Snowmass2021 - Letter of Interest

Radiation Tolerant Silicon Photo-mulitipliers for Next-Generation Particle Space Telescopes

Thematic Areas:

☐ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
☐ (IF3) Solid state tracking
☐ (IF4) TDAQ
☐ (IF5) MPGD
■ (IF6) Calorimetry
☐ (IF7) Electronics ASICs
☐ (IF8) Noble elements
☐ (IF9) Cross Cutting

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Abstract:
Scintillation detectors have a long history in high energy (HE) astrophysics and particle physics. Recently, significant development has occurred to make Silicon Photomultipliers (SiPMs) a viable light collection alternative in scintillation detectors. To fully realize the benefits of using SiPMs as light collection devices for scintillation detectors in space, resources must be applied to fully characterize radiation damage in the current SiPMs and ultimately developing radiation tolerant and/or radiation hard devices. This ensures that future missions can take advantage of the benefits of SiPMs (low voltage, mass, power, and volume).

Introduction: Scintillation detectors have a long history in HE astrophysics as seen in the instruments on the *Compton Gamma-ray Observatory* and on the *Fermi* Gamma-ray Space Telescope. Major discoveries during the last decade were enabled by scintillation detectors. The NaI and BGO scintillation detectors of *Fermi*-GBM[7] (Figure 1) detected the first photons from the gravitational wave event GW170817A.[1] This detection proved that short γ-ray bursts result from neutron star mergers and expanded our understanding of jet physics and the speed of gravity. The association of a γ-ray flare detected by *Fermi*-LAT whose calorimeter[3] is comprised of logs of CsI scintilllators (Figure 1) with a neutrino event from the active galactic nucleus TXS 0506+056[4] showed that neutrinos are produced in the environments surrounding nature's particle accelerators, supermassive black holes.

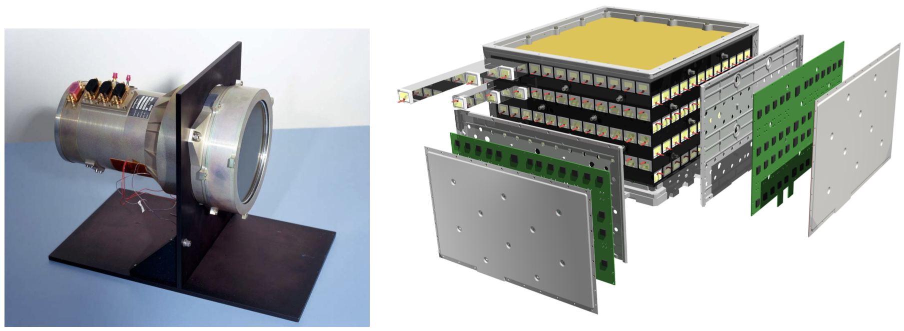

Figure 1: *Left:* The *Fermi*-GBM NaI scintillation detectors[7] are comprised of 12.7 cm diameter crystals coupled to a PMT. Future detectors like this could use smaller and lighter SiPMs with similar performance and lower bias voltages. *Right:* The *Fermi*-LAT calorimeter is comprised of CsI logs coupled to PIN diodes. Future detectors of this type could take advantage of similarly compact SiPMs with higher gain[3].

Scintillator Devices in HE Astrophysics: Scintillation detectors work by coupling a scintillating material with a light collection device. The scintillation material (such as the NaI used in *Fermi*-GBM) absorbs the energy of an incoming photon and emits scintillation light usually at a lower energy than the incoming photon. The scintillators can directly detect incoming radiation in the energy range from tens of keV to about 1 MeV directly (like in *Fermi*-GBM). Scintillators can also be part of larger tracker systems to detect γ rays indirectly, via secondary particles produced either by Compton scattering (primary γ-ray energies from tens of MeV to hundreds of MeV, e.g. in the proposed AMEGO[6] mission) or electron/positron pair cascades (primary γ-ray energies from hundreds of MeV to about 1 TeV, e.g. in *Fermi*-LAT). The type of scintillator and their size and shape are determined by the scientific requirements of the mission.

Light collection devices commonly used in the past are photomultiplier tubes (PMTs) and PIN diodes. This device converts the scintillation light produced by the scintillator into an electrical signal. PMTs are vacuum tubes consisting of a photocathode that emits a primary electron via the photoelectric effect and a series of dynodes that produce many secondary electrons via electron multiplication. Thus, a single detected photon produces a large number of electrons. In cases where high voltage or available volume are a concern, PIN diodes have been used (like the calorimeter on *Fermi*-LAT). A PIN diode is a robust solid state device that produces a single electron-hole pair when a single photon is absorbed resulting in a linear relationship between the incoming flux and electrical signal. Thus, a PIN diode does not have the large gain of a PMT and cannot be used with scintillators with low-light yields or in situations where energy resolution is a driver.

