Advanced Scintillators and Readout Devices for High-Energy Astronomy

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Abstract

Among the top priorities for high-energy astronomy in the coming decade are sensitive all-sky surveys in the poorly explored hard X-ray and medium-energy gamma-ray bands. Such observations have historically been carried out by instruments based on inorganic scintillators read out by photo-multiplier tubes. Scintillator detectors are robust, simple, and low-cost, and offer large volumes, high stopping power, and fast timing. Recent technological advances in scintillator materials and readout devices offer the promise of greatly improved energy resolution and timing combined with lower overall instrument mass, volume, and power requirements. We therefore believe that investing in the development of advanced scintillators and readout devices will pay off in the form of sensitive, cost-effective gamma-ray observatories.

Introduction

Among the top priorities for high-energy astronomy in the coming decade are sensitive, all-sky surveys in the hard X-ray/soft gamma-ray (10 keV – 600 keV) and medium-energy gamma-ray (0.5 – 20 MeV) bands. Such surveys will significantly advance our knowledge of a wide variety of non-thermal, high-energy physical processes in the universe. These observations will require space-borne gamma-ray telescopes with large collecting areas and large detector volumes, wide fields-of-view, good angular and energy resolution, and sophisticated background rejection abilities in order to achieve the required levels of sensitivity. Historically, observations in the soft- and medium-energy gamma-ray bands have been conducted using detectors based on inorganic scintillators read out by photo-multiplier tubes (PMTs). These observations were limited by the modest energy and time resolution of traditional scintillator materials (e.g., NaI and CsI), and by the demands on mission resources imposed by the bulky, fragile, high-voltage PMTs. Recent technological advances in the development of both ***new scintillator materials*** (e.g., $LaBr_3$:Ce) and ***new scintillation light readout devices*** (e.g., silicon photo-multipliers, or SiPMs), however, promise to greatly improve the observational capabilities of future scintillator-based gamma-ray telescopes, while retaining the relative simplicity, reliability, large volumes, and low-cost of scintillator instruments. We therefore believe that technology development efforts aimed at optimizing the performance of, space-qualifying, and lowering the cost of new scintillators and readout devices would be a valuable investment in the future of high-energy astronomy.

Scientific Opportunities

The application of this new scintillator and readout technology is likely to provide benefits for gamma-ray detectors that operate in the poorly explored energy band from ~10 keV up to ~20 MeV. This entire energy range is in need of an all-sky survey with at least ten times the sensitivity of previous surveys in order to detect and study representative samples of a wide variety of high-energy cosmic sources. This will set the stage for future, targeted observations using sophisticated instruments whose design will depend on the results of the surveys. The science may be separated into two energy regimes, with some overlap, based upon the type of instrument that is called for. The first regime is that below ~0.6 MeV, where collimated detectors or coded aperture imagers (e.g., Fenimore & Cannon 1978) are likely to be employed. The second regime corresponds to that from ~0.5 MeV up to ~20 MeV, where a Compton telescope (e.g., Schönfelder et al. 1993) is the likely candidate for a future mission.

Hard X-ray/Soft Gamma-Ray Band (10 – 600 keV)

The primary science driver for an all-sky survey in the hard X-ray/soft gamma-ray band is a complete census of accreting black holes in the Universe. This goal motivates the Black Hole Finder Probe (BHFP) mission concept, part of the former NASA Science Roadmap, "Beyond Einstein" (currently being renamed the "Physics of the Cosmos" program). Many accreting black hole sources (especially stellar-mass black holes and Seyfert galaxies) have spectra that peak in this energy band. Since the high energy emission from black hole sources can often be obscured by intervening matter (either within the source itself or elsewhere along the line of sight), observations at energies above ~10 keV are necessary. Meanwhile, observations up to ~600 keV will be important for monitoring changes in the thermal/non-thermal character of the source spectra. An important secondary science goal is the most complete population of gamma ray bursts (GRBs) ever compiled, as gamma ray burst spectra peak in this energy range. Accreting neutron stars also emit in this energy band, some of which have exhibited cyclotron line features in the 10-100 keV energy range. Several other line features are present in this energy band. These include a 158 keV line from the decay of ^{56}Ni produced in Type Ia supernovae; the 68 and 78 keV lines from the decay of ^{44}Ti and the 122 keV line from the decay of ^{57}Co produced in core-collapse supernovae; and the 511 keV line (and perhaps its associated backscatter feature) from electron-positron annihilation. Recent studies the Galactic 511 keV line emission have hinted at intriguing correlations with a particular class of X-ray binaries (Weidenspointner et al. 2008), but much more sensitive observations are needed. Of particular interest in this energy band will be an all-sky survey with a time resolution that permits variability studies of sources on timescales of years to milliseconds. The partial-sky surveys conducted by the coded-aperture INTEGRAL (Bird et al. 2006) and Swift (Tueller et al. 2009) satellites have laid the groundwork for a more complete and more sensitive survey in the next decade. For example, the Swift survey has achieved ~1 mCrab sensitivity from 14 – 195 keV (Tueller et al. 2009); the goal of the BHFP survey is 0.05 mCrab over roughly this energy range.

