Status of the CSES-Limadou space mission after three years in flight

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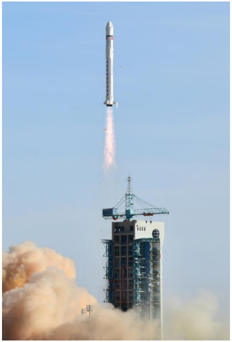
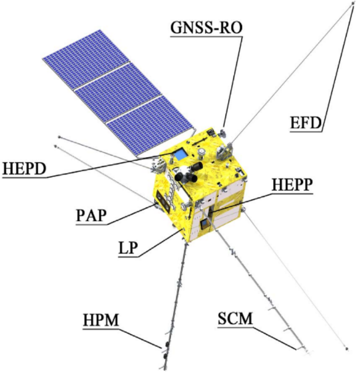
The China Seismo-Electromagnetic Satellite (CSES-01) mission objectives

- Monitoring the near-Earth electromagnetic environment
- Measuring iono-magnetospheric perturbations possibly due to seismo-electromagnetic phenomena
- Monitoring man-made electromagnetic effects at Low Earth Orbit altitude
- Studying spectra of charged particles precipitating from Van Allen radiation belts
- Observing changes in solar activity

The CSES-01 satellite

Platform	Mass	$\simeq$ 700 kg
Orbit	Type	Sun-Synchronous
	Altitude	507 km
	Inclination	97°
	Period	94 minutes
	Local time descending node	14:00
	Revisit period	5 days
Mission	**Life Span**	$\geq$ **5 years**





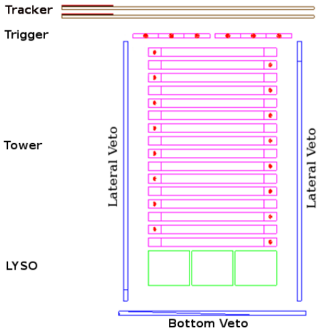
The Italian instrument, HEPD-01, was launched on board CSES-01 from the Jiuquan Satellite Launch Center in the Gobi Desert (Inner Mongolia) on February 2$^{\text{nd}}$, 2018

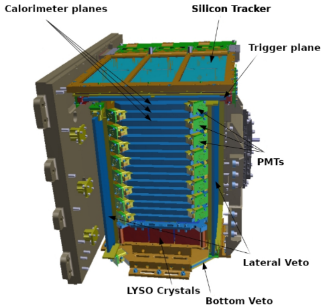
CSES-Limadou Collaboration

The Italian Collaboration is named after the Italian missionary in China, Matteo Ricci (1552-1610), whose Mandarin name was Li-madou. Several Italian institutes and universities are involved:

- Italian Space Agency (ASI)
- Italian National Institute for Nuclear Physics (INFN)
- Universities of Trento, Bologna, Rome Tor Vergata, Naples and UNINETTUNO
- Italian National Institute of Astrophysics and Planetology (INAF-IAPS)
- Italian National Institute of Geophysics and Volcanology (INGV)

High-Energy Particle Detector (HEPD-01)





- 2 planes (213.2×214.8×0.3 mm^3) of double-sided silicon microstrip sensors (**TRACKER**) → track-related information
- 1 layer (20×18×0.5 cm^3) of plastic scintillator (**TRIGGER**) → start acquisition
- range calorimeter comprising:
  - 16 layers of 15×15×1 cm^3 plastic scintillators (**TOWER**), read out by 2 PMTs each→ energy deposit
  - 3×3 matrix (15×15×4 cm^3) of inorganic crystals (**LYSO**), read out by 1 PMT each → increase range
- 5 5 mm-thick plastic scintillator planes (**VETO**) → reject up-going or not fully-contained particles [1]

En. range (e^-)	3 MeV-100 MeV
En. range (p)	30 MeV-250 MeV
Angular resol.	$< 8^\circ$ @ 5 MeV
Energy resol.	< 10% @ 5 MeV
Acceptance	∼400 cm^2sr
Mass (+ el.)	∼44 kg

Main results of HEPD-01

Low-energy cosmic-ray physics:

- Galactic cosmic-ray (GCR) hydrogen spectra in the 40–250 MeV range (published in [2])
- Cosmic electron plus positron spectrum in the 10-100 MeV range (preliminary)
- Re-entrant lepton spectrum in the 10-100 MeV range (preliminary)