The applications and designs of scintillation detectors in space are varied and complicated and include many creative solutions depending on the exact scientific requirements. However, all of these devices have the basic design of a scintillation material and a light collection device.

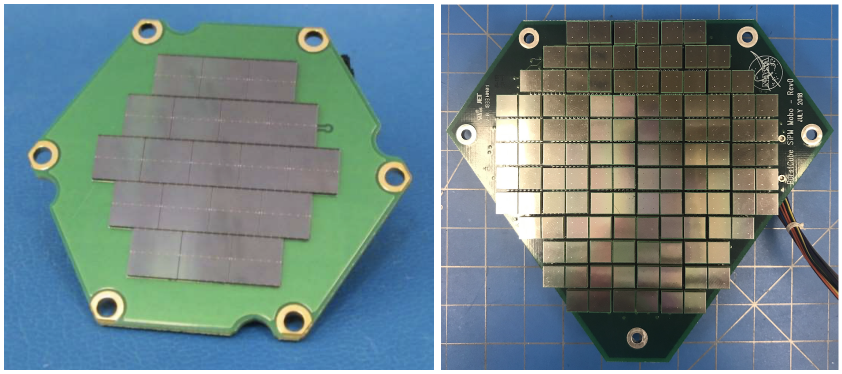

Figure 2: *Left:* The SIRI-1 mission flew SiPMs for one year and observed a ∼130% increase in the SiPM bias due to radiation damage. SIRI-2 will use this readout board comprised of 19 6 mm SiPMs coupled to a hexagonal SrI_2:EU scintillator[8]. *Right:* BurstCube will fly four detectors comprised of 116 6 mm SiPMs each coupled to cylindrical CsI detectors.[9]. These missions and others like them are path-finders for space qualifying SiPMs for use in future large-scale missions like AMEGO.[6]

SiPMs in Astrophysics: Recently, significant development has occurred to make SiPMs a viable light collection alternative in scintillation detectors (Figure 2). A SiPM is a solid-state single photon detection device based on single-photon avalanche diodes. A single SiPM is comprised of many 10's of thousand avalanche diode cells operating in Geiger mode which can vary in size. Thus, these devices have a high gain unlike the older PIN diode and they have a large dynamic range. SiPMs have several advantages over traditional PMTs: they are robust, small in volume and mass, and do not require high voltage to operate (bias voltages are typically in the 10's of volts). They have similar gains and photo-detection efficiencies as PMTs. Over the last few years, significant improvements have been made in reducing afterpulsing and lowering the dark count making these devices a viable alternative to PMTs.

Several groups are space-qualifying SiPMs including SIRI-1[8], GRID[13] and future missions like BurstCube[9] and MAMBO[12]. During SIRI-1's one year sun-synchronous orbit, the bias current increased by ∼130% due to radiation damage. This highlights the main downside to using SiPMs in a space environment: in low earth orbit (typical for HE missions, other orbits commonly used for heliophysics and planetary science experience higher levels of radiation), the instruments on a mission will experience radiation due to charged particles (protons cause the most damage). This radiation will cause defects in SiPMs and lead to an increase in dark current. Several groups have recently studied this using terrestrial beam-test data[2;5;8;10;11]. It is important to note that the space environment is not as strenuous as that in most terrestrial particle physics experiments. Mitigating radiation effects for space is also beneficial to the overall particle physics community.

Currently, radiation damage is reduced or mitigated by increasing shielding to reduce the total ionizing dose of radiation, controlling the temperature of the SiPMs to reduce the total dark current, and increasing the total bias current over the lifetime of the mission. These solutions are not ideal since increasing shielding adds mass to usually mass-constrained instruments, controlling the temperature is difficult in a space environment (it adds complexity, mass and usually requires more power) and increasing the bias current does not mitigate against the increase in noise (or low-energy threshold). A more permanent, robust solution is needed for future large-scale missions to enable the adoption of SiPMs.

Conclusion: To fully realize the benefits of using SiPMs as light collection devices for scintillation detectors in space, resources must be applied to fully characterize radiation damage in current SiPMs and ultimately developing radiation tolerant and/or radiation hard devices. This ensures that future missions can take advantage of the benefits of SiPMs (low voltage, mass, power, and volume).

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