Relativistic Electron Precipitation Detections with CALET on the International Space Station

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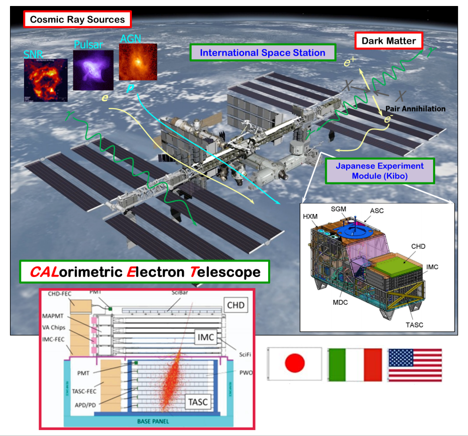
ABSTRACT

The CALorimetric Electron Telescope (CALET) is a high-energy astroparticle physics experiment installed on the International Space Station, and taking data since October 2015. While designed for studying the origin and the propagation of galactic cosmic rays, CALET is also able to provide a continuous monitoring of space-weather phenomena affecting the near-Earth environment, including solar energetic particle and relativistic electron precipitation (REP) events. In this work we present preliminary results of the REP observations made over a four-year acquisition time (2015-2019), investigating their correlations with the interplanetary and geomagnetic conditions. We also took advantage of a multi-spacecraft study using the twin Van Allen Probe measurements to complement CALET detections in low-Earth orbit, enabling a more complete picture of the global precipitation rates and drivers.

Relativistic Electron Precipitation

Relativistic electron precipitation (REP) is a space-weather phenomenon commonly observed at high latitudes, in which energetic electrons trapped in the geomagnetic field are lost into the upper or middle atmosphere. It plays an important role in the magnetosphere dynamics, in particular during depletion intervals of the outer belt, and it has also a significant impact on the electrodynamics and chemical structure of the atmosphere. REP events are thought to be predominantly originated by pitch-angle scattering into the loss cone by plasma waves, field-line curvature scattering or loss through the magnetopause. Statistically, they occur more frequently during the declining phase of the solar cycle, mostly in association with high-speed streams (HSSs) and under active geomagnetic conditions.

