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Key Points:
- CALET on board ISS is space weather monitoring the duskside REP events
- Rapid 5-20 s modulations are regularly found in phase at >1.6 and >3.6 MeV detectors
- The rapid REP modulations are useful to diagnose the nonlinear growth of EMIC waves

Supporting Information:
- Supporting Information S1
- Figure S1

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Relativistic electron precipitation at International Space Station: Space weather monitoring by Calorimetric Electron Telescope

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Abstract The charge detector (CHD) of the Calorimetric Electron Telescope (CALET) on board the International Space Station (ISS) has a huge geometric factor for detecting MeV electrons and is sensitive to relativistic electron precipitation (REP) events. During the first 4 months, CALET CHD observed REP events mainly at the dusk to midnight sector near the plasmapause, where the trapped radiation belt electrons can be efficiently scattered by electromagnetic ion cyclotron (EMIC) waves. Here we show that interesting 5–20 s periodicity regularly exists during the REP events at ISS, which is useful to diagnose the wave-particle interactions associated with the nonlinear wave growth of EMIC-triggered emissions.

1. Introduction

Relativistic electron precipitation (REP) events have been observed for a half century since the findings of unusually enhanced ionization of the mesosphere using radio waves [*Bailey and Pomerantz*, 1965; *Rosenberg et al.*, 1972]. It has been therefore discussed that such MeV electron precipitation may affect the ozone chemistry in the middle atmosphere [*Callis et al.*, 1991]. *Foat et al.* [1998] measured X-ray bursts extending up to MeV energies with a balloon-borne detector at high latitude in the dusk sector and estimated the origin to be 1.7 MeV electrons. They also reported an interesting 10–20 s periodicity in the X-ray count rate during the REP event. Following a pioneering theoretical prediction of *Thorne and Kennel* [1971], *Lorentzen et al.* [2000] suggested that the REP event of *Foat et al.* [1998] was a result of pitch angle scattering of MeV electrons by an energy-selective resonance with electromagnetic ion cyclotron (EMIC) waves which are generated by injected protons near the plasmapause associated with a substorm. *Lorentzen et al.* [2000] also discussed that modulation of EMIC wave growth may be responsible for the observed 10–20 s periodicity. *Millan et al.* [2002] found a number of similar REP events at the dusk-to-midnight sector and called them as "duskside REP." *Millan et al.* [2002] did not observe the similar periodicity; instead, they reported modulations with a much lower frequency of mHz. Recently, *Shoji and Omura* [2013] simulated a modulated wave growth of EMIC-triggered emissions, and *Kubota et al.* [2015] simulated energy-dependent 5–20 s intensity modulation of REP events, associated with some idealized subpacket structures of EMIC-triggered rising tone emissions.

Direct measurements of REP events have also been conducted by spacecraft during the last four decades. REP events are a common feature near the high-latitude boundary of the radiation belt and were initially called "precipitation spikes." REP events have 2–3° extent in latitude, and sometimes persist for hours, as measured by several spacecraft [*Anderson et al.*, 1968; *Imhof et al.*, 1986]. The pitch angle distribution of MeV electrons in REP events has been identified as isotropic with filled loss cone by the polar-orbiting SAMPEX satellite [*Blake et al.*, 1996]. The isotropy is consistent with a widely extended precipitation region in longitude, and multiple "precipitation bands" are also observed with a complex structure within each band. The REP events frequently contain the most intense flux encountered throughout a pass. *Miyoshi et al.* [2008] showed ground-based observations of EMIC waves and isolated proton aurora at the same time under a REP event as identified by the POES satellite. Extending the work by *Miyoshi et al.* [2008], *Carson et al.* [2013] showed a statistical study of such REP events using POES satellites and showed an occurrence peak at around L value of 4–6 in the premidnight sector.

Spacecraft systems are influenced by MeV electrons [*Baker et al*., 1987], and the International Space Station (ISS) is not an exception. Calorimetric Electron Telescope (CALET) on board ISS has measured GeV-TeV electrons and nuclei in $Z = 1–40$ and gamma ray bursts since October 2015 [*Torii et al*., 2015]. We are monitoring [*Asaoka et al*., 2015] the high count rate of the charge detector (CHD) as "bad space weather," especially in high-latitude paths to carefully operate the high-voltage system of CALET. During the first 4 months of operations, we have noticed that REP events have the most intense flux to raise the CHD count rate close to the saturation level for several tens of seconds, regularly associated with impressive 5–20 s intensity modulation. The purpose of this study is to report the possibility of utilizing the CALET CHD count rate as the most sensitive MeV electron detector ever, by showing that basic occurrence characteristics of REP events as seen by CALET during the first 4 months are consistent with duskside REP events. We discuss the possibility of space weather forecasting of the REP events at ISS and also test a possible generation mechanism of 5–20 s intensity modulation.

