Applications for New Scintillator Technologies in Gamma Ray Astronomy

Mark L. McConnell¹,², Peter F. Bloser¹, Jason Legere¹, James M. Ryan¹

¹Space Science Center, University of New Hampshire, Durham, NH 03824 USA
²Dept. of Earth, Oceans, and Space, Southwest Research Institute, Durham, NH 03824 USA
E-mail: mark.mcconnell@unh.edu

Abstract. Scintillators have long been used for probing the high energy universe. The reliability and low cost of scintillator-PMT detectors have made them the de facto standard for experiments on high altitude balloons and in orbiting satellites. New scintillators and new readout technologies offer important opportunities for more capable experiments. Recent scintillator developments include faster signals, increased light output, improved energy resolution, and better handling characteristics. Although PMTs remain effective for scintillator readout, new technologies offer more compact, rugged devices with much lower operational voltages. The adoption of these technologies is not without its difficulties, especially for space applications, where the technology readiness level can be an important consideration. To illustrate these issues, we will discuss the use of scintillators in Compton imaging experiments. At energies from about 500 keV to 30 MeV, Compton telescopes are the most effective means of imaging the gamma ray sky. To date, the only Compton telescope that has flown in space was the COMPTEL instrument on NASA’s Compton Gamma Ray Observatory (CGRO). CGRO, launched in 1991 and de-orbited in 2000, was based entirely on the use of technologies from the 1980’s. We have been working on an improved Compton telescope design, called the Advanced Scintillator Compton Telescope (ASCOT). It is much like COMPTEL, but utilizes up-to-date scintillator and readout technologies.

1. Introduction
Gamma-ray astronomy is not easy. First, it is necessary to observe from above the atmosphere. Second, the very low flux of photons from celestial γ-ray sources means that the combination of observation time and effective area must be large. Getting large instruments into space is a challenge. Third, orbiting instruments operate in a very high radiation environment. The radiation consists of cosmic rays plus the by-products of cosmic ray interactions with the Earth and with the spacecraft itself. The detector itself can even become a source of radiation. Consequently, the instrumental background can be quite high. Scintillator technology has long played a crucial role in γ-ray astronomy. Scintillators are a proven technology that can often be fabricated in large areas at relatively low cost. Although their energy resolution may be somewhat limited, there are many advantages to scintillation detectors (in particular, their timing characteristics) that often make them the detector of choice for many applications in astrophysics. Here we review some of the ways in which scintillators have been used in astrophysics and then discuss some of the work we have done utilizing some of the scintillator technologies.
2. Gamma Ray Telescopes

Within the energy range from above 10 keV up to several hundred GeV, the range covered by orbiting γ-ray telescopes, there are three primary modes of photon interaction – photoelectric absorption, Compton scattering and pair production. For imaging of γ-rays, there are three basic designs, each of which is tailored to a particular interaction process.

2.1. Coded Mask Imaging

At energies below ~1 MeV, the regime where the photoelectric effect is the dominant photon interaction mechanism, the typical approach to γ-ray imaging is the use of a coded mask [1]. Imaging is achieved by creating a shadow of an opaque mask (opaque to the photons of interest), which must then be measured using some position-sensitive detection plane. An accurate measure of the projected shadow allows for the reconstruction of the incident flux distribution. The requirement of having an opaque mask with reasonable geometry (not too thick so as to distort off-axis imaging) limits the energy range to below 1 MeV. In addition, the presence of a passive mask in a high radiation environment can also increase the instrument background due to activation effects. Nonetheless, coded mask telescopes have proven to be especially effective at energies below a few hundred keV. Scintillators have often been used for the position-sensitive detection plane. Discrete detector elements have sometimes been used, but location sensitive scintillation detectors have also been employed. Notable examples of orbiting coded mask instruments include SIGMA/GRANAT [2], INTEGRAL/IBIS [3], INTEGRAL/SPI [4], and Swift/BAT [5].