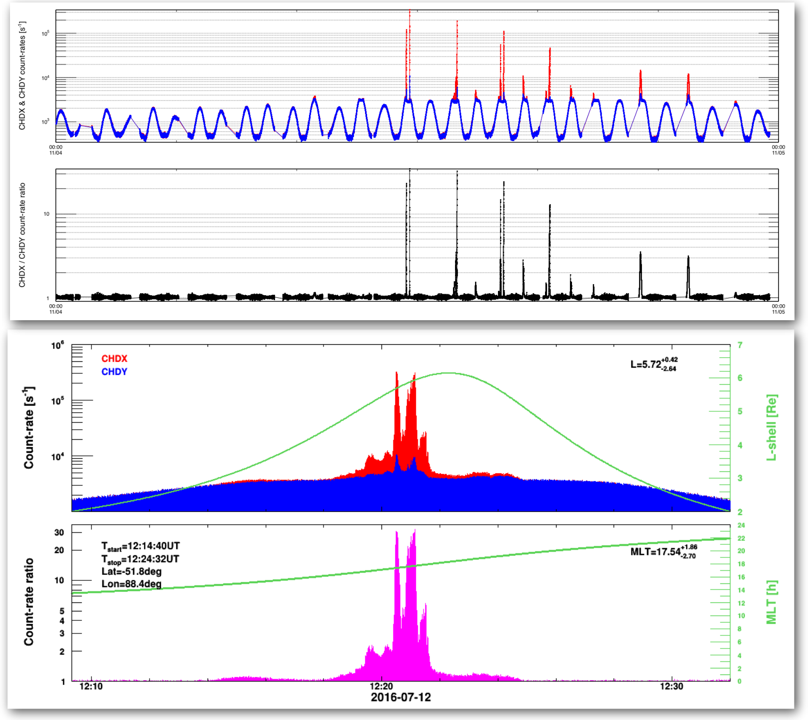
The CALET experiment



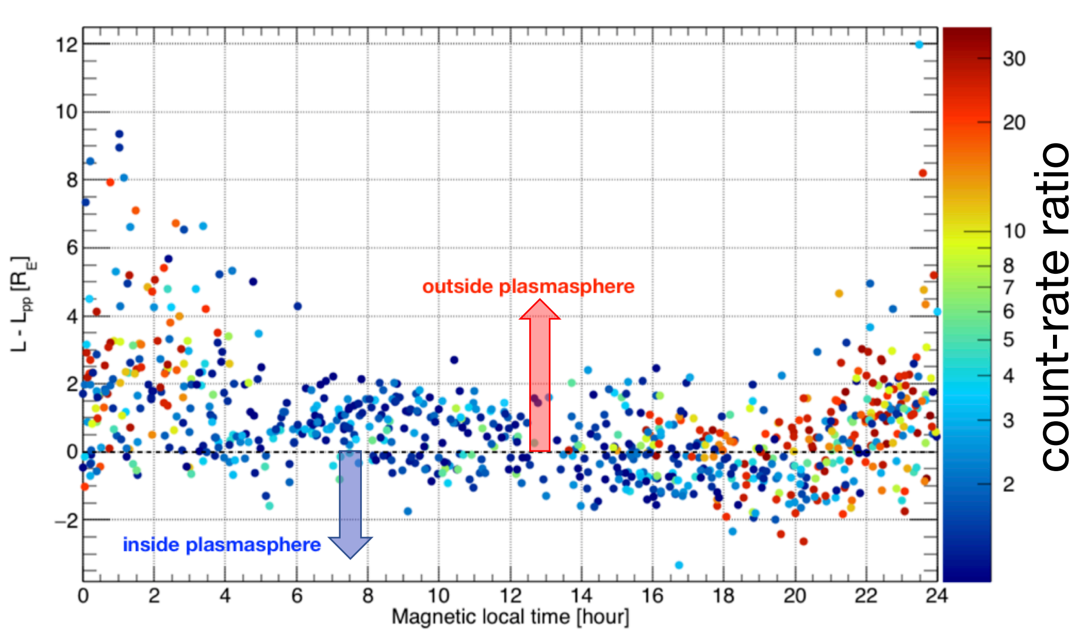
The CALET experiment is the result of an international collaboration involving Japan, Italy and USA [1]. It is a large-area high-performance instrument installed on the international space station (ISS) on Aug 2015, aimed to the investigation of cosmic-ray sources, including potential Dark-Matter signals, through the spectral measurement of all-electron and gamma-ray from 1 GeV to 20 TeV, protons, heliums, and heavier nuclei up to 1 PeV/particle, and the ultra-heavy (Z > 28) nuclei composition above 600 MeV/n. CALET is also able to provide a continuous monitoring of the space weather phenomena affecting the near-Earth environment, including solar energetic particles at high geomagnetic latitudes, inner-belt protons in the South-Atlantic anomaly region, and relativistic electron precipitation (REP) events near the inner boundary of the outer radiation belt [2,3,4,5]. The instrument consists of 3 sub-detector systems: two-layered hodoscope of plastic scintillators (CHD) providing charge measurements (Z=1 to ~40); a finely-segmented imaging calorimeter (IMC) used to determine the incoming-particle trajectory; an homogeneous full absorption calorimeter (TASC) providing energy measurements and lepton/hadron discrimination.

