CHAOS, a particle sensor to bridge the gap between standard spacecraft and ground-based SEP measurements

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Abstract

High-energy particles originating either from the Sun, *Solar Energetic Particles* (SEPs), or our Galaxy, Galactic Cosmic Rays (GCRs), have been observed for decades with spacecraft and ground-based instruments. However, there is a gap in the energy spectral region from beyond the nominal science-grade spacecraft instrument (100 MeV) to that of ground-based recordings. One of the instruments that cover this energy range was the Kiel Electron Telescope (KET) on board the Ulysses mission. The key capability, the detection of protons and helium with energies up to 2 GeV was achieved through the use of Cherenkov radiation detectors. This concept has been recently adopted to extend the energy range of the High Energy Telescope (HET) aboard Solar Orbiter, within the students' project CHerenkov Atmospheric Observation System (CHAOS) that combines the dE/dx-dE/dx-method of HET with a velocity threshold provided by an Aerogel Cherenkov detector. The instrument was successfully deployed during the Balloon Experiments for University Students (BEXUS) 35 stratospheric balloon mission in 2024 and provided measurements of the proton and helium spectra above the Regener–Pfotzer maximum, showing that CHAOS is well suited as a radiation monitor for harmful near-relativistic SEPs events.

Introduction

High-energy solar energetic protons ($> 100\,\mathrm{MeV}$) are crucial for both heliophysics and applications because they probe shock and flare acceleration processes, influence particle transport, and are directly linked to *Ground Level Enhancements* (GLEs) Reames (2013); Shea & Smart (2012). Their high penetration allows them to bypass typical spacecraft shielding, increasing the risk of single-event effects and system degradation Dodd & Massengill (2003). In the atmosphere, these protons produce secondary cascades that determine radiation exposure at flight altitudes and contribute to real-time dose assessments Mertens et al. (2013). Sustained observations in this energy range are therefore essential for advancing scientific understanding and improving operational space-weather protection Reames (2013); Shea & Smart (2012); Dodd & Massengill (2003); Mertens et al. (2013).

ΔE–E telescopes that *stop* particles, the highest demonstrated proton energies are achieved by SOHO/ERNE's High-Energy Detector (HED), which provides differential spectra for protons and He up to ∼140 MeV/n using the ΔE–E technique Valtonen (2001). Instruments that report higher proton energies (to above ∼500 MeV/n) do not rely on stopping ΔE–E at the top end but instead use other response modes for penetrating particles Kühl et al. (2015).

The measurement of Solar Energetic Particles (SEPs) in the energy range from above 100 MeV to below a few GeV thus poses a long-recognized and persistent observational challenge. This range lies in a critical transition region between conventional space-borne particle telescopes and ground-based neutron monitor networks.