2. Observations

The charge detector (CHD) is placed at the top of the apparatus to provide a measurement of the electric charge of the incoming particle via the Z^2 dependence of the specific ionization loss in the double layered, segmented, plastic scintillator array. Each layer consists of 14 plastic scintillator paddles, with dimensions 450 mm (L) × 32 mm (W) × 10 mm (H). The two layers of paddles, CHD-X and CHD-Y, are orthogonally arranged to determine the incident position of cosmic rays. The CHD and related front end electronics are designed to provide incident particle identification with sufficient charge resolution over a large dynamic range for charges from $Z = 1$ to $Z = 40$ [*Marrocchesi et al*., 2013]. The analog sum of signals in each CHD layer feeds a discriminator with approximately 0.6 MeV threshold to produce a trigger counter signal. Coincidence between these two signals produces the event trigger for cosmic rays. The trigger counter signals are counted with a scalar, and the numbers in every second are recorded as a part of the housekeeping data. They are used in this analysis to obtain the count rates of the CHD-X and the CHD-Y.

The CHD is covered by an aluminum surface 2 mm thick, which stops electrons of less than approximately 1 MeV. The EJ-200 plastic scintillator with a thickness of 10 mm stops 2 MeV electrons. Considering these energy depositions, and the 0.6 MeV discriminator threshold, CHD-X and CHD-Y can be used as approximately >1.6 MeV and >3.6 MeV electron detectors, respectively. The sampling time interval is 1.0 s. The geometric factor of CHD-X for 1.6 MeV electrons is 6.3×10^3 cm^2 sr, assuming the isotropic pitch angle distribution of REP events [*Blake et al*., 1996]. The count rate of 10^5 s^{-1} at CHD-X can therefore be approximately converted to 10 cm^{-2} s^{-1} sr^{-1} MeV^{-1} at 1.6 MeV, although the exact values should be obtained by cross calibrations with some other independent instruments in near future. Approximately 400 ns dead time correction is also significant especially for extremely high count rate, and the real count rate at 5.0×10^5 s^{-1} is 1.25 times larger than observed, for example. At the count rates below 10^5 s^{-1}, the correction is considerably smaller, less than 4%.

The ISS orbital inclination of 51.6° and the flight altitude of approximately 400 km cover the magnetic latitudes (MLATs) ranging from −67° to 63°, and there are unique opportunities to scan some REP events from west to east in 10 min. At high MLAT, the background count rates due to galactic cosmic rays are almost constant at about 3.0×10^3 s^{-1} for both CHD-X and CHD-Y detectors. We ignore the small background counts to obtain the intensity ratio, r_{XY}, between the two detectors to make the analysis robust, avoiding zero division. In this study, we identify REP events by the threshold value of 10^5 s^{-1} at CHD-X detector.

3. Results and Discussions

Figures 1 shows an example of CALET CHD data for the 12 min time interval 0930 UT to 0942 UT on 10 November 2015. It is worthwhile to note here that on the same day, European Space Agency's INTEGRAL satellite unexpectedly observed X-rays from hard electron precipitations (http://sci.esa.int/integral/57257-integral-x-rays-earths-aurora/). One of the largest flux enhancements of MeV electrons was observed at CALET CHD for less than 1 min at 0939 UT on 10 November 2015. This particular 1 min interval of REP event is expanded in Figure 2 to see the ratio r_{XY} and the phase difference

