# SPaRKLE on board Space Rider: A miniaturized laboratory in low Earth orbit for low-energy particles

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**Summary.** — SPaRKLE, the Small Particle Recognition Kit for Low Energies, is a compact detector for $\gamma$-ray and low-energy charged particle physics in Low Earth Orbit. Upon successful completion of the project phases, SPaRKLE will be installed on Space Rider, an uncrewed orbiting laboratory, for a mission lasting approximately two months. During the mission, SPaRKLE will measure particle fluxes and investigate transient phenomena such as Gamma-ray Bursts (GRBs) and Terrestrial Gamma-ray Flashes (TGFs). Designed within a CubeSat unit, SPaRKLE includes a Cerium-doped Gadolinium Aluminium Gallium Garnet (GAGG) scintillator calorimeter, silicon detectors, and plastic scintillator anti-coincidence detectors. It will perform event-based particle identification and detect X-ray and $\gamma$-ray photons.This paper presents an overview of the project, its mission objectives, detector operations, and technological innovations.

## 1. – Introduction

SPaRKLE, the Small Particle Recognition Kit for Low Energies, has been selected for the "ESA Academy Experiments programme" by the European Space Agency. Once the design process and all project phases are successfully completed, SPaRKLE will be installed on Space Rider (SR), an uncrewed orbiting robotic laboratory, for a mission lasting approximately two months. During its mission, SPaRKLE will measure particle fluxes in Low Earth Orbit (LEO) and investigate transient phenomena, including Gamma-ray Bursts (GRBs) and Terrestrial Gamma-ray Flashes (TGFs). The instrument, designed to fit within a single CubeSat unit, includes a Cerium-doped Gadolinium Aluminium Gallium Garnet (GAGG) scintillator inorganic scintillator calorimeter, silicon detectors, and plastic scintillator anti-coincidence detectors. Beyond its scientific objectives, SPaRKLE will act as a technological pathfinder by testing Silicon Photomultipliers (SiPMs) for scintillator readout in space and evaluating their post-flight performance.

Serving as a miniature laboratory, SPaRKLE will study space weather phenomena, high-energy astrophysical transients, and atmospheric physics transients. The paper is structured as follows: Section 2 outlines the scientific motivations behind the SPaRKLE mission, including studies of GRBs, TGFs, and charged particle radiation. Section 3 provides an overview of the mission objectives and the capabilities of the Space Rider platform. Section 4 discusses the design and detection concepts of the SPaRKLE instrument. Section 5 presents the expected performance of the payload. Section 6 concludes with a summary of the project's status and future outlooks.

## 2. – The Scientific Motivations behind the SPaRKLE Mission

In Low Earth Orbit (LEO), the study of radiation and gamma-ray emissions offers valuable insights into phenomena originating from both space and terrestrial sources.

**2**˙1. *Gamma-Ray Bursts (GRBs).* – GRBs are intense bursts of gamma rays produced by energetic astrophysical events such as supernovae or the merging of neutron stars. Understanding the temporal structure and energy spectrum of GRBs is crucial for elucidating their progenitors. Notable space-borne experiments dedicated to GRB physics include *Fermi GBM*, *BATSE*, *INTEGRAL*, *Swift*, and *AGILE*. An intriguing aspect of GRBs is their role in multi-messenger astronomy, exemplified by the event GRB-GW170817 [2]. SPaRKLE serves as a demonstrator for compact and cost-effective detectors, functioning as alert monitors for GRBs in extended networks.

**2**˙2. *Terrestrial Gamma-ray Flashes (TGFs).* – TGFs are brief but intense bursts of gamma rays originating from thunderstorms, typically occurring above the clouds during lightning activity [3] . Comprehensive data collection is critical for creating databases and refining origin models. Missions like *Fermi GBM*, *AGILE*, and *RHESSI* have established TGF catalogs. New data will enhance understanding of TGF emission properties. Additionally, miniaturized TGF detectors on Space Rider offer a practical opportunity to assess feasibility and in-flight performance, extending Earth's coverage with distributed space architectures.