2.2. Compton Imaging

In the regime where Compton scattering is the dominant interaction process (roughly between 1 and 30 MeV), Compton imaging is employed. This technique takes full advantage of the Compton scattering process by measuring the kinematics of each Compton scattered photon. The measurement of the Compton kinematics for a single photon event requires measuring the location and energy loss at the site of the Compton scatter. It also requires a measure of the scattered photon energy and direction, which can be ascertained by a second detector designed to absorb the scattered photon. The arrival direction of the incident photon can be determined to within some annulus on the sky. The angular radius of this “event circle” is determined by the measured Compton scatter angle and the width of the event circle is determined, in part, by the energy resolution. An analysis of overlapping event circles can be used to determine the photon arrival direction. The only dedicated Compton telescope flown to date was the Compton Imaging Telescope (COMPTEL) on the Compton Gamma-Ray Observatory (CGRO) [6].

2.3. Pair Production Imaging

Pair production telescopes rely on the conversion of an incident photon into an electron-positron pair. Accurate tracking of pairs is required to determine the arrival direction of the incident photon (based on the initial momentum vectors of the outgoing electron and positron) and the incident photon energy (from the opening angle between the electron and positron momentum vectors). Scattering of the electron and positron distorts the tracks and limits the performance. This can be an especially significant problem at lower energies. Typically, track chambers or solid state strip detectors are used for track measurement. Scintillation detectors, however, can play an important role. Large volume scintillators (with limited spatial resolution) are often used as calorimeters to insure a full energy measurement of the electron and positron. Notable examples of orbiting pair telescopes include SAS-II, COS-B [7], CGRO/EGRET [8], Fermi/LAT [9], and AGILE [10].
3. MeV Astronomy

Historically, the field of γ-ray astronomy has grown over the past 50 years with a series of balloon and spacecraft instruments. These efforts have led to a series of successful orbital missions that have included the Compton Gamma-Ray Observatory (CGRO) [11], INTEGRAL [12], and Fermi. The scientific results from these missions have revolutionized our understanding of the γ-ray sky. Collectively, however, these instruments have not provided a uniform sensitivity coverage of the γ-ray spectrum. In particular, the region from about 1 MeV up to about 50 MeV has been poorly studied relative to neighboring energy regimes. The reduced sensitivity coverage in this part of the spectrum is sometimes referred to as the “MeV Gap.” As astronomers are now looking to plan future γ-ray missions, the need to fill in this gap with more sensitive instrumentation is widely recognized as one of the next strategic goals. This particular part of the spectrum covers the domain of the Compton telescope. It also encompasses the lower energy part of the pair production regime, where scattering of the electron-positron pair limits the angular resolution, and therefore the sensitivity, of pair production imaging. It also corresponds to a part of the spectrum that is experimentally challenged by significant levels of background.

Most γ-ray lines from nuclear de-excitation can be found in the energy range of roughly 1–10 MeV, the so-called “nuclear line region.” On orbit, the intense charged particle background results in the activation of many materials. Consequently, the spacecraft and the instrument itself literally glow in γ-rays. A suitable choice of materials (e.g., carbon fiber material rather than aluminum) can help limit the induced background, but the instrument itself must still be capable of recognizing and rejecting these background sources.

Over the years, several efforts have been made to develop a next-generation Compton telescope. Some have been based on solid state detector technologies, such as Ge or Si-strip detectors [13, 14, 15]. Others have explored the use of time-projection-chambers [16, 17]. Our work leverages our past experience with the COMPTEL experiment and has focused on the use of scintillator-based designs, recognizing the important capabilities of new types of scintillator material couple with new readout technologies.