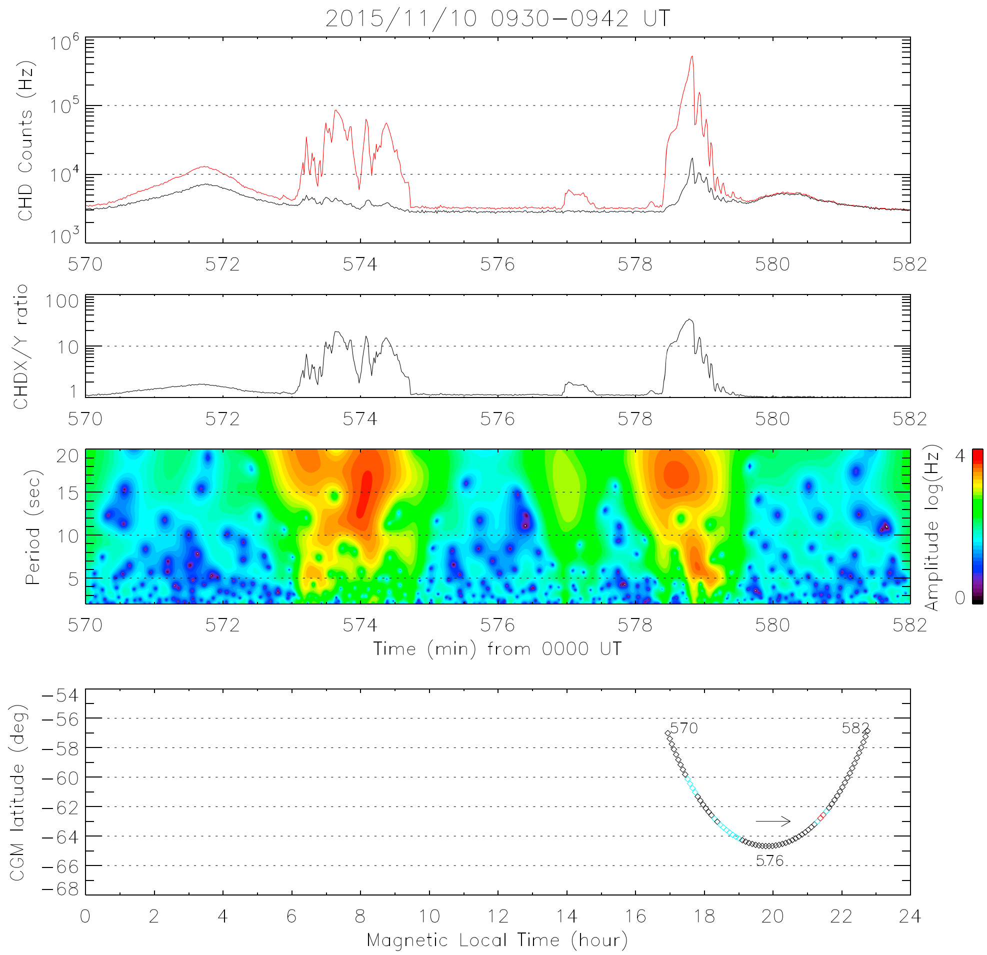

Figure 1. Relativistic electron precipitation (REP) event at the International Space Station (ISS) for the time interval from 0930 to 0942 UT on 10 November 2015. From top to bottom, shown are the count rates of CHD-X (red) and of CHD-Y (black), the ratio of the CHD-X to the CHD-Y counts, color-coded *S* transform amplitude to see the periodicity, and the magnetic latitude and magnetic local time of the ISS orbit. The position of ISS is colored in sky blue when the CHD-X count exceeds 10^4 s^{-1} and is colored in red when it exceeds 10^5 s^{-1}.

between CHD-X and CHD-Y counts in detail. The ratio r_{XY} decreased from >20 to unity at −64 to −62 MLAT and 21–22 magnetic local time (MLT) sector, showing a very similar modulation with CHD-X and CHD-Y counts without any clear phase difference.

S transform [*Stockwell et al.*, 1996] is a useful method of time-frequency representation to accurately measure the periodicity especially when the number of corresponding waves is limited [*Kataoka et al.*, 2009]. The third panels of Figures 1 and 2 show the *S* transform amplitude of log counts of CHD-X. It is clearly found that the modulation periodicity changed from 7 to 5 s during the REP event for the time interval from 0938:50 UT to 0939:10 UT.