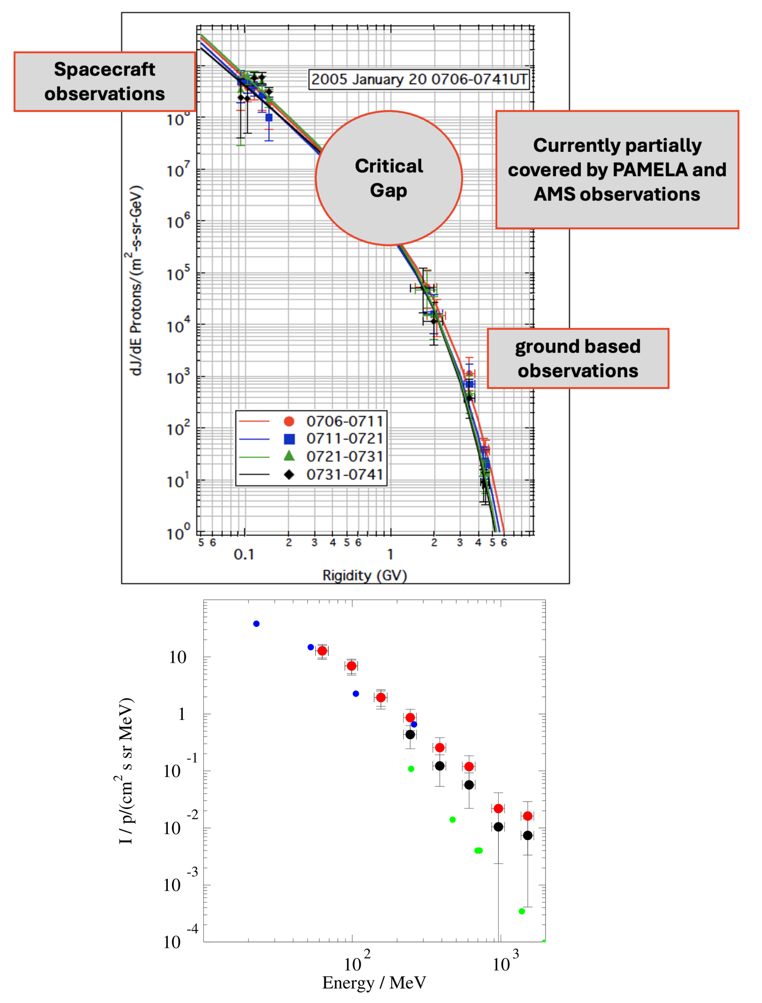

Figure 1: Upper panel: Measured and derived rigidity spectra of protons observed during the *Ground Level Enhancement* (GLE) Nr. 69 on 2005-01-20. The fluxes at low rigidities are from space borne instruments and at high rigidities derived from Neutron Monitors (NMs). Lower panel: SOHO/EPHIN derived fluxes given by the red and black symbols compared to the NM derived fluxes (green symbols).

Current extension of SOHO/EPHIN to GeV proton fluxes

The *Electron Proton Helium INstrument* (EPHIN) is a particle telescope with a field of view of about 83° and a geometry factor of 5.1 cm^2 sr that measures electrons with energies between 0.25 and 10.4 MeV as well as protons and Helium in the energy range of 4.3 up to above 53 MeV/nucleon. Kühl et al. (2015) have presented a method that extends the energy range of EPHIN for protons up to energies of above 1 GeV utilizing the $dE/dx - dE/dx$-method.

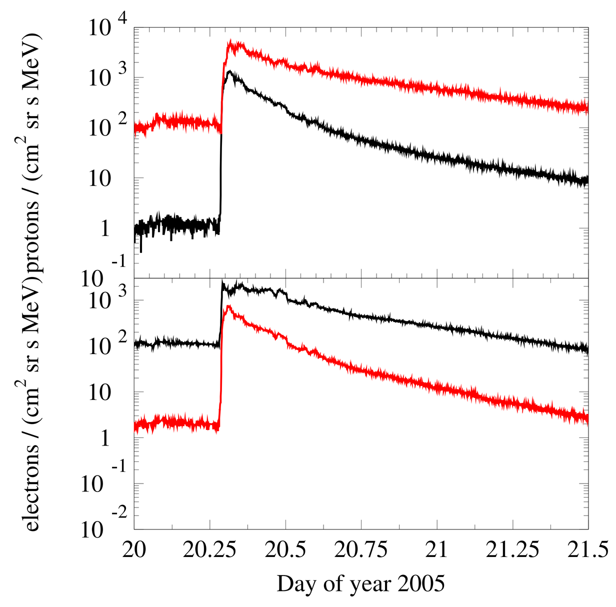

Figure 2: EPHIN measurements during GLE Nr. 69.

The time profile and energy/rigidity spectra of GLE Nr. 69 are shown in Fig. 2 and 1 respectively. **Comparing the NM derived fluxes with the ones derived by the $dE/dx - dE/dx$-method from EPHIN we find a significant hardening in the EPHIN spectra due to a significant electron contribution.**

Improving instrumentation

In order to separate electrons above 10 MeV from protons with energies below 2 GeV the KET aboard Ulysses utilized two Cherenkov detectors, one with a refractive index of 1.065 made of silica aerogel and another one made of lead-fluoride (PbF_2) crystal with a thickness of 2.5 radiation lengths.