Medium-Energy Gamma-Ray Band (0.5 – 20 MeV)

A broad range of astrophysical science is best studied via observations in the so-called medium-energy gamma-ray band, from roughly 0.5–20 MeV. Medium-energy gamma rays probe extreme physical conditions in the Universe that give rise to nuclear interactions and relativistic particles. The only Compton telescope in this energy range to fly in space with sufficient sensitivity to make useful astronomical observations was the COMPTEL instrument on the CGRO satellite (Schönfelder et al. 1993). COMPTEL provided only a dim, blurry view of the MeV gamma-ray Universe, but it was sufficient to demonstrate that the science return of a more sensitive instrument will be rich. For example, this energy band includes the range (1-10 MeV) where nuclear lines are important. Studies of the 1.8 MeV line from ^{26}Al by COMPTEL have helped shed light on the role of nucleosynthesis in the galaxy (Diehl et al. 1995). COMPTEL was able to place upper limits on ^{56}Co gamma-ray line emission from one SN and marginally measure another (Morris et al. 1998). A significant level of diffuse emission from the interstellar medium is also present in this energy range, but current models of galactic gamma-ray production in cosmic-ray/gas interactions fail to provide a satisfactory explanation (Strong et al. 2000) for this galactic glow. Measurements of the cosmic diffuse emission by COMPTEL have been important for resolving long-standing mysteries regarding the origin of this radiation. Finally, a broad range of cosmic particle accelerators are luminous in MeV gamma rays, including solar flares, black holes (e.g., Cyg X-1; McConnell et al. 2002), and pulsars. A number of AGN sources, the so-called blazars, have their peak emissions in this range. A factor of ~10 increase in sensitivity compared to COMPTEL is necessary in order to move from merely *detecting* a few examples of each of these astrophysical sources to *studying* a representative sample of each source class.

Technical Approach: Advanced Scintillators and Readouts

The development of new technology for gamma-ray instrumentation is closely linked to the requirements for the next generation of gamma-ray telescopes. For example, the desire to obtain X- and gamma-ray images of objects with accompanying high resolution spectra has only become feasible with the development of detectors, primarily solid-state (e.g., Ge or CZT), that possess the properties of excellent energy resolution and excellent position resolution. However, instruments are becoming increasingly expensive and complicated. Their expense and complexity, in turn, threaten their future prospects in the context of NASA budgets that do not grow as fast as technology develops. Developing detector materials that do not have large intrinsic costs and do not entail high costs associated with supporting electronics is important, if those materials provide much, if not all, of the power to achieve the agency's scientific goals. New scintillator materials, supplemented by new light readout devices, promise to meet this need. In addition, for certain applications, mainly those requiring large individual detector volumes and very high stopping power (e.g., high-energy calorimeters and shielding), scintillators will continue to be the preferred technical solution regardless of cost. Advanced materials will enhance the science return in these cases.

Scintillators in High-Energy Astronomy

Scintillator detector materials such as NaI(Tl), CsI(Na), BGO, and various organic plastics and liquids have long been the work horses of high-energy astronomy. Examples include the A4 instrument on HEAO-1 (NaI/CsI; Matteson 1978), GRANAT/SIGMA (NaI; Bouchet et al. 2001), the phoswich detector system on BeppoSAX (NaI/CsI; Frontera et al. 1997), and all four instruments on the Compton Gamma Ray Observatory (CGRO): BATSE (NaI; Fishman et al. 1992), OSSE (NaI/CsI; Johnson et al. 1992), EGRET (NaI calorimeter; Kanbach et al. 1988), and COMPTEL (liquid scintillator, NaI calorimeter; Schönfelder et al. 1993). The advantages of scintillators include a wide range of material options, low cost, simple and reliable implementation, radiation hardness, high stopping power, large volumes, room temperature operation, good energy resolution, and very fast timing.