The data slightly before the REP event at 0939 UT also have useful information as shown in Figure 1. For the time interval from 0930 to 0933 UT, a smooth increase and decrease of CHD-X and CHD-Y counts were observed from −58 to −63 MLAT, which can be assumed to be trapped MeV electrons with a loss cone [cf. *Blake et al.*, 1996] and usually has harder spectra (small ratio r_{XY}) than REP events at ISS. For the time interval 0933–0935 UT, at −63 to −65 MLAT and 18–19 MLT sector, another REP event with highly modulated counts was observed. The REP event is therefore likely extended to 18–22 MLT, assuming that both high counts are the same REP events at different locations. The ratio r_{XY} increased from unity to 20 from low to high latitudes, showing again a very similar modulation with CHD-X and CHD-Y counts. The periodicity is relatively short at 5 s at the low-latitude part and relatively long at 10–20 s at the high-latitude part.

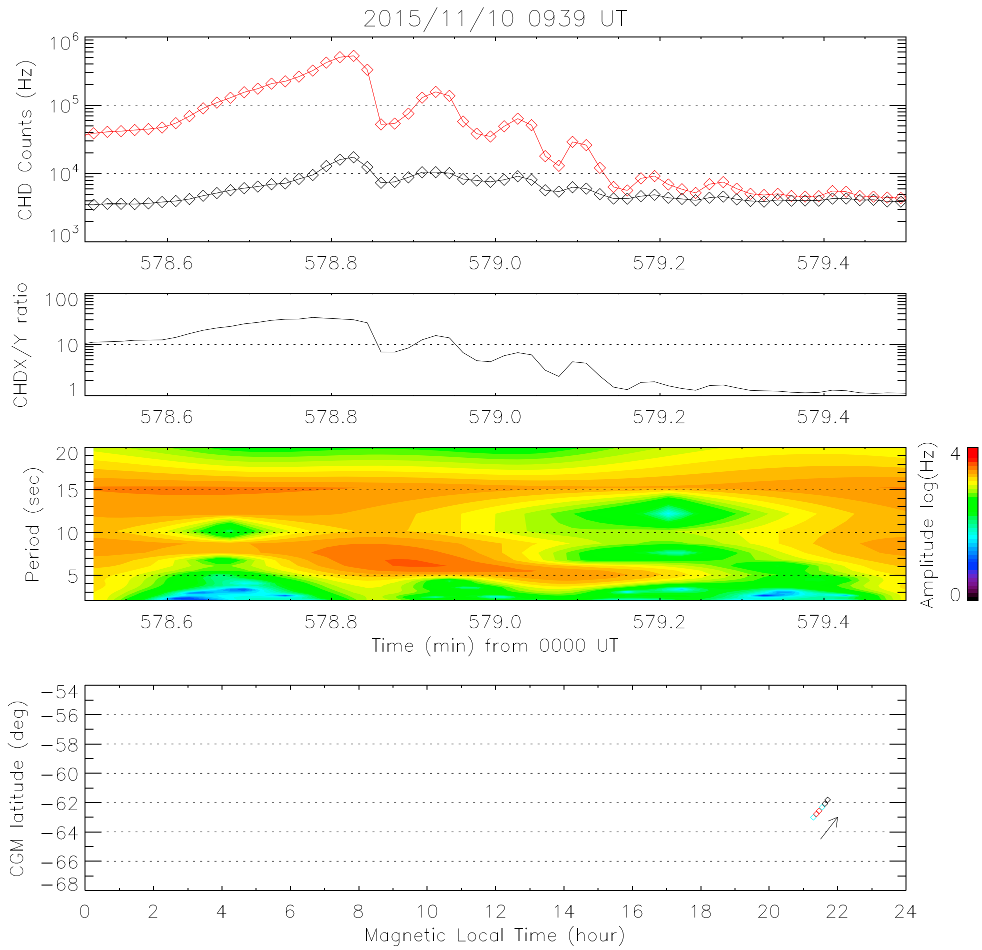

Figure 2. Same as Figure 1 except for the expanded time interval for 1 min across 0939 UT on 10 November 2015. There are no clear phase differences among the CHD-X, CHD-Y, and the ratio.