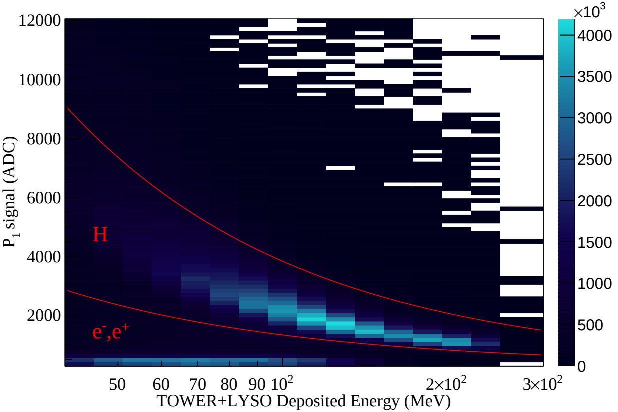
Physics of the radiation belts:

- Proton fluxes inside the South Atlantic Anomaly (SAA) in the 40-250 MeV range (currently under review at PRD)

Solar and magnetosphere physics:

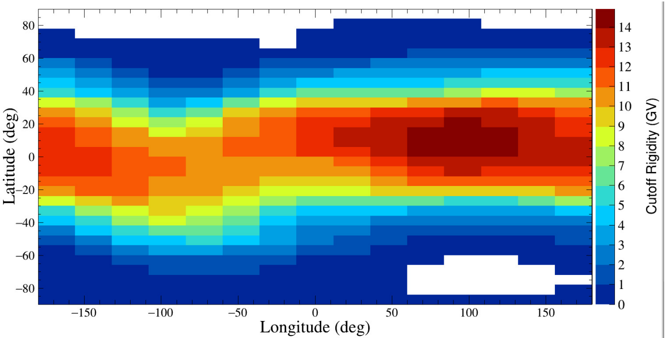
- Observation of the August 2018 geomagnetic storm (published in [3])
- Observation of the May 2021 geomagnetic storm (preliminary)

Particle identification with HEPD-01



- Calorimeter (TOWER+LYSO) measures the energy loss per unit length $\rightarrow$ **good separation of various species** ($> 90\%$)
- Check with Monte Carlo simulations for selection efficiency estimation

- **Three semiannual galactic hydrogen spectra** as a function of energy **between 40 and 250 MeV** were obtained in three different consecutive time periods (**from August 6th 2018 to January 5th 2020**)
- Static map (IGRF-12 [4] + Tsyganenko-89 [5]) was used to select galactic particles. Even if HEPD-01 is switched off at ±65°, its high field-of-view allows to collect GCRs for a fair amount of time per day

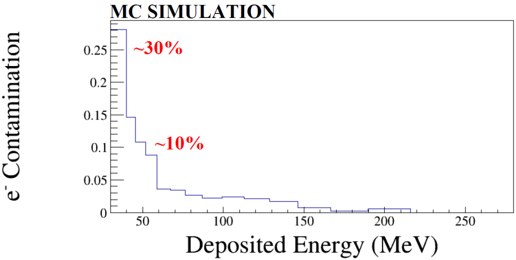


Analysis and flux evaluation

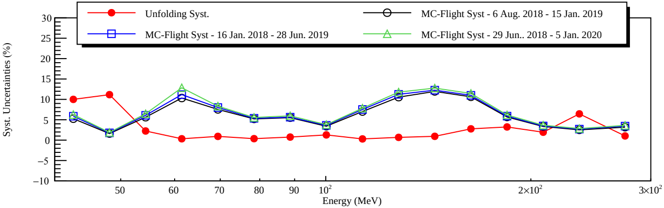
- Only fully-contained protons were included in the flux sample to better estimate the initial energy of the proton
- Multi-particle events were rejected by requiring no hits on the VETO system and only a single hit trigger paddle in the final sample
- Only a single hit crystal of LYSO was required to reject possible electromagnetic showers due to mis-identified high-energy electrons
- Up-going protons were rejected by requiring no hits in the bottom layer of the VETO system
- Selection efficiencies were checked with Monte Carlo simulations
- Bayesian approach was used to take into account passive structures of HEPD-01 and unfold the final spectrum