3.1. CGRO/COMPTEL

The COMPTEL instrument was designed to image γ-rays in the 1–30 MeV energy range [6]. The principle of operation is illustrated in Fig. 1. It consisted of two layers of scintillation detectors. The upper (D1) detector layer (Fig. 2) consisted of seven large volume liquid scintillator (NE 213A) tanks (28.5 cm in diameter by 8.5 cm thick), each read out by an array of eight PMTs. The lower (D2) detector layer (Fig. 3) consisted of fourteen large volume NaI(Tl) scintillator crystals (28.2 cm in diameter and 7.5 cm thick) read out by an array of seven PMTs. In each case, signals from the PMT array were used to localize the event interactions to within 1-2 cm. The two detector layers (each surrounded by plastic anti-coincidence shielding to reject charged particles) were separated by distance of 1.5 m. Incoming photons would Compton scatter in the low-Z liquid scintillator in the D1 layer. The interaction location and energy deposit would be measured in the D1 detector. The scattered photon would subsequently travel downward and be fully absorbed by an interaction in D2. Once again, the location of the interaction and the total energy loss were measured.

The COMPTEL design incorporated two key features that were designed to help identify and reject background. The time-of-flight (ToF) between D1 and D2 was used to discriminate between downward-moving and upward-moving gamma rays, and also to distinguish between photons (moving at the speed of light) from slower moving neutrons (Fig. 4). (Neutrons generated by cosmic ray interactions in the atmosphere and in the spacecraft are a significant on-orbit background.) The 1σ ToF resolution was about 1 ns, which, given the 1.5 m separation of the D1 and D2 detector layers, was more than adequate to distinguish between upward and downward photons and also to identify a significant neutron component (Fig. 4). In addition...
to ToF, the D1 detectors also incorporated pulse shape measurements. The pulse shape could be used to distinguish true Compton scatter events from inelastic neutron scattering events (Fig. 5). This provided a second level of neutron rejection. Valid events could be identified utilizing both ToF and pulse-shape discrimination (PSD) measurements, along with the charged-particle rejection afforded by the plastic anti-coincidence system.

COMPTEL proved to be a successful project. It demonstrated techniques that could be used to limit the background, but the sensitivity was limited, in part because of its limited effective area. During its nine year mission, it detected only about 25 point-like sources on the entire sky [18], but it also proved its utility by mapping diffuse emissions in the galaxy, most notably the 1.8 MeV line from radioactive 26 Al [19]. Background rejection techniques were also key in the measurement of the isotropic cosmic diffuse γ-ray emission, showing that previous measurements had suffered from background-related issues.

Figure 1. The COMPTEL instrument used Compton imaging for 1–30 MeV γ-rays, but had limited polarization sensitivity.
4. An Advanced Compton Telescope
For several years, we have been investigating ways of improving on the COMPTEL design using the latest in scintillator technology [20, 21, 22]. This effort is embodied in an instrument that we call ASCOT (Advanced Scintillator COMpton Telescope) [23, 24, 25]. The ASCOT design incorporates the use of modern scintillator materials to retain the simple design and proven, ToF background rejection method, while using modern light readout devices to eliminate bulky and fragile photomultiplier tubes (PMTs) with their high-voltage requirements.

Recent advances in inorganic scintillator technology, such as the availability of Cerium-doped Lanthanum tri-Bromide ($\text{LaBr}_3(\text{Ce})$ [26]) and Cerium tri-Bromide ($\text{CeBr}_3$ [27]) have opened up a wide range of exciting new possibilities for high-energy astronomy and space science. Both materials offer good energy resolution for gamma-ray measurements, competitive with that of semiconductor detectors while retaining the many strengths of scintillators: simple and reliable implementation, high stopping power, large volume, room temperature operation, and very fast timing. In addition, new growth techniques have greatly increased the utility of organic...
scintillator crystals, such as stilbene [27] and p-terphenyl [28], that feature high light output and good differentiation between electron and proton signals via PSD. Combined with recent advances in light readout technologies, such as Si photomultipliers (SiPMs), the scintillators can now be used in configurations with significantly reduced mass, volume, and power.