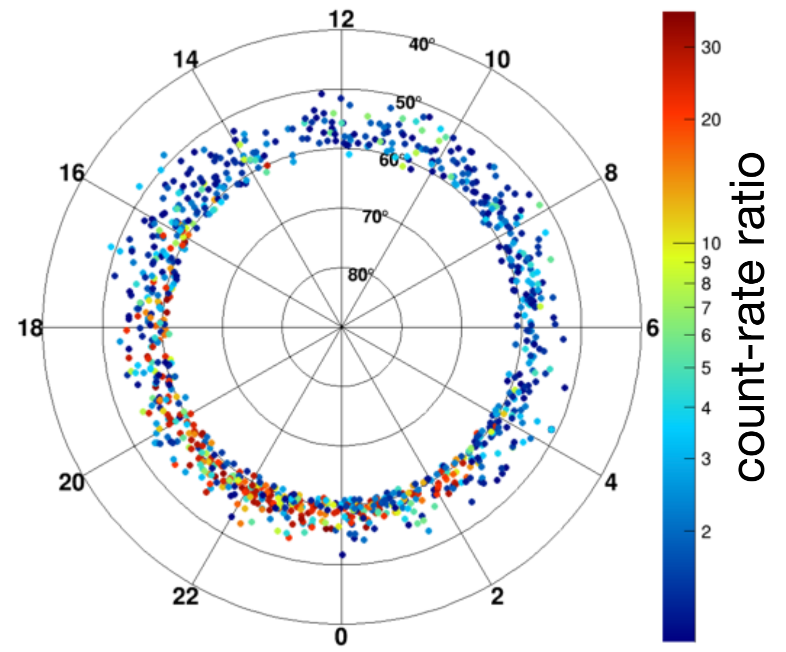
Data analysis

CALET REP observations are based on the count-rate information of the two CHD orthogonal layers, CHDX and CHDY, with a detection threshold corresponding to ~1.5 and ~3.4 MeV electrons, respectively. The present study is based on the dataset collected between October 2015 to May 2020, during the extended solar minimum phase between solar cycles 24 and 25. The analyzed sample includes data collected at relatively high geomagnetic latitudes (McIlwain's L>2 R_E), excluding periods of high-energy SEP events (e.g., during early September 2017 [3]). As shown in the top-right figure, REP events are recognizable as spikes in the CHD count rates. Displayed data do not include observations made in the SAA (B<0.25 G and L<2.6 R_E). Specifically, REP intervals were identified by requiring a count-rate ratio: R_{xy} = CHDX/CHDY > 1 + 3σ_R, where σ_R is the statistical uncertainty on R_{xy}. Overall, almost 3.8x10^4 REP intervals were selected. However, as discussed later, the sample includes a significant background component associated with the loss-cone electron population beneath the outer radiation belt, mostly detected in the geographic region South of the SAA. The bottom-right figure reports a sample REP interval observed by CALET. The top panel shows the temporal profiles of the CHDX (red) and CHDY (blue) count rates, while the bottom panel displays the corresponding count-rate ratio (magenta), which can be used to provide an estimate of the REP event spectral hardness. The two green curves indicate, respectively, the L-shell (top) and the magnetic local time (MLT, bottom) values along the orbit. The magnetic variables were estimated by using the International Geomagnetic Reference Field-13 [6] and the Tsyganenko & Sitnov 2005 [7] models for the description of the internal and external geomagnetic field, respectively.