It is found that the 5–20 s quasiperiodic modulations in CHD-X and CHD-Y counts and in the ratio always exist for other REP events, which can be a result of a very efficient MeV electron precipitation associated with the nonlinear wave growth of EMIC-triggered emissions, as recently proposed by several sophisticated simulations [*Omura and Zhao*, 2012; *Shoji and Omura*, 2013; *Kubota et al*., 2015]. The predicted MeV electron resonance with some idealized narrowband and rising tone EMIC-triggered emissions is highly energy dependent [*Kubota et al*., 2015], and some phase differences in counts and in ratio are expected to be observed as the temporal variations. However, we cannot find any clear phase differences in counts or in ratio at ISS so far. The mechanism of intensity modulations may therefore be more complex than expected. For example, if the actual EMIC-triggered emissions had dominantly broadband complex features, we do not necessarily expect clear phase differences. There are technical limitations that ISS observations cannot distinguish the spatial or temporal variations, and CALET CHD actually measures the integral flux which may smear out the energy dependence. Cutting edge simulations combined with the in situ observations of wave-particle interactions from JAXA's coming ERG mission [*Shiokawa et al*., 2006] and from NASA's ongoing Van Allen Probes will soon provide critical data to test the hypothesis, which can be directly compared with the observed REP events at ISS.

To briefly summarize the first 4 month observations of REP events in October–December 2015 and in January 2016, MLT-MLAT positions of all of the observed REP events are shown in Figure 3. The data coverage of the ISS CALET CHD observations for the same 4 months is also shown in the supporting information. The ratios of CHD-X to CHD-Y counts are color coded, and the threshold value to draw the points is the high CHD-X counts exceeding 10^5 s^{-1}. Warm-colored patchy curves are of REP events,

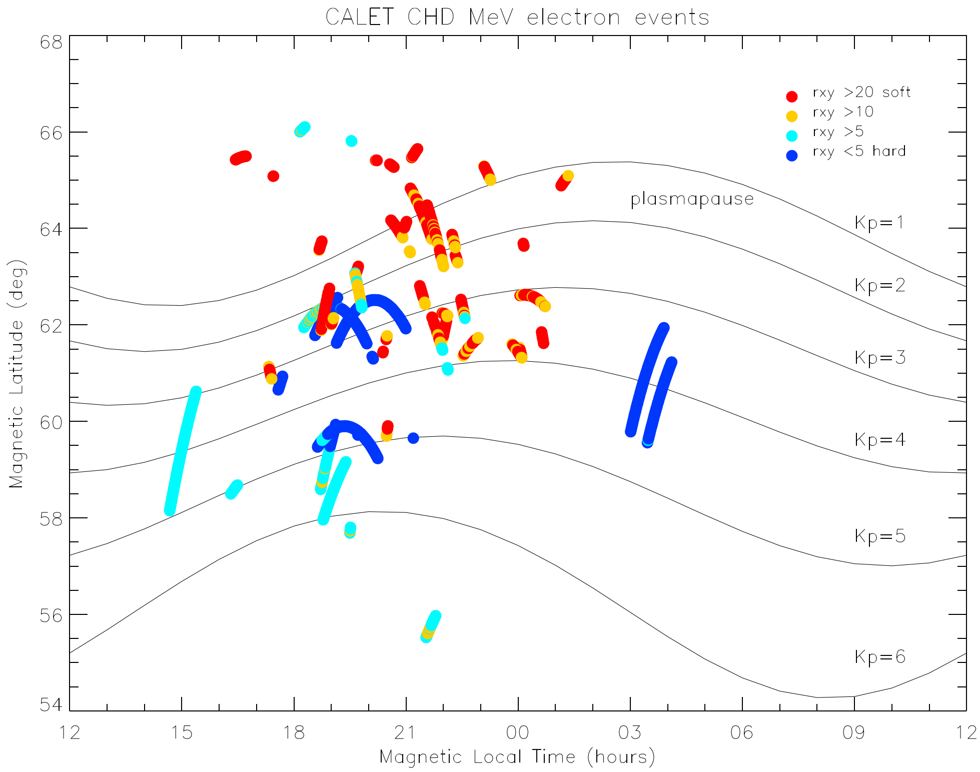

Figure 3. Positions of all of the REP events observed for the 4 month time interval in October–December 2015 and in January 2016. The ratios of CHD-X to CHD-Y counts are color coded for the whole time interval satisfying the CHD-X count exceeding $10^5\,s^{-1}$. Warm-colored patchy curves are of REP events, and several blue-colored continuous curves are from trapped radiation belt electrons. The REP events are clustered at 61–66 MLAT in the dusk to midnight sector. The energy spectra of REP events are generally softer at higher latitude for each event.