In recent years there has been a shift in emphasis from scintillators to solid-state detectors in high-energy astronomy, such as the CZT detector plane for the BAT instrument on Swift (Barthelmy 2004). Solid-state detector materials such as CZT and Ge offer extremely good energy resolution (a few percent or less) and position resolution (~mm or less). These advantages come at the expense of increased cost and complexity, small-volume detector elements, slow time response, and, in the case of Ge, the need for cryogenic cooling. Since future survey missions will require large volumes of detector material, the cost and complexity alone present serious challenges for using solid-state detectors in these missions. In addition, high-energy spectrometers, calorimeters, and active shields require large individual detector elements, and so scintillators remain, and will remain, the preferred solution. Current examples include the burst monitor (NaI and BGO; von Kienlin et al. 2004) and large-volume CsI calorimeter on GLAST (Johnson 2003) and the active BGO shield on INTEGRAL/SPI (Schanne et al. 2003).

New scintillator materials have recently become available that make scintillator detectors once again competitive with solid-state detectors for all applications but those where the highest possible energy resolution is critical. The most advanced of these at the current time is **$LaBr_3$:Ce** (van Loef et al. 2001; Shah et al. 2003, 2004a; Rozsa et al. 2009). $LaBr_3$ is a high-Z, high-density material (5.08 g cm^{-3}, vs. 3.67 g cm^{-3} for NaI) with 60% higher light output than NaI. It is a blue scintillator, with the scintillation light peaking at ~380 nm. Its light output and exceptional linearity give it an energy resolution that is far better than NaI (2.6% FWHM vs. 7% at 662 keV; Fig. 1) and is competitive with CZT. Moreover, its very short decay time (~20 ns, vs. 230 ns for NaI) permits very high count rates and/or very precise coincidence timing (less than 300 ps). $LaBr_3$ has been shown to be radiation

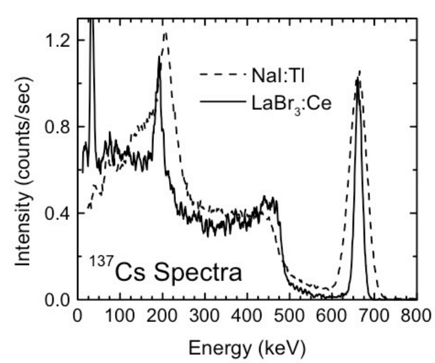

Fig. 1 Energy spectrum of a ^{137}Cs source obtained with a 1 cm^3 $LaBr_3$ detector. FWHM at 662 keV is 2.6%. The comparison NaI(Tl) spectrum has an energy resolution of 6.7% (FWHM). (From Shah et al. 2004)

hard and suitable for the spaceflight environment (Bloser et al. 2006; Owens et al. 2007; Budden et al. 2008a). The primary drawbacks of $LaBr_3$ are its sensitivity to moisture, requiring hermetic packaging, and its cost, ~\$300 cm^{-3}.

Advanced Readout Devices

The use of scintillators in space flight applications remains constrained by the volume, mass, power, and cost of the associated readout device for the scintillation light. PMTs are large, fragile vacuum tubes that require high voltage (typically 1000 V or more) and extensive mechanical support; their size can easily exceed that of the detector they are reading out. More recently, good results have been obtained using avalanche photo-diodes (APDs), but these still require several hundred volts and have gains of only ~1000, requiring a low-noise preamplifier stage. It would therefore be extremely valuable, considering the severe mass and power constraints of space missions, to find an alternate light readout device that matches or surpasses the quantum efficiency, gain, dynamic range, and speed of a PMT in a compact, rugged, low-power package. New solid-state devices offer such an opportunity.

Silicon Photo-Multipliers (SiPMs)

The *silicon photo-multiplier* (SiPM), also known as the *solid-state photo-multiplier* (SSPM) or the *multi-pixel photon counter* (MPPC), is a novel photo-detector originally developed in Russia for high-energy physics applications (Buzhan et al. 2001; Buzhan et al. 2003; Balagura et al. 2006; Stapels et al, 2005, 2006). It consists of a two-dimensional array of small structures, typically ~50 µm is size, each of which acts as an independent APD. These APDs, which can be thought of as pixels, are reversed-biased 10%-20% above their breakdown voltage so that they operate in "limited Geiger mode": when a photon is absorbed, the electric field is high enough that a large avalanche is quickly generated which produces a large signal that is **not** proportional to the number of photons that were absorbed. A resistor in series with the pixel quenches the avalanche after several 10s of ns. The outputs of all the pixels are summed together so that the intensity of the incident light is proportional to the **number** of pixels that absorb photons. This operating principle is illustrated in Fig. 2.