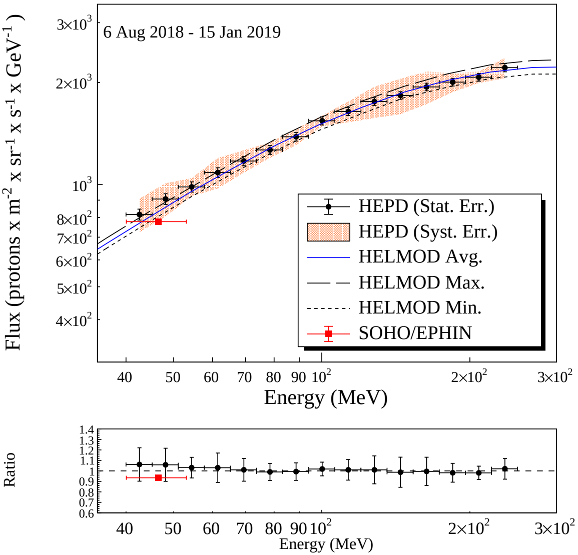
Contamination and systematic uncertainties

Contamination of the flux sample due to high-energy electrons is below 10% above ∼50 MeV

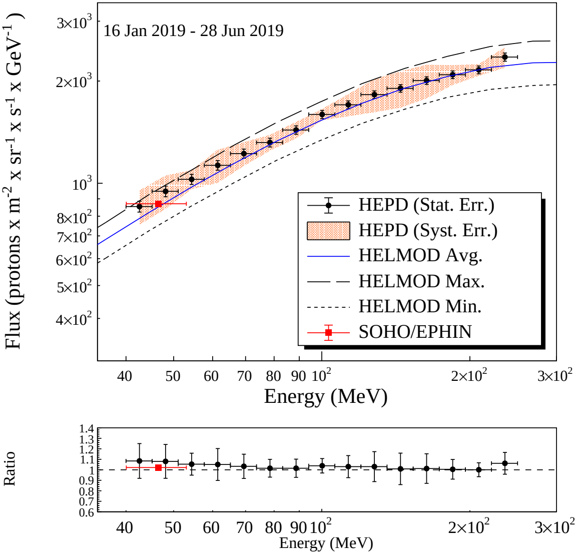


Unfolding-related uncertainty evaluated once over the 2018-2019 period, while MC-flight uncertainty evaluated over 6-month periods

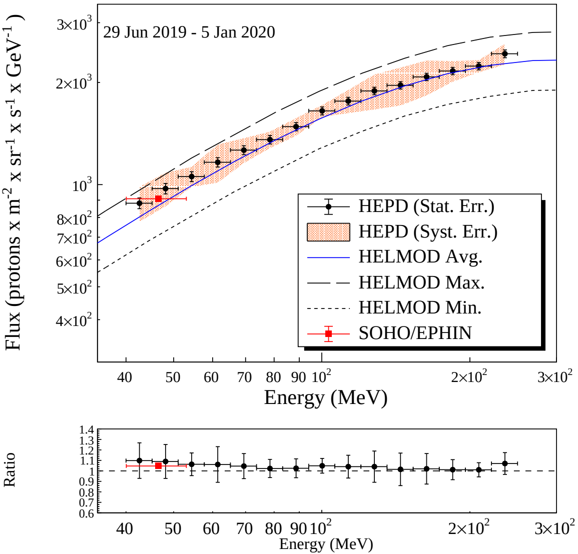



6 Aug 2018 - 15 Jan 2019
Flux (protons x m^{-2} x sr^{-1} x s^{-1} x GeV^{-1})
Energy (MeV)
HEPD (Stat. Err.)
HEPD (Syst. Err.)
HELMOD Avg.
HELMOD Max.
HELMOD Min.
SOHO/EPHIN
Ratio
Energy (MeV)

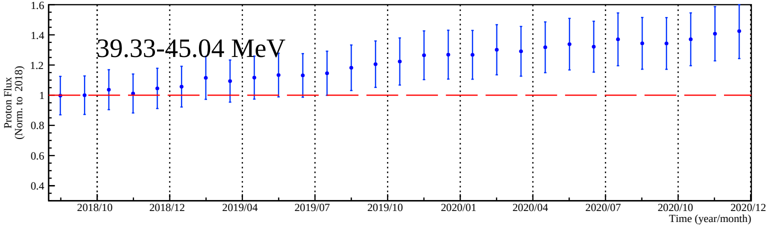
HEPD-01 results on GCR hydrogen spectra (2/3)