REP event spatial distribution

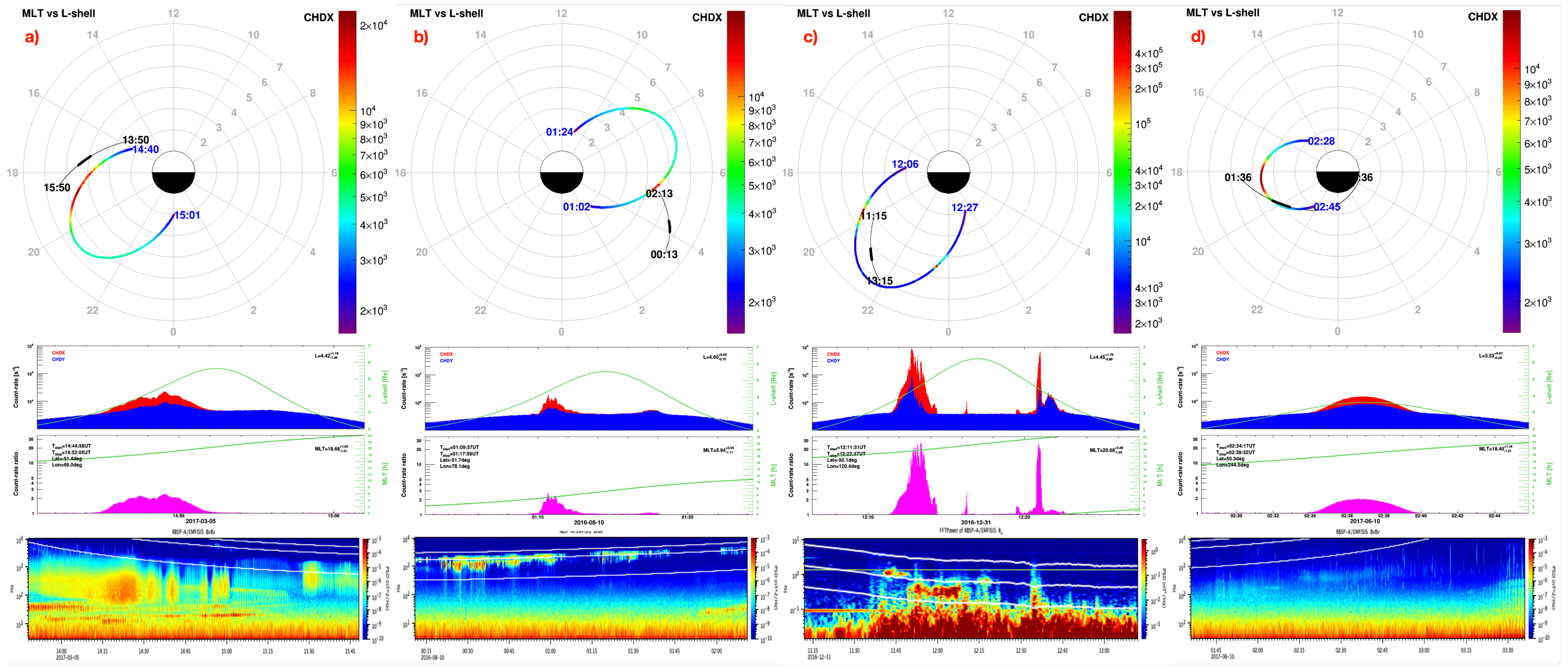




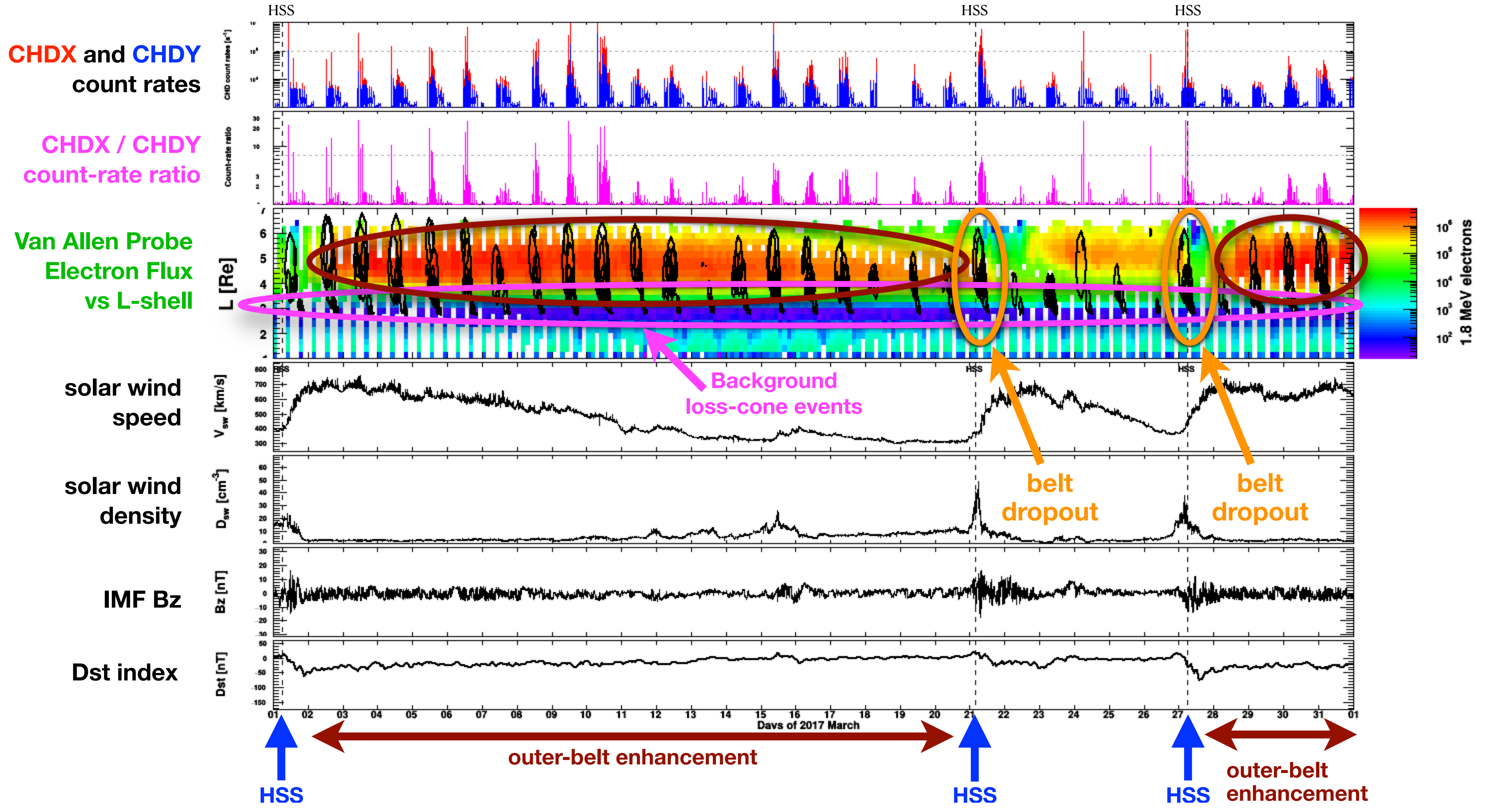
As expected, REP events were found to concentrate around the plasmapause (left panel), evaluated with the empirical model by [8]. On average, soft-spectrum (i.e. high CHDX/CHDY count-rate ratio) events were recorded outside the plasmasphere around the pre-midnight sector as shown in the right panel, reporting the REP distribution as a function of magnetic latitude and MLT (with the color code indicating the count-rate ratio), in line with the general trend of outer-belt electron fluxes.