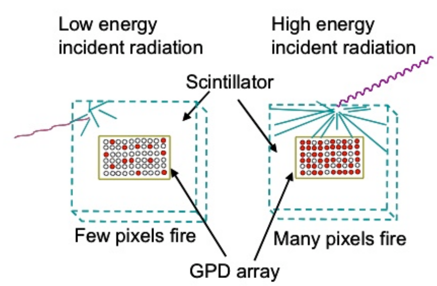

Fig. 2. SiPM principle of operation. Scintillation photons are produced in proportion to the energy of the incident radiation. The number of pixels that fire in the SiPM is a function of the incident energy. (From Stapels et al. 2005)

The advantages of the SiPM include: high gain (~10^6) at low operating voltages (typically 30-70 V), compactness, insensitivity to magnetic fields, fast timing response (rise times less than 1 ns), and the potential for low cost and CMOS compatibility, which would permit integration of processing electronics in one compact package. Disadvantages include a tradeoff between effective quantum efficiency and dynamic range, and sensitivity of the gain to temperature. Most SiPMs are sensitive to red light, but blue-sensitive devices are commercially available (at the cost of higher bias voltage, ~70 V).

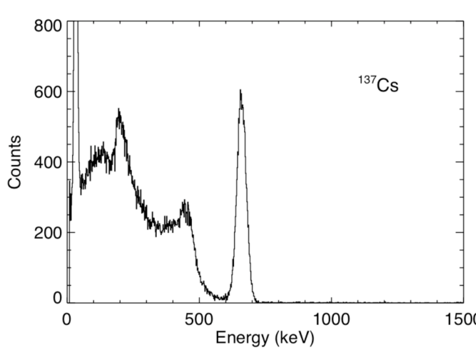

Fig. 3. ^{137}Cs spectrum measured using the S10985-050C MPPC coupled to $LaBr_3$. The energy resolution at 662 keV is 6.2% (FWHM).

SiPMs have been shown to perform well as light readout devices for $LaBr_3$ scintillators (Bloser et al. 2008). For example, Fig. 3 shows a ^{137}Cs spectrum obtained with a 0.5″ × 0.5″ $LaBr_3$ detector read out by a 6 mm × 6 mm blue-sensitive S10985-050C MPPC from Hamamatsu Corp. The resolution at 662 keV is 6.2% (FWHM), and is limited only by the small collecting area of the device.

The most pressing technology development needed for SiPMs is the ability to create large light collection areas (e.g., closely tiled arrays), cost reduction, and space-qualifications (especially radiation hardness and temperature stability).

Silicon Drift Diodes (SDDs)

Silicon Drift Detectors (SDDs) are low-capacitance photon detectors for the optical light emitted by scintillators (Lechner et al. 2008). In an SDD a large volume of a high resistivity semiconductor, e.g. n-type silicon, is depleted by a small sized n+ bulk contact reverse biased with respect to rectifying p+ junctions covering both surfaces of the structure. In an SDD the p+ junctions are strip-like segmented and biased in such a way that an electric field parallel to the surface exists. Electrons released within the depleted volume by the absorption of ionizing radiation or by thermal generation drift in the field towards the n+ substrate contact, which acts as collecting anode and is connected to an amplifier. In an advanced SDD design optimized for applications in photon spectroscopy the p strip system for the generation of the drift field has the shape of concentric rings (Fig. 4). Each electron generated in the volume is collected at the anode in the center, taking advantage of the small value of the anode capacitance, which is almost independent of the detector area. To reduce noise further, the first transistor of the amplifying electronics can be integrated on the SDD chip. Compared to a photodiode of equal size the SDD is able to work at higher count rates and yields a substantially better energy resolution, because the signal is less sensitive to the noise contribution of the subsequent amplifying electronics. There is no internal gain, so there is no dependence of pulse height on temperature or bias voltage (~100 V). SDDs of this type have been produced in large numbers and are available in a variety of shapes and sizes from 5 mm² up to 1 cm². To increase the sensitive area without loss in performance, monolithic SDD arrays have been fabricated. Good spectroscopic performance has been achieved using SDDs coupled to scintillators, due to their high quantum efficiency and low noise, with energy resolutions (FWHM) at 662 keV of 4.4% for CsI(Tl) and 2.7% for $LaBr_3$ reported at room temperature (Lechner et al. 2008). Imaging arrays are under development. One drawback for certain applications is that the timing resolution is not as good as a PMT or SiPM.