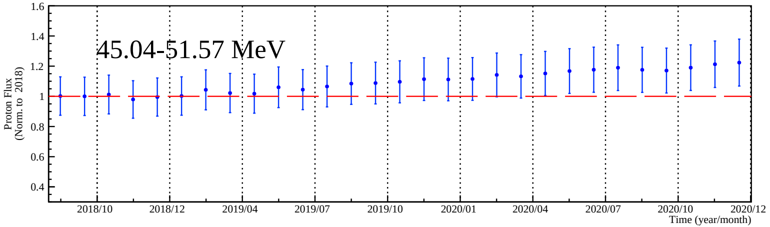


HEPD-01 results on GCR hydrogen spectra (3/3)

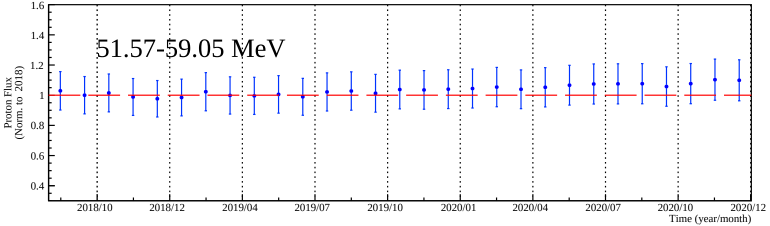


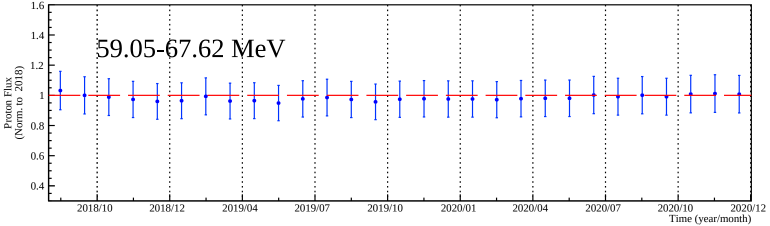
HEPD-01 results: solar modulation (1/2)





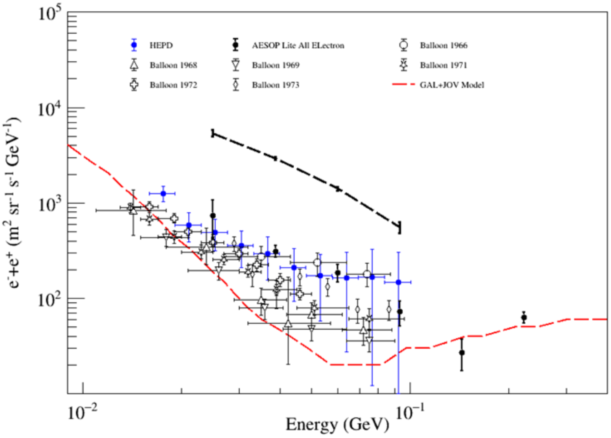
HEPD-01 results: solar modulation (2/2)





Cosmic electron plus positron spectrum

- HEPD-01 is not able to separate electrons from positrons
- Preliminary spectrum of ∼400 cosmic electrons plus positrons (61 days of collected statistics) selected by using backtracing



Re-entrant lepton spectrum (1/2)

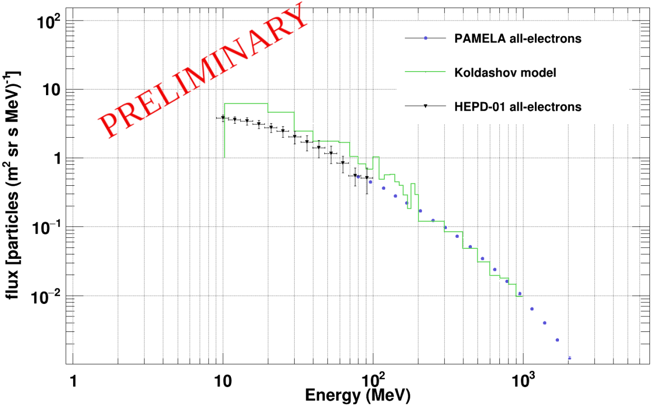
- Electrons and positrons are largely produced (in roughly equal number) by the nuclear component of the GCRs in reaction with the Earth's atmosphere: $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$