A balloon prototype of ASCOT is currently being prepared for a balloon flight from Ft. Sumner, NM in the fall of 2017 [29]. The instrument (Fig. 6) is composed of arrays of 15 mm × 15 mm × 25 mm scintillator elements. Each scintillator element is read out by a 2 × 2 sub-array of SensL SiPMs. The D1 detector assembly is composed of two layers of p-terphenyl scintillator (one module of which is shown in Fig. 7). The D2 detector assembly is composed of a single layer of CeBr$_3$ scintillator (one module of which is shown in Fig. 8). The energy resolution of one single CeBr$_3$ element has been measured as 6.1% at 662 keV (FWHM). The ToF resolution of ASCOT has been measured using one p-terphenyl pixel and one CeBr$_3$ pixel. At 1.2 MeV, a 1σ ToF resolution of 225 ps was measured. This represents a four-fold improvement over the 1 ns resolution of COMPTEL. The improved ToF resolution enables a much smaller D1-D2 separation of 15 cm (as compared with the 150 cm of COMPTEL). The much smaller separation results in a significant improvement of sensitivity and a much larger FoV. It is hoped that the first results from ASCOT will be obtained next fall, demonstrating that a next-generation COMPTEL instrument can be based on the same basic design, but with the latest in scintillator technologies.

5. Importance of Scintillators in Astrophysical Research

Scintillation detectors remain an important component of many γ-ray telescopes. They represent a reliable, flight-proven technology that is robust under a variety of operating conditions. They are relatively low in cost, and can be fabricated in a variety of shapes and sizes. New readout technology, such as SiPMs, make scintillators even more attractive by reducing mass and volume, while maintaining the desirable characteristics of PMTs.
Figure 6. The design of the ASCOT balloon payload, which is scheduled for a balloon flight from Ft. Sumner, NM in the fall of 2017. The instrument itself is shown on the left. The full balloon payload is shown on the right.

Figure 7. One of eight p-terphenyl scintillator modules that will be used for the D1 layer of ASCOT.

Figure 8. One of four CeBr₃ scintillator modules that will be used for the D2 layer of ASCOT.

5.1. Acknowledgments
This work was supported by NASA Grants NNX15AI70G, NNX12AB36G, NNX13AC89G, NNX08AK47G, NNX10AC14G, and NNX10AG10G.

References
[1] Caroli E, Stephen J B, Di Cocco G, Natalucci L and Spizzichino A 1987 Space Science Reviews 45 349–403
[2] Bouchet L, Roques J P, Ballet J, Goldwurm A and Paul J 2001 Astrophysical Journal 548 990–1009
[3] Ubertini P, Lebrun F, Di Cocco G, Bazzano A, Bird A J, Broenstad K, Goldwurm A, La Rosa G, Labanti C, Laurent P, Mirabel I F, Quadrini E M, Ramsey B, Reglero V, Sabau L, Sacco B, Staubert R, Vigroux L, Weisskopf M C and Zdziarski A A 2003 Astronomy and Astrophysics 411 L131–L139
[4] Vedrenne G, Roques J P, Schönfelder V, Mandrou P, Lichti G G, von Kienlin A, Cordier B, Schanne S, Knödlseder J, Skinner G, Jean P, Sánchez F, Caraveo P A, Teegarden B, von Ballmoos P, Bouchet L, Paul P, Matteson J L, Boggs S E, Wunderer C, Leleux P, Weidenspointner G, Drouchkou P, Diehl R, Strong A W, Cassé M, Clair M A and André Y 2003 Astronomy and Astrophysics 411 L69–L70

Applications of Novel Scintillators for Research and Industry 2016 (ANSRI 2016) IOP Publishing Journal of Physics: Conference Series 763 (2016) 012008 doi:10.1088/1742-6596/763/1/012008
Teegarden B, Ubertini P, Vedrenne G and Dean A J J 2003 *Astronomy and Astrophysics* **411** L1–L6