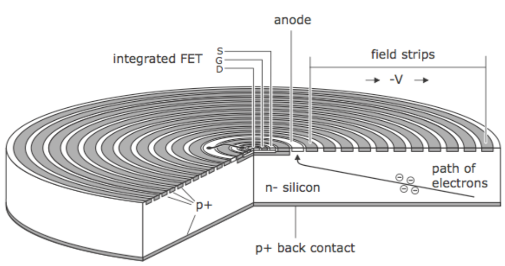

Fig. 4. Cylindrical SDD. Electrons are guided by the radial electric field to the small collecting anode in the center. (From Lechner et al. 2008)

Examples of Scintillator-Based Gamma-Ray Missions Under Development

Numerous institutions (University of New Hampshire; Max Planck Institute; University of Alabama, Huntsville; Louisiana State University; Los Alamos National Laboratory) are developing concepts for future soft- and medium-energy gamma-ray missions, with the goal of performing sensitive all-sky observations. These concepts all are based on scintillator detectors because of the inherent advantages discussed above, and all would benefit from new scintillator and readout technology.

FACTEL

The University of New Hampshire (UNH) is currently studying a concept for a Compton telescope using fast scintillators to improve on the performance of COMPTEL. This Fast Compton Telescope (FACTEL), would follow COMPTEL by employing a liquid scattering detector, but would replace the NaI calorimeter with $LaBr_3$ (Ryan et al. 2007). Using $LaBr_3$ in the calorimeter offers the following significant advantages over NaI: 1) **Faster Timing**: Valid events require coincident hits in both detectors with a time delay corresponding to the time of flight (ToF) for a photon between them. The fast response of the $LaBr_3$ would permit a much smaller ToF window for improved background rejection. 2) **Improved Energy Resolution**: The better energy resolution of $LaBr_3$ would translate directly into superior angular resolution for the telescope, in addition to improved energy resolution for gamma-ray line studies. 3) **Better Stopping Power**: The higher effective Z and density of $LaBr_3$ increases the efficiency of the calorimeter for capturing the full energy of scattered photons. To maximize both the timing and energy response, both the scattering and calorimeter layers would consist of individual detector elements ~2 cm in size with individual readouts.

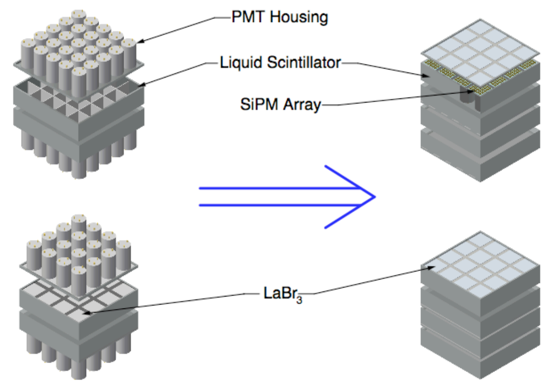

Fig. 5. Subsection of the FACTEL Compton telescope using liquid scintillator for the scattering layer and $LaBr_3$ for the calorimeter. Replacing PMTs (left) with SiPMs (right) would allow additional detector layers to be contained in the same total volume, while reducing the amount of passive material and eliminating the need for high voltage.

While we are currently assuming the use of fast PMTs, such as the 1″ Hamamatsu R4998, as the readout devices, the advantages of SiPMs for this application would be very significant (Fig. 5), provided the energy and timing response is equivalent. The use of SiPMs would allow the detectors to be packed closely together and permit, for example, additional layers of detectors to be stacked within the same total volume, increasing the efficiency. Even more importantly, the use of SiPMs would dramatically reduce the fraction of passive mass in the instrument, which is critical to achieving high efficiency and low background in a Compton telescope. Maintaining excellent timing and energy resolution in each detector element is crucial.

CASTER

In November of 2003, UNH's Coded Aperture Survey Telescope for Energetic Radiation (CASTER) was selected by NASA for concept study funding as part of the call for Einstein Probe mission concepts (McConnell et al. 2006). The primary motivation for CASTER was the availability of new scintillator materials that offered the hope of using traditional detector technologies for achieving the goals of the BHFP. The CASTER science instrumentation consists of an array of 16 coded aperture imagers. Each of the 16 imagers covers the full energy range from 10 to 600 keV, though some are optimized for <200 keV and some for >200 keV. The detection plane in each case consists of an array $LaBr_3$ scintillators, with each individual scintillator read out by a multi-anode photo-multiplier tube (MAPMT) (Fig. 6). The advantage for CASTER of $LaBr_3$ over, e.g., CZT, is the possibility to achieve similar energy and