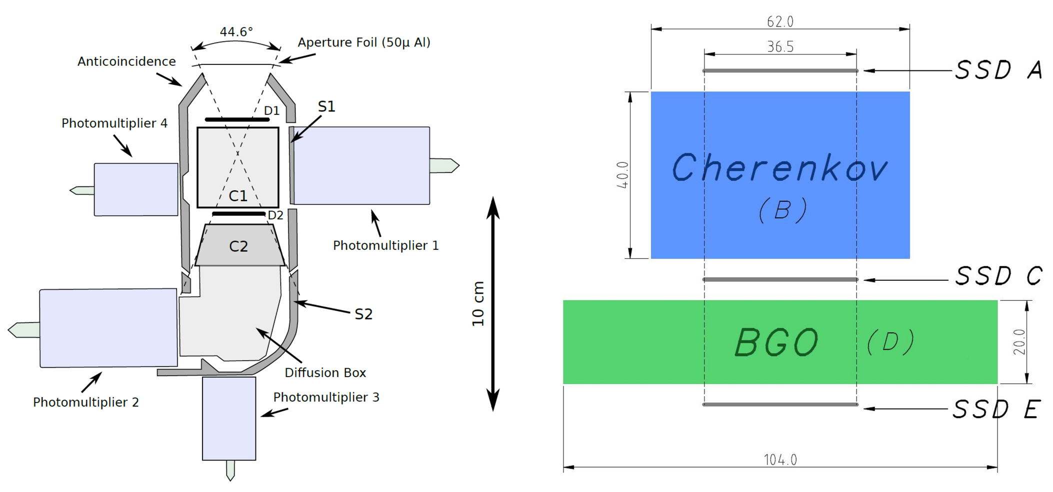

Figure 3: Left: Sketch of the KET: Cherenkov detectors C1 and C2, silicon SSDs D1 and D2 and scintillation detectors S1, S2 and anti-coincidence A. Right: Cross section through the CAD model of CHAOS's sensor head with labels for the instrument's different detector stages.

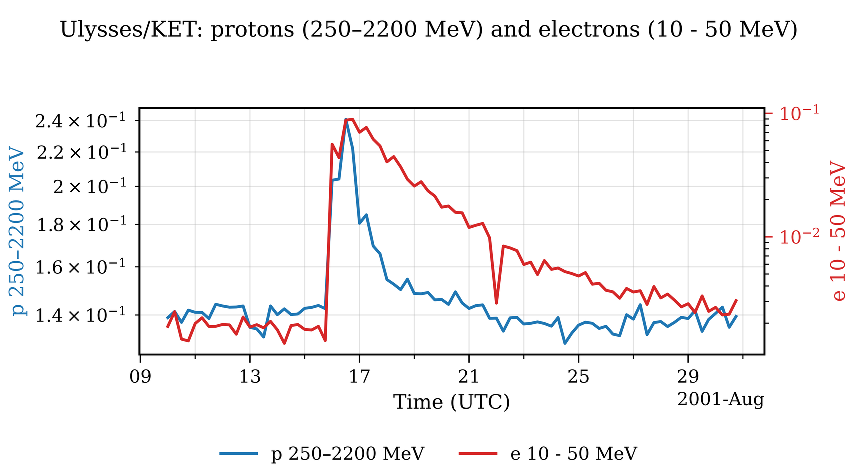

Figure 4: Ulysses KET count rates of 320 - 2200 MeV protons (blue) and of 10 - 50 MeV electrons (red) during August 10 to 31, 2001.

Protons between 320 and 2200 MeV are well separated from electrons in the Ulysses KET, allowing the determination of clean proton spectra.

CHerenkov Atmospheric Observation System (CHAOS) an instrument to monitor GLEs

The need for reliable proton spectra in the energy range covered by the KET became evident from analyzing X-ray data from XMM-Newton Marelli et al. (2021). the energy-dependent emission of photons in the aerogel due to the Cherenkov effect. CHAOS is a student-led spin-off from this study. The sensor unit is sketched in Fig. 3. The layers A, C and E consist of 300 μm thick Solid State Detectors (SSDs) and the layers B and D are given by a silica aerogel Cherenkov detector and the bismuth germanium oxide (BGO) calorimeter, respectively.

CHAOS was selected by European Space Agency (ESA) and German Aerospace Center (DLR) for flying on a balloon during the BEXUS 35 campaign (see contribution by Pohley et al. in CD6).

Here we present a GEANT simulation and first results from the balloon flight and a measurement campaign at the CERF facility at CERN.