**2**˙3. *Charged particle radiation detection.* – Radiation environment research is crucial for dosimetry,as it determines the total absorbed doses by astronauts, spacecrafts, and onboard electronics. Models like AE8/AP8 [4] were trained with data from 1966 to 1980. Additional datasets have come from missions like *NOAA-POES*, *CRRES*, and *SAMPEX*. In the South Atlantic Anomaly (SAA), LEO orbits intersect intense proton fluxes, posing challenges for large experiments. SPaRKLE, with its low geometric factor, is uniquely positioned to measure charged particles in harsh regions like the SAA and the poles, enhancing our understanding of space radiation and offering insights for radiation damage assessment, safety, and Space Weather. Furthermore, the study of low-energy particle fluxes is essential to investigate potential correlations between particle precipitation and seismic activity, while also validating models of Magnetosphere-Ionosphere-Lithosphere Coupling (MILC).

## 3. – Space Rider platform and SPaRKLE Mission Objectives

Space Rider [5] is an ESA programme providing Europe with an affordable, reusable space transportation system for routine access and reentry from Low Earth Orbit (LEO). It comprises an AVUM Orbital Module and a reusable Reentry Module, designed for multiple flights. Space Rider will transport payloads in its Multi-Purpose Cargo Bay (MPCB), performing in-orbit operations and returning on-ground for post-flight analyses. The MPCB can point in various directions, including Earth or deep space, ensuring optimal conditions for scientific and technological missions by supporting diverse experiments.

According to this paradigm, SPaRKLE is a flexible laboratory that can investigate various physical phenomena depending on the attitude mode that the hosting platform has acquired. This flexibility increases the overall mission contribution to space science by enabling SPaRKLE to carry out research suited to particular scientific goals.

The Scientific Objectives of SPaRKLE can be subdivided into Primary Scientific Objectives (PSO), and Secondary Scientific Objectives (SSO):

- PSO-1. Study the sensitivity to transient $\gamma$-ray and X-ray emissions along LEO such as GRBs, in case the Field of View (FOV) of the experiment is pointing to deep space, or TGFs, in case the FOV of the experiment is pointing to Earth.
- SSO-1. Investigate the influence of Space Weather events on the ionospheric environment along LEOs.
- SSO-2. Characterise the charged particle composition in the upper ionosphere along LEOs and in the SAA.

## 4. – SPaRKLE Instrument Design and Detection Concept

The scientific payload, shown in Fig. 1, includes two 100 $\mu$m thick silicon detectors and four Cerium-activated GAGG scintillator calorimeters. These elements are surrounded by plastic Anti-Coincidence Scintillators (ACSs). All the scintillating materials in the payload will be readout by SiPMs. Using a similar approach to [6, 7], SPaRKLE uses active collimation and the $\Delta E - E$ technique for event-based particle identification. Standard tracking techniques are unsuitable for low-energy particles due to multiple

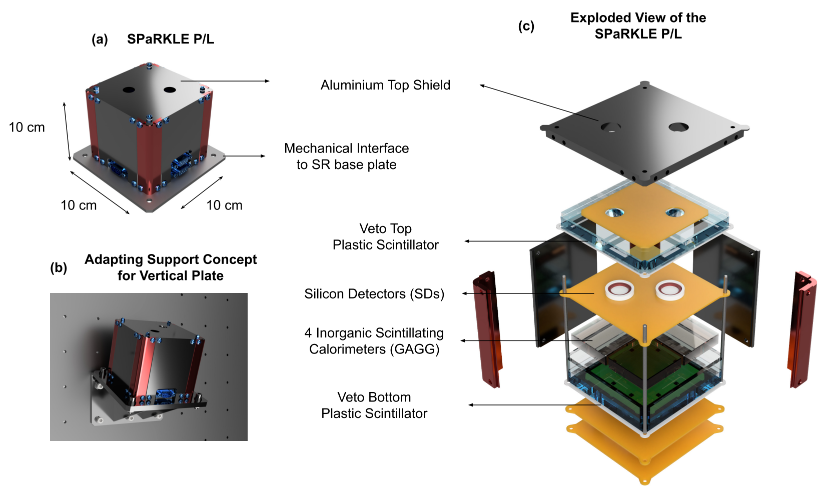


Fig. 1. – (a) External envelope of the SPaRKLE payload. (b) Adapting support concept for anchoring to a vertical plate. (c) Exploded view of the SPaRKLE payload.