- Re-entrant electrons and positrons are generated with upward-going directions, but their trajectories are bent back to the Earth itself by the geomagnetic field

- In order to separate electrons and positrons from protons, ionization energy losses inside each calorimeter plane are required to be compatible with the expectation for a singly charged minimum ionizing particle (MIP)

- Sub-cutoff particles are selected outside the SAA:
  $1.1\ R_E <$ L-shell $< 1.2\ R_E$ and $B > 23000$ nT

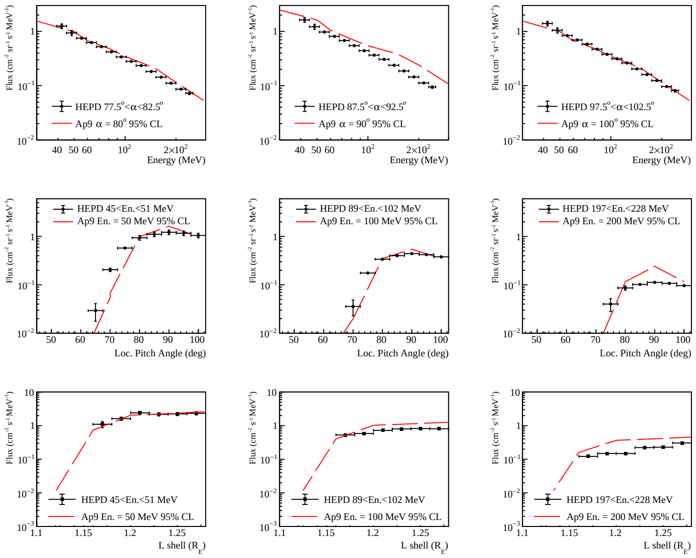
- HEPD-01 data are shown together with PAMELA measurements [6] (same L-shell cut and **good agreement in the overlapping region**) and with a theoretical model [7] used for the calculation of secondary electron and positron fluxes at the top of atmosphere
- Our future goal is to extend the measurement below 10 MeV



Proton fluxes inside the SAA (1/3)

- Geomagnetically trapped protons forming the so-called inner radiation belt. The South Atlantic Anomaly (SAA) is the closest region to the Earth's surface
- Such protons are originated from β-decay of free neutrons produced in the interaction of GCRs with the Earth's atmosphere, known as Cosmic Ray Albedo Neutron Decay (CRAND) mechanism
- The scientific community has been considerably involved in modeling such space radiation environment with the aim of better assessing the significant radiation hazard to spacecraft and human crews
- The NASA AE9/AP9 set of models for high-energy electrons and protons, respectively, is the most complete and recent one [8]
- Since both AE9 and AP9 are partly incomplete, it is of key importance to test such models and, above all, to provide new and reliable data-sets from in-flight instruments to improve their predictions

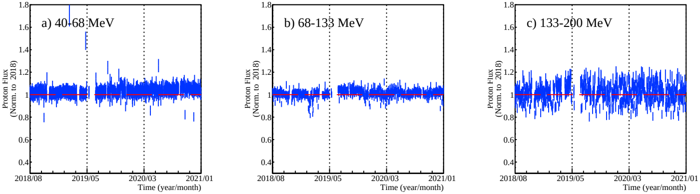
Proton fluxes inside the SAA (2/3)



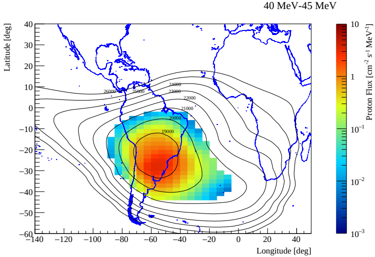
SAA proton energy spectra (top panels), pitch angle profiles (middle panels) and L-shell profiles (bottom panels) between August 2018 and December 2020, compared with predictions from AP9 model at 95% C.L.