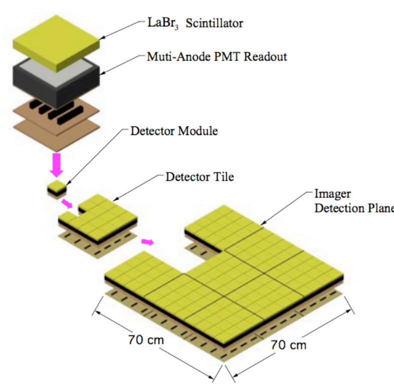

Fig. 6: CASTER detector plane.

position resolution (~1 mm, via the Anger camera technique) with far fewer electronics channels, while lowering the dead time due to the fast time response, and extending the sensitive energy range up to 600 keV due to the greater detector thickness possible. Replacing the MAPMTs with arrays of SiPMs or SDDs would save mass and remove high voltage requirements. The viability of CASTER would be further enhanced by reductions in the cost of $LaBr_3$, or the availability of newer, cheaper scintillators with similar properties.

GRIPS

The Gamma-Ray burst Investigation via Polarimetery and Spectroscopy (GRIPS), under development at the Max Planck Institute, is envisioned as a hybrid telescope capable of imaging gamma rays from 200 keV to 50 MeV via Compton scattering and pair production (Greiner et al. 2009). The main instrument is the gamma-ray monitor (GRM), consisting of a tracker made of 64 layers of double-sided Si strip detectors and a calorimeter made of 5 mm × 5 mm $LaBr_3$ crystals of varying lengths, read out at the end by SDDs (Fig. 7). Incident photons either Compton scatter or pair produce in the tracker; the stack if Si detectors tracks the recoil electron or e^+/e^- pair for event reconstruction and background rejection. The Compton-scattered photons are absorbed in the calorimeter. $LaBr_3$ is the detector material of choice for the calorimeter due to its thickness, stopping power, and energy resolution. SDDs readouts provide good energy resolution with minimal mass and power requirements.

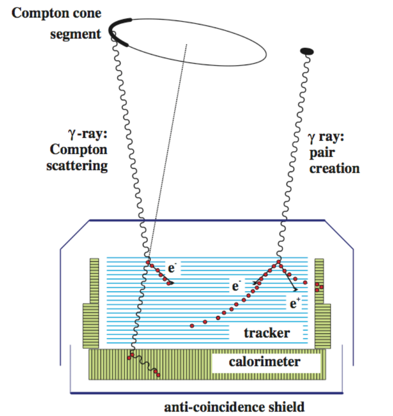

Fig. 7: GRIPS GRM design and measurement principle (from Zoglauer et al. 2008).

LOCO

The Lunar Occultation Observer (LOCO) mission concept (Miller 2008) is a viable, highly cost-effective approach for a next-generation nuclear astrophysics investigation under development at the University of Alabama, Huntsville. Fundamental benefits derive from both the imaging approach (occultation) as well as its orbit (lunar). LOCO will utilize the Lunar Occultation Technique - the temporal modulation of source fluxes as they are repeatedly occulted by the Moon - to detect and image both point and extended sources (Fig. 8). Occultation imaging eliminates the need for complex, position sensitive detectors. Instead, LOCO will incorporate a large-area (~4-5 m^2) scintillator-based spectrometer array to achieve the required flux sensitivity. Since intrinsic imaging capability is not required, an array of modest spectrometer modules will form this sensitive instrument.

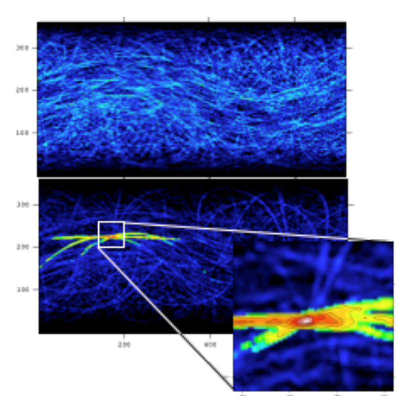

Fig. 8: Occultation image generated for baseline LOCO configuration. Shown are the lunar limb projections (top), a likelihood weighted image, and the image of a hypothetical astrophysical source at the position of the Crab Nebula (inset).