and blue-colored continuous curves can be assumed to be trapped radiation belt electrons. The energy spectra are generally softer at higher latitude for each REP event, which is consistent with the general trend of radiation belt electrons. Possible plasmapause locations are also drawn using a *Kp*-dependent model of *O'Brien and Moldwin* [2003]. Data points from the Southern Hemisphere are merged with those of the Northern Hemisphere by flipping the sign of MLAT. It is found that the REP events are clustered at 61–66 MLAT at the dusk to midnight sector near the plasmapause, where plenty of strong EMIC-triggered emissions have also been observed [*Pickett et al.*, 2010]. It is also noted that some REP events are found well outside the plasmapause. These occurrence characteristics are consistent with previously reported duskside REP events [*Millan et al.*, 2002]. In order to further tell the closeness of each REP location to the plasmapause, Figure 4 shows the REP locations as a function of MLT and ΔL, where ΔL is defined as each individual REP's L value minus the corresponding plasmapause L value. It is found from Figure 4 that majority of REP events systematically occur outside of the model plasmapause.

It is also noted that a low-intensity REP event can often be found in a previous ISS orbit of an intense REP event, probably because REP events generally show gradual evolution and decay on an hourly time scale. In fact, all of the observed REP events so far occurred during or within a few hours after substorms. Further, a number of REP events occurred during the first 2 weeks in November 2015 when the trapped flux of >2 MeV electrons was higher than average at geosynchronous orbit. These circumstances should be further investigated for a space weather forecast of the REP events at ISS.

In summary, the space weather monitoring data of the CALET CHD at ISS uniquely contribute to investigation of the fundamental plasma physics of the radiation belt and the ozone chemistry of the middle atmosphere, in addition to forecasting the radiation environment at ISS.

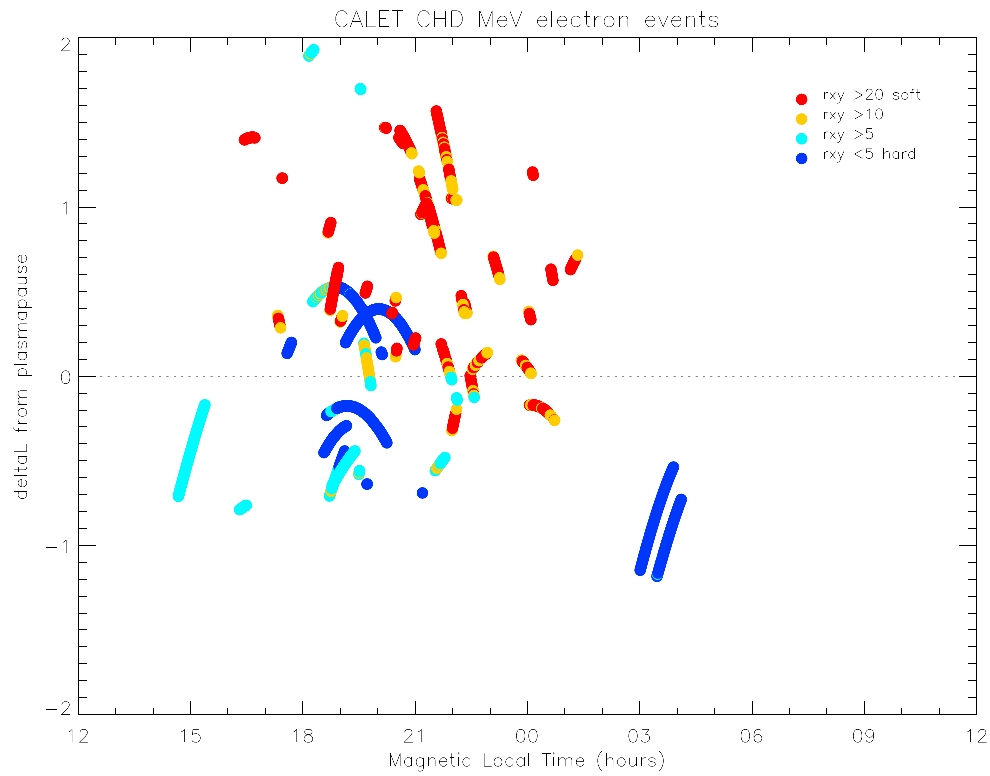

Figure 4. Same as Figure 3 except for the vertical axis of the ΔL from the plasmapause, where ΔL is defined as each individual REP's L value minus the corresponding plasmapause L value.

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