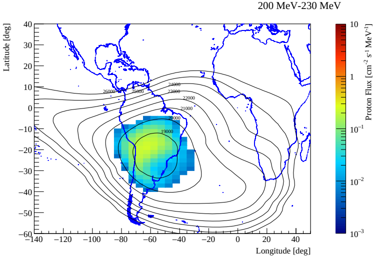
Proton fluxes inside the SAA (3/3)

The time-intensity profiles of the proton fluxes are constant in time



Low-energy protons are present in almost the whole SAA (B < 20500 nT, L-shell < 1.3 R_E), while the high-energy ones are concentrated in the innermost area





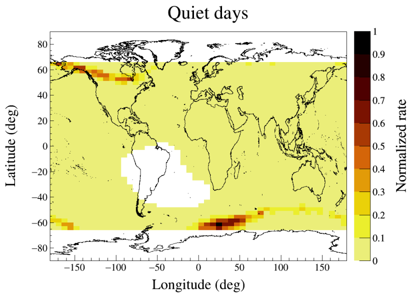
Geographical maps of omnidirectional proton fluxes (August 2018-December 2020) as a function of latitude and longitude for a low-energy bin (40-45 MeV, left panel) and for a higher one (200-230 MeV, right panel)

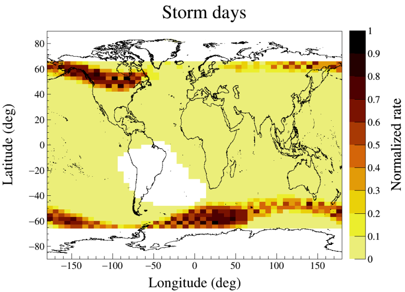
HEPD-01 as a space weather monitor

- For what concerns Solar Energetic Particles (SEPs), the past minimum was rather quiet and after 2017 no major SEP events occurred
- As the maximum of solar activity cycle approaches, the number of SEPs will increase for sure and it will be possible to carry out our original purpose of SEP-classification starting from their spectral index, duration, energy extension, origin point in the solar disk, etc.
- Even without SEP events, **we have been able to assess the capability of HEPD-01 during transient phenomena like the geomagnetic storms of August 25^{th} 2018 and May 12^{th} 2021**
- A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere, caused by coronal mass ejections (CMEs), solar flares, co-rotating interaction regions (CIRs), etc.
- More (and more powerful) geomagnetic storms will be studied in the next future

HEPD-01 response to the August 2018 storm (1/2)

An **increase in HEPD-01 count rate** was observed **at both northern and southern latitudes**, especially in the southern region, as a consequence of the storm's arrival



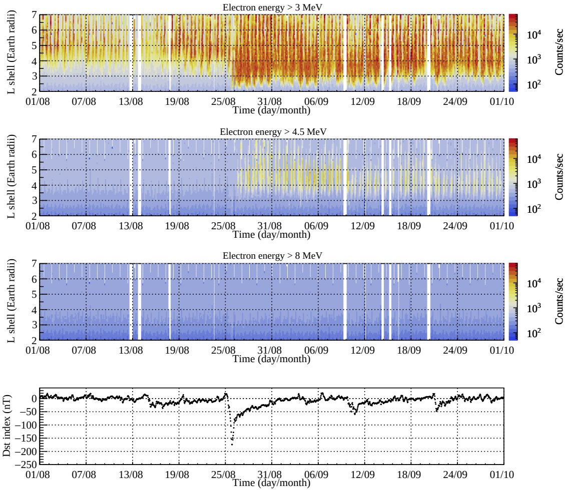


Left: HEPD-01 trigger rate map before the impact of the storm (20th-23rd August)
Right: HEPD-01 trigger rate map after the impact of the storm (25th-27th August)

Both maps are related to the trigger configuration providing the lowest energy threshold for electron detection (> 3 MeV)

HEPD-01 response to the August 2018 storm (2/2)