To achieve the desired spectral resolution and maximize science return, our current spectrometer design incorporates $LaBr_3$ as the detection medium. Two scintillator readout technologies are considered for LOCO: traditional photomultiplier tubes (PMTs) and silicon photomultipliers (SPMs). Silicon photomultipliers represent an attractive ***enabling***

technology and alternative to PMTs since they: can be tiled (maximizing sensitive area), eliminate the need for high-voltage distribution sub-system, reduce instrument mass and volume, and have excellent intrinsic pulse-height resolution. They are also rugged and insensitive to magnetic fields. We are currently working with a vendor to evaluate, test, and space-qualify SPMs - including a future design having a peak sensitivity @ 400 nm (appropriate for $LaBr_3$).

LaBRAT

LaBRAT (LAnthanum Bromide-based Rotating Aperture Telescope) is an engineering prototype for a balloon-borne hard X-ray/low energy gamma-ray imaging telescope being developed at Louisiana State University. It is designed to be a sensitive, wide field-of-view, high angular resolution instrument capable of observing X-ray and gamma-ray point sources and diffuse emission with ~10' angular resolution on a series of long duration balloon flights. The central detector is based on $LaBr_3$. Imaging is accomplished using a rotating modulation technique (Smith et al. 2004). A Rotational Modulator (RM) consists of a single grid of transparent and opaque slats above an array of a relatively small number of detectors (Fig. 9). As the grid rotates, the signal transmitted from a source to each individual detector is modulated between 0 and 100%. This count profile is cross-correlated with pre-calculated modulation profiles to produce an initial source image. Further processing of the image with a "cleaning" technique can accurately resolve point sources to better than the geometric resolution of the instrument (Budden et al. 2008b).

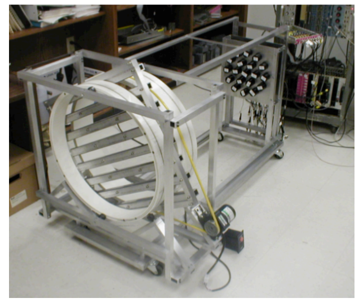

Fig. 9: Prototype LaBRAT telescope, with rotating grid at the front and 19 $LaBr_3$ detectors at the rear.

A coded aperture device achieves its good angular resolution by virtue of high position resolution on the detector plane; i.e., a coded aperture requires a relatively large number of fine-grained detector pixels and a correspondingly large number of electronics channels. An RM records event arrival times in a small number of simple, non-position-sensitive detectors, and therefore obtains its results with an extremely straightforward readout system. The fast $LaBr_3$ decay time allows for high time resolution and obviates the need for high spatial resolution. The RM's sensitivity, weight, and angular resolution are comparable to that of a coded aperture device, but the RM has significantly lower complexity, power, and cost. An array of standard 1½″ $LaBr_3$ scintillators has been used in the laboratory to demonstrate the resolution and performance of the rotating modulator (Budden et al. 2008b), including image reconstruction techniques.

Technology Development Priorities

We conclude by highlighting promising technology developments avenues that, if successful, will further enhance the value of new scintillators and readout devices for high-energy astronomy. We expect significant progress on all of these fronts in the next few years, which in turn will enable highly sensitive gamma-ray instruments for missions in the coming decade.

Development of New Scintillator Materials

While $LaBr_3$:Ce is the most advanced, several other recently developed scintillator materials that are attractive for gamma-ray astronomy are in earlier stages of development and/or suffer more significant drawbacks. Radiation Monitoring Devices, Inc. (RMD) is researching novel organic and inorganic scintillators for gamma-ray spectroscopy, PET instrumentation, thermal and fast neutron detection, homeland security applications and nuclear non-proliferation.

LSO (Melcher & Schweitzer 1992) is very dense (7.4 g cm^{-3}) and fast (~40 ns), but its energy resolution is similar to NaI and it suffers from a large intrinsic internal background due to radioactive ^{176}Lu. LuI_3:Ce (Shah et al. 2004b) has higher stopping power than $LaBr_3$ and potentially even higher light output, but is difficult to grow and also has high internal background. $SrI_2:Eu^{2+}$ has similar stopping power to $LaBr_3$ and, possibly, even higher light output, but it is very slow (1.1 µs); $SrI_2:Ce^{3+}/Na^+$, on the other hand, is fast (25 ns), but currently of poor optical quality (Wilson et al. 2008). An exciting discovery would be a "red" scintillator well-matched to the sensitive spectral range of SDDs and (30 V) SiPMs; $LaBr_3:Pr^{3+}$ has scintillation emission from 500 – 700 nm and very high light output, but is very slow (~10 µs; Glodo et al. 2005).