[13] Boggs S E 2006 *New Astronomy Reviews* **50** 604–607

[14] Boggs S E, Coburn W, Smith D M, Bowen J D, Jean P, Kregenow J M, Lin R P and von Ballmoos P 2004 *New Astronomy Reviews* **48** 251–255

[15] Novikova E I, Wulf E A, Phlips B F, Zoglauer A, Weidenspointner G and Kippen R M 2005 Simulations of a Si-based Advanced Compton Telescope *Nuclear Science Symposium Conference Record, 2005 IEEE* pp 985–989

[16] Aprile E, Curioni A, Giboni K L, Oberlack U G and Zhang S 2008 *Nuclear Instruments and Methods in Physics Research Section A* **593** 414–425

[17] Aprile E, Curioni A, Egorova V, Giboni K, Oberlack U G, Ventura S, Doke T, Takizawa K, Chupp E L and Dunphy P 2001 A liquid xenon time projection chamber for gamma-ray imaging in astrophysics: present status and future directions *Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment* (Columbia Univ, Dept Phys, Columbia Astrophys Lab, New York, NY 10027 USA) pp 256–261

[18] Schönenfelder V, Bennett K, Blom J J, Bloemen H, Collmar W, Connors A, Diehl R, Hermelen W, Iyudin A, Kippen R M, Knöldeseder J, Kuiper L M, Lichti G G, McConnell M L, Morris D, Much R, Oberlack U G, Ryan J M, Stacy G, Steinle H, Strong A W, Suleiman R, van Dijk R, Varendorff M, Winkler C and Williams O R 2000 *Astronomy and Astrophysics* **355** 1–3

[19]Diehl R 1995 *Experimental Astronomy* **6** 103–108

[20] Bloser P F, Legere J S, Bancroft C M, Jablonski L F, Wurtz J R, Ertley C D, McConnell M L and Ryan J M 2014 *Nuclear Inst. and Methods in Physics Research* **763** 26–35

[21] Bloser P F, Legere J S, Bancroft C M, McConnell M L and Ryan J M 2014 Scintillators with silicon photomultiplier readouts for high-energy astrophysics and heliophysics *Proceedings of the SPIE* ed Takahashi T, den Herder J W A and Bautz M Space Science Ctr., The Univ. of New Hampshire (United States) (SPIE) pp 914414–914414–11

[22] Bloser P F, Legere J S, Bancroft C M, McConnell M L, Ryan J M and Schwadron N 2013 Scintillator gamma-ray detectors with silicon photomultiplier readouts for high-energy astronomy *Proceedings of the SPIE* ed Siegmund O H The Univ. of New Hampshire (United States) (SPIE) pp 88590A–88590A–8

[23] Bloser P F, Legere J S, Bancroft C M, Ryan J M and McConnell M L 2016 *Nuclear Inst. and Methods in Physics Research* **812** 92–103

[24] Bloser P F, Ryan J M, Legere J S, Julien M, Bancroft C M, McConnell M L, Wallace M, Kippen R M and Tornga S 2010 *Proceedings of SPIE* **7732** 64

[25] Bloser P F, Ryan J M, Legere J S, Julien M, Bancroft C M, McConnell M L, Wallace M, Kippen R M and Tornga S 2009 *Proceedings of SPIE* **7435** 12

[26] van Loef E V D, Dorenbos P, van Eijk C W E, Krämer K and Güdel H U 2001 *Applied Physics Letters* **79** 1573–1575

[27] Kim H D, Cho G S and Kim H J 2013 *Radiation Measurements* **58** 133–137

[28] Matei C, Hambsch F J and Oberstedt S 2012 *Nuclear Instruments and Methods in Physics Research Section A* **676** 135–139

[29] Bloser P F, Sharma T, Legere J S, Bancroft C M, McConnell M L, Ryan J M and Wright A M 2016 *Proceedings SPIE* **9905** 99050K–99050K–7