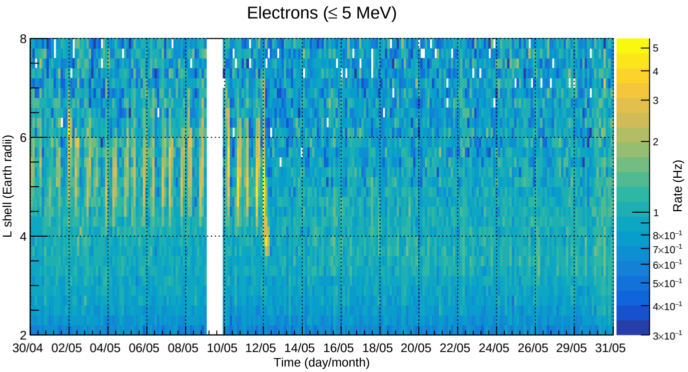
A **clear enhancement of HEPD-01 trigger rate during the storm's recovery phase** was observed at **L-shells $\gtrsim$ 3**, thus suggesting a phenomenon of acceleration of energetic electrons



Top three panels: Trigger rates for three different HEPD-01 configurations over the period August-September 2018
Bottom panel: Time evolution of the Disturbance storm-time index

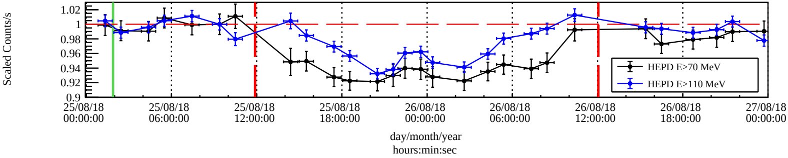
HEPD-01 response to the May 2021 storm

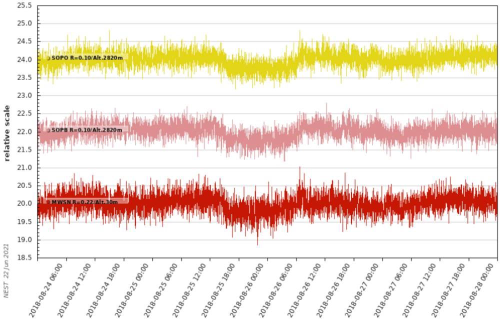
We observed a **dropout in ≤ 5 MeV electron rate, downstream of May 12th storm**: this is consistent with the absence of prolonged substorm activity during recovery, which hampers wave-induced post-storm acceleration of "seed" populations to MeV energies and consequent replenishment of depleted regions



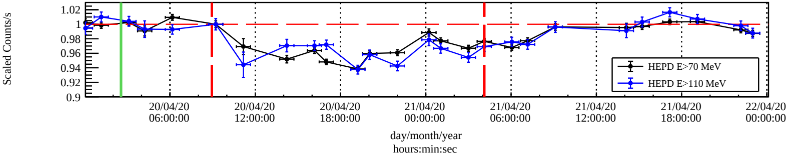
Forbush decrease observations (1/2)

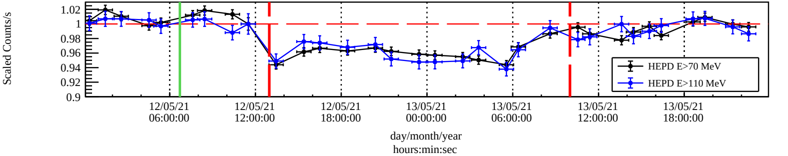
A Forbush decrease is a rapid and temporary decrease
in the observed GCR intensity following a coronal mass ejection.
For the August 2018 geomagnetic storm, we detected
a Forbush decrease (also registered by several neutron monitors)





We observed the following Forbush decreases for the April 20th 2020 and May 12th 2021 geomagnetic storms, respectively:





Conclusions

The CSES-Limadou mission can be considered as an extension of PAMELA (2006–2016) and AMS-02 in the study of **low-energy cosmic rays** and **trapped particles in the radiation belts**:

- We obtained **the first results on galactic hydrogen in the 40-250 MeV range**, at 1 au, since a series of balloon flights in 1960s/1970s
- We obtained **the first results on SAA protons below 250 MeV** at Low Earth Orbit during the minimum activity phase between the 24th and the 25th solar cycles
- **Analyses on cosmic and re-entrant lepton spectra are ongoing**

Considering the sky-rocketing focus on **space weather research** in this last decade, **HEPD-01's results prove promising**, especially in view of the already-planned constellation of CSES satellites in the next few years. **CSES-02 is currently under construction** and is expected to offer further insight into low-energy physics and space weather studies throughout the 25th solar cycle.

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