Wave drivers

We took advantage of the plasma wave measurements of the Van Allen Probes in the equatorial plane to investigate the drivers of the MeV electron precipitation observed by CALET. A coordinated study is in progress based on the analysis of conjunction intervals during the time period in which both missions were operative (October 2015 – June 2019). Four sample events are reported here. The MLT vs L dial plots in the the top panels display the trajectory of the ISS during the selected REP interval (~20-min), with the color code indicating the CHDX count rate; for comparison, the black curve denotes the trajectory of one of the Probes during the 2-hour interval around CALET detection, marked by the thick segment. The middle panels display the CALET count-rates and count-rate ratios. Finally, the bottom panels show the magnetic field measurements made by the Probes during the 2-hour interval around CALET detection. Such results suggest, for the first three events, an association with three different wave drivers, namely plasmaspheric Hiss waves (a), whistler-mode chorus waves (b) and electromagnetic ion cyclotron (EMIC) waves (c), respectively. On the other hand, the forth event (d) is a typical loss-cone event commonly observed at relatively low drift shells, apparently not linked to any particular wave activity (see discussion below).



CALET REP observations and contextual data



To have a clearer view of the detected REP events, we compared CALET observations (top two panels) to outer-radiation belt electron measurements (third panel) and other contextual data, including interplanetary and geomagnetic parameters (last four panels). This figure shows the different observations as a function of time, during a sample month (March 2017). In particular, the third panel shows the 1.8 eV electron flux measured by the Van Allen Probes vs L-shell, with the black ovals marking the corresponding CALET REP detections. We can essentially subdivide the CALET REP sample into three categories. The first corresponds to events recorded during periods of enhanced outer-belt electron intensities (dark-red ovals). The second comprises events detected during intervals of outer-belt depletions (orange ovals), typically following the arrival of solar-wind structures. The third category includes ordinary loss-cone electrons, commonly observed at relatively low latitudes around L~3 R_E (magenta oval). This precipitation is not necessarily linked to local scattering mechanisms, and constitutes a background component to REP events.

Summary and future work

The CALET experiment on the ISS is able to provide a continuous monitoring of space-weather phenomena affecting the near-Earth environment, including relativistic electron precipitation. Its observations in LEO can be used to complement those of the Van Allen Probes in the highly-eccentric orbit. We are carrying out a coordinated study between the two missions to identify the wave populations generated near the magnetic equator which are potentially responsible for the electron precipitation directly observed in CALET. In addition, taking advantage of the large recorded data sample, we plan to perform a statistical investigation of REP occurrence vs solar-wind/geomagnetic drivers, in order to sort REP events by wave-driver and precipitation type (temporal profiles, spectral hardness, etc.), enabling a more complete picture of the global precipitation origin and rates.

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