another possibility is that the precipitation in those events included a significant lower energy component.

5. Discussion and Summary

[18] In this study we have considered the experimental link between highly energetic particle precipitation and EMIC waves. EMIC waves observed in the Finnish pulsation magnetometer chain are associated with large changes in subionospheric VLF propagation. The response is consistent with precipitation occurring near the plasmapause, where EMIC waves may resonate with relativistic electrons. During these events there were only small responses in the Finnish riometer chain measurements, consistent with relativistic precipitation causing peak ionization enhancements well below the altitudes where riometers are most sensitive. This study shows that EMIC waves and intense relativistic electron precipitation can be strongly linked, as expected by previously reported theoretical modeling.

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