Coulomb scattering. Therefore, SPaRKLE includes a plastic scintillator veto with two channels on top, tagging and rejecting particles not aligned with the channels' FOV.

The detection concept of SPaRKLE is illustrated in Fig. 2. Event-based particle identification is achieved by analyzing the topology of events. Good particle identification is obtained when a charged particle enters the detector, depositing a partial amount of energy ($\Delta E$) in the silicon detector and stops within the GAGG calorimeter, releasing the remaining kinetic energy ($E$). X-rays and $\gamma$-rays can be distinguished by their unique signature of complete energy release in the calorimeter.

## 5. – Expected Performances

In order to characterize the particle identification capabilities of the payload, a Particle Identification (PID) parameter can be defined as given by Eq. (1):

$$\text{PID}_{\text{parameter}} = \log_{10}\left(\frac{\Delta E}{1\ \text{MeV}}\frac{E_{tot}}{1\ \text{MeV}}\right) \tag{1}$$

where $\Delta E$ is the energy deposited in the silicon detector and $E_{tot}$ is the total reconstructed kinetic energy (i.e., the sum of the energy deposited in the silicon detector and the GAGG calorimeter). As shown in [6, 7], for non-relativistic particles, this parameter is expected to be proportional to the particle's mass times its charge squared (PID $\propto mZ^2$).

The characterization of the instrument's expected performance has been carried out using a Monte Carlo simulation developed with the GEANT4 toolkit [8].

In Fig. 3, the left panel shows a scatter plot of the energy deposited in the GAGG calorimeters versus the energy deposited in the silicon detectors. The two well-separated populations represent electrons (e-) and protons (p). For this analysis, the silicon detector is assumed to have an energy resolution constant with energy, with a Gaussian standard deviation of 10 keV, typical for standard PIN silicon detectors. For the GAGG calorimeter, an energy resolution of ≈10% has been conservatively assumed [9]. The right panel shows the total reconstructed kinetic energy versus the particle identification parameter (PID).

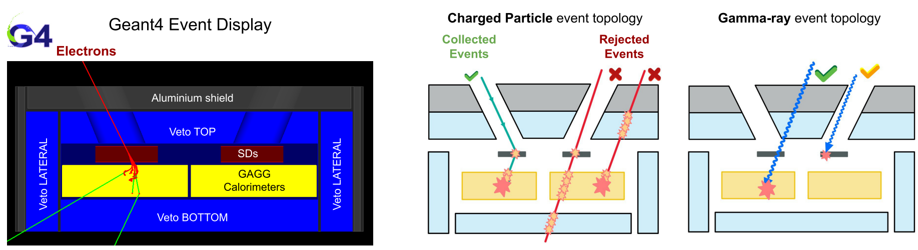


Fig. 2. – Illustration of the detection concept adopted by SPaRKLE. On the left panel, the event display of the Geant4 MonteCarlo model of the instrument with some electron tracks with energy in the range 5-10 MeV. This illustration also displays the internal sensitive elements of the payload. On the right panel, are reported some sketches for visualizing the topology of the events caused by charged particles and photons (X-rays and $\gamma$-rays).