$CeBr_3$ (Shah et al. 2005) is perhaps the most promising material of all, with physical properties similar to $LaBr_3$, but potentially even faster (~17 ns) and with negligible internal background. $CeBr_3$ appears to have intrinsically higher light yield than $LaBr_3$ (68 vs. 63 photons keV^{-1}); the best energy resolution achieved to date is ~3.5% at 662 keV. It may also be less expensive to fabricate than $LaBr_3$.

These and other materials, including $LaBr_3$:Ce, all require further development, including dopants and growth methods, in order to increase yields, improve optical quality, and bring down cost.

Nanocomposite Scintillators

Single-crystal $LaBr_3$ detectors remain expensive (~\$300 cm^{-3}), and the yields of other materials suffer from difficult crystal growth processes. Los Alamos National Laboratory (LANL) is involved in pioneering research into new gamma-ray detectors that should be capable of energy and timing resolution that approach $LaBr_3$, but at a cost similar to non-spectroscopic detectors like plastic.

Recently, the well-known concept of nanocomposite materials has been extended to scintillators, in which nanoparticles of inorganic scintillators are embedded in a transparent organic polymer matrix (McKigney et al. 2007a). To produce a functional material, the size of the inorganic particles must be small enough that the optical transmission properties of the polymer matrix are not affected by the refractive index mismatch of the particles and the polymer. This has been demonstrated with LaF_3:Ce nanocomposites (McKigney et al. 2007b). The key to making an optical material with long attenuation length is to produce a nanocomposite comprised of inorganic scintillator particles with diameters of 1 to 5 nm.

In initial work, a photopeak with 16.5% (FWHM) energy resolution at 662 keV using a CeF_3 nanocomposite was achieved. This performance is comparable to that expected from a single crystal of CeF_3. LANL has also recently synthesized particles of $LaBr_3$:Ce with particle diameters less then 5 nm. Such particles, dispersed at high mass-loading in a polymer matrix, will result in a scintillating material with near-ideal optical properties. Such materials promise the performance of crystalline $LaBr_3$ at a fraction of the cost.

Readout Devices

The ability to fabricate SiPMs using a commercial CMOS process provides a great leap in technology and makes possible many potential advantages for astronomy and space applications. The potential for a reduced mass and cost per channel is especially enhanced when the effects of integrated electronics are considered. With a typical PMT readout, a high voltage supply, preamplifier, shaping amplifier, and digitizer are required for each channel. Utilizing a commercial CMOS environment allows the electronics to be integrated right on the chip with the sensor elements. The potential for on-chip integrated electronics for pulse-shape processing, temperature compensation, and other functions allows drastic reductions in cost, complexity and mass of supporting electronics. An example integrated processing solution is shown in Fig. 10. The integrated detector chip in the photograph includes pixel-level signal processing that converts the pixel pulse to a logic level, and then a pulse height sorter that provides a seven-bin energy resolution.

Unlike vacuum technology, the cost per device is drastically lowered in bulk quantities. For total areas exceeding a few hundred square centimeters, the cost per square centimeter is only a few hundred dollars. The bulk cost savings is in addition to the potential gains from integrated electronics.

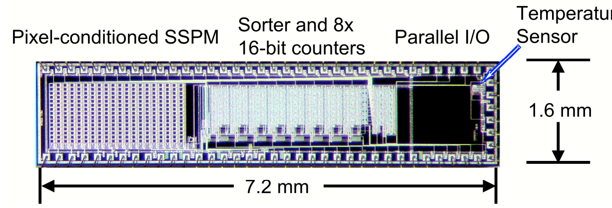

Fig. 10: Complete detector-on-a-chip: at left is a SSPM array with integrated signal processing. In the center are 8 16-bit counters that store the pulse-height sorted values of the pulses and the number of elapsed clock pulses.

Several potential future advances could make CMOS SSPM technology even more attractive. Initially the development of more application specific integrated components tailored towards particular experimental aims can provide a low cost solution with maximum data collection and throughput. Advances in spectral and geometric response on both ends of the visible spectrum are possible with increased research. Back illumination of thinned devices can possibly offer 100% fill factor and be able to steer charges generated by shallow-penetrating blue photons before they recombine (Stapels et al. 2009). Research to develop CMOS SSPMs in even smaller photolithography processes can increase the potential density of supporting electronics and allow high fill factor CMOS imaging arrays. Studies are required for improved packaging, such as methods to connect hydroscopic crystals to the SSPM before sealing the entire unit, or even growing crystals or crystal film right on the SSPM.

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