CHAOS GEometry And Tracking (GEANT) simulations

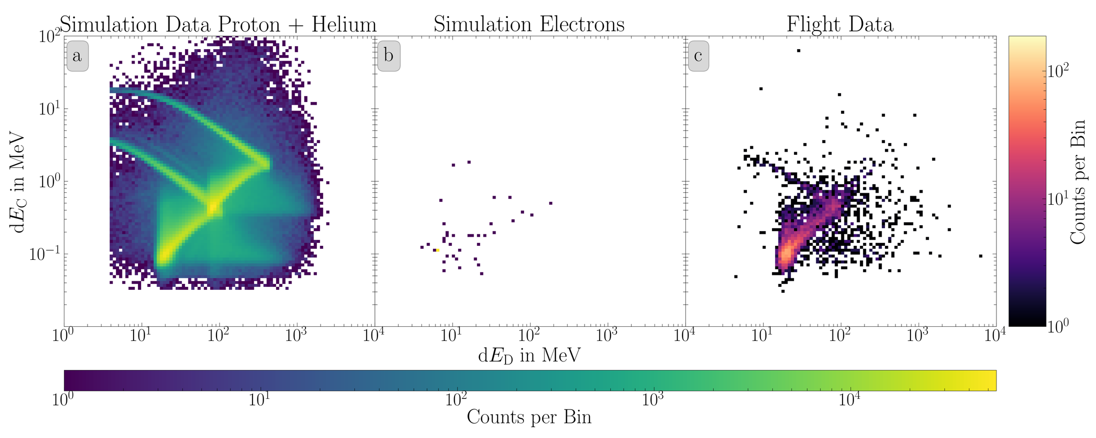

Figure 5: GEANT simulation of the energy loss distribution of protons and helium (left), electrons (middle) and in flight measurements (right) in detector D vs C utilizing the $\overline{A}BCD$-coincidence.

Energy response

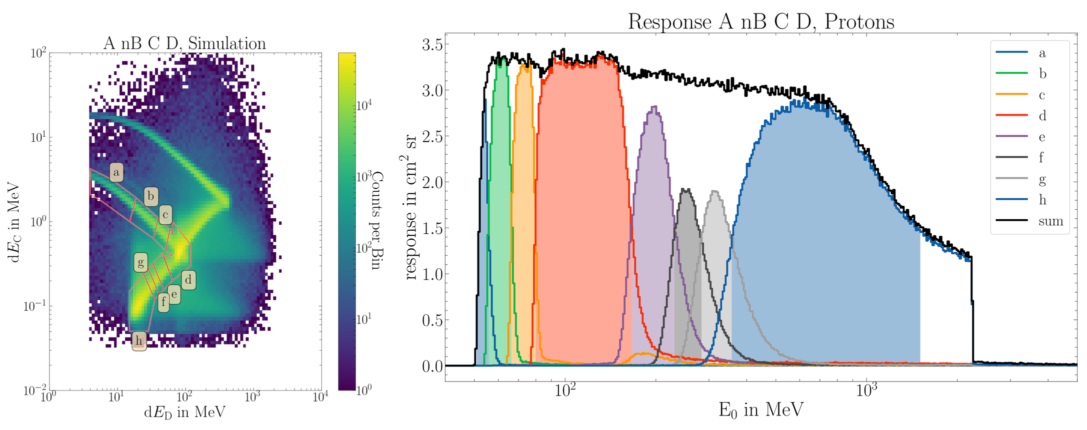

Figure 6: Left to right: Selection of energy loss ranges and corresponding response function.

Energy spectra

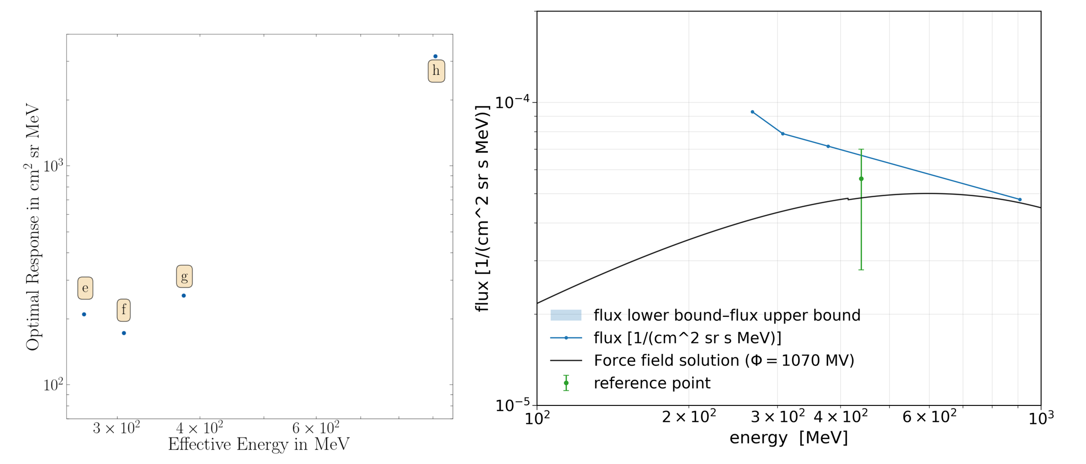

Figure 7: Response factors as function of efficient energy (left) and measured proton spectra during the floating phase on October 2, 2024 (right). The energy spectra measured by SOHO/EPHIN and a Force Field Solution wit $\Phi = 1070$ MV are overplotted.

Summary and Conclusion

CHAOS was successfully deployed on a stratospheric balloon. Energy spectra for protons utilizing efficient response factors and energies are in good agreement with measurements from SOHO/EPHIN and the expected fluxes derived from the FFS.

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