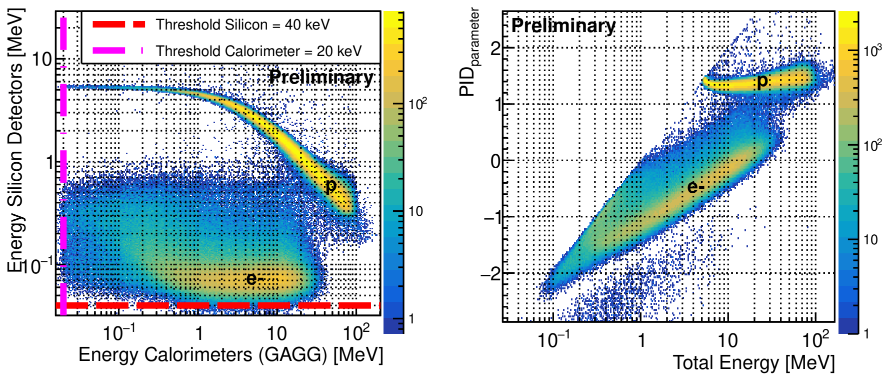


Fig. 3. – Scatter plots demonstrating the event-based charged particle identification capability using the $\Delta E - E$ technique for SPaRKLE. **(Left)** Energy deposited in the silicon detector vs. energy deposited in the GAGG calorimeter. The thresholds for the silicon detectors (40 keV) and GAGG calorimeters (20 keV) are indicated by the red and magenta dashed lines, respectively. **(Right)** Particle Identification (PID) parameter as a function of total energy.

The expected performance of SPaRKLE in terms of geometric factor and effective area is illustrated in Fig. 4. The left panel shows the geometric factor as a function of incident energy for electrons (blue) and protons (red). The instrument demonstrates good sensitivity for electrons in the range [0.4, 40] MeV and for protons in the range [5, 80] MeV, in which the sensitivity range has been defined as the interval in which the geometric factor of the detectors is greater than 0.1 cm$^2$ sr. The right panel depicts the effective area for photon detection with (red) and without (blue) confinement imposed by the bottom veto. In fact, at photon energies larger than 10 MeV pair production becomes dominant and the event cannot be fully contained within the calorimeter. The peak on-axis effective area is approximately 50 cm$^2$ at about 100 keV.

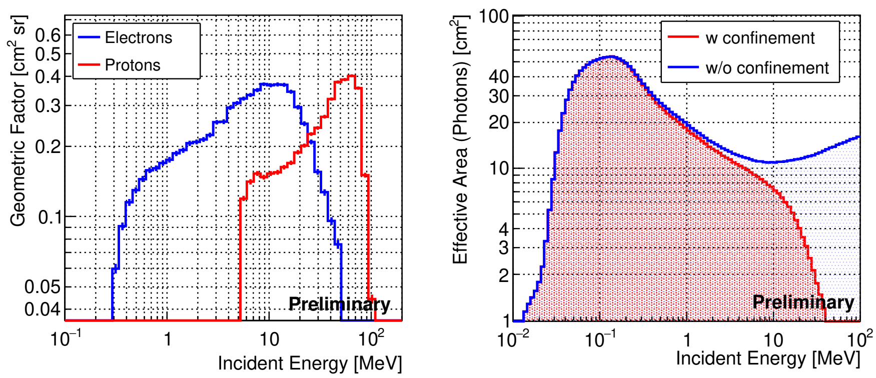


Fig. 4. – (Left) Geometric factor as a function of incident energy for electrons (blue) and protons (red). (Right) Effective area for photon detection with (red) and without (blue) confinement.

## 6. – Conclusions and Outlooks

This paper presented the SPaRKLE payload, a compact detector for gamma rays and low-energy particles. Currently approaching the Preliminary Design Review, SPaRKLE shows promising performance with sensitivity ranges of 0.4 to 30 MeV for electrons and 5 to 80 MeV for protons. The effective area for photon detection peaks at approximately 50 $cm^2$ at about 100 keV. Future work includes experimental validations and optimization of the payload's functionality. SPaRKLE aims to advance scientific knowledge and demonstrate the feasibility of miniaturized space-based detectors.

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