The Physics and Status of the Gamma-ray Large Area Space Telescope

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A gamma-ray pair conversion telescope is being developed for the Gamma-ray Large Area Space Telescope mission. It is based upon silicon-strip detectors for particle tracking and a CsI calorimeter for energy measurement. The use of such modern particle detection technology will result in more than a factor of 30 improvement in sensitivity over previous missions. In this paper we describe the instrument conceptual design and explore how it will be exploited to greatly improve our ability to study astrophysical sources of high-energy gamma rays.

I. INTRODUCTION

NASA's EGRET experiment on the Compton Gamma-Ray Observatory revolutionized the field of gamma-ray astronomy [1]. It was the first instrument with the effective area and background rejection necessary to detect and observe a large number of galactic and extragalactic gamma-ray sources. Such sources have an inherent interest to astrophysicists and particle physicists studying high-energy, nonthermal processes, and telescopes capable of studying emission of the highest energy gamma rays play an important role in completing the broad, multi-wavelength-band coverage that is crucial to progress in modern astrophysics. The success of EGRET and the questions raised by its discoveries demand a follow-on mission with greatly expanded capabilities. The GLAST mission is designed to improve upon the sensitivity of EGRET by a factor of 30 at 100 MeV and by even more at higher energies, including the largely unexplored 30–300 GeV band.

II. GLAST INSTRUMENT DESIGN

GLAST, like its predecessors, is a gamma-ray pair-conversion telescope. The overall instrument concept is illustrated in Fig. 1.[1] It is segmented into 25 nearly identical tower modules. Each tower contains 16 x,y pairs of silicon-strip tracking planes. Immediately above each of the first 14 x,y detector planes is a thin (0.035 radiation length) lead converter foil. Following the tracker is a finely segmented 10-radiation-length-thick CsI crystal calorimeter. Photons convert in the tracker, and their incident direction is measured by tracking the resulting electron-positron pair. The energy is then measured in the calorimeter. A third essential detector system is the set of plastic scintillator anti-coincidence counters surrounding the sides and top of the tracker. They serve as the first line of defense against background from charged cosmic rays.

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[1] A competing instrument concept based on scintillating fiber technology for both the tracker and calorimeter is being developed by a separate collaboration and is not discussed here. See the Fiber-GLAST project at http://www.batse.msfc.nasa.gov/instruments/sifter.

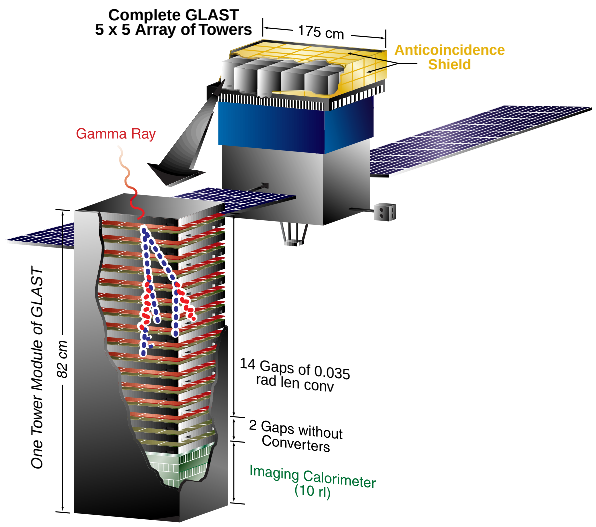

FIG. 1. The GLAST instrument design. The instrument is drawn on the top of a representative spacecraft, together with an expanded view of a single tower module.

GLAST is designed to improve upon EGRET's point-source sensitivity in at least four significant ways:

1. The effective area is increased by improving both the geometric area and the detection efficiency. The prediction for the baseline GLAST design is shown in Fig. 2c and compared with the EGRET effective area. Note the especially large improvement at high energy, where the EGRET gamma-ray efficiency suffers from self-veto. The GLAST trigger is being carefully designed to avoid such an effect.

2. The angular resolution is improved at all energies. At low energies the resolution is unavoidably dominated by multiple scattering of the electron and positron, primarily in the converter material itself. That effect can be minimized, however, by minimizing the lever arm between the scattering and the position measurement. To do so requires that the position-sensitive detectors be thin and located as close as possible to the converter foils. It is equally important that the detectors be highly efficient, for if the first point on the tracks is missed, then the resolution of low and intermediate energy photons is degraded by about a factor of two. Silicon-strip detectors fit those requirements very well. They are thin and nearly 100% efficient within their active area. Cracks between detectors reduce the overall efficiency, but their effect on the resolution can be largely avoided by placing the converter foils only over the active area and by rejecting photons that convert in other material in the crack regions. The predicted GLAST angular resolution, or point-spread-function (PSF), is shown in Fig. 2a and compared with what EGRET has achieved. Note that even at low energy the EGRET resolution deviates strongly from the $1/E$ dependence expected from multiple scattering, indicating an appreciable contribution from the inherent resolution of the spark chambers. GLAST is designed such that the inherent resolution of the detectors themselves does not contribute significantly until the photon energy is above about 1 GeV. There are important scientific reasons for designing the instrument to perform optimally at such high energies, as discussed below. This requirement dictates the pitch of the detectors (200 μm) relative to the spacing between detection planes (3 cm) and is easily satisfied by silicon-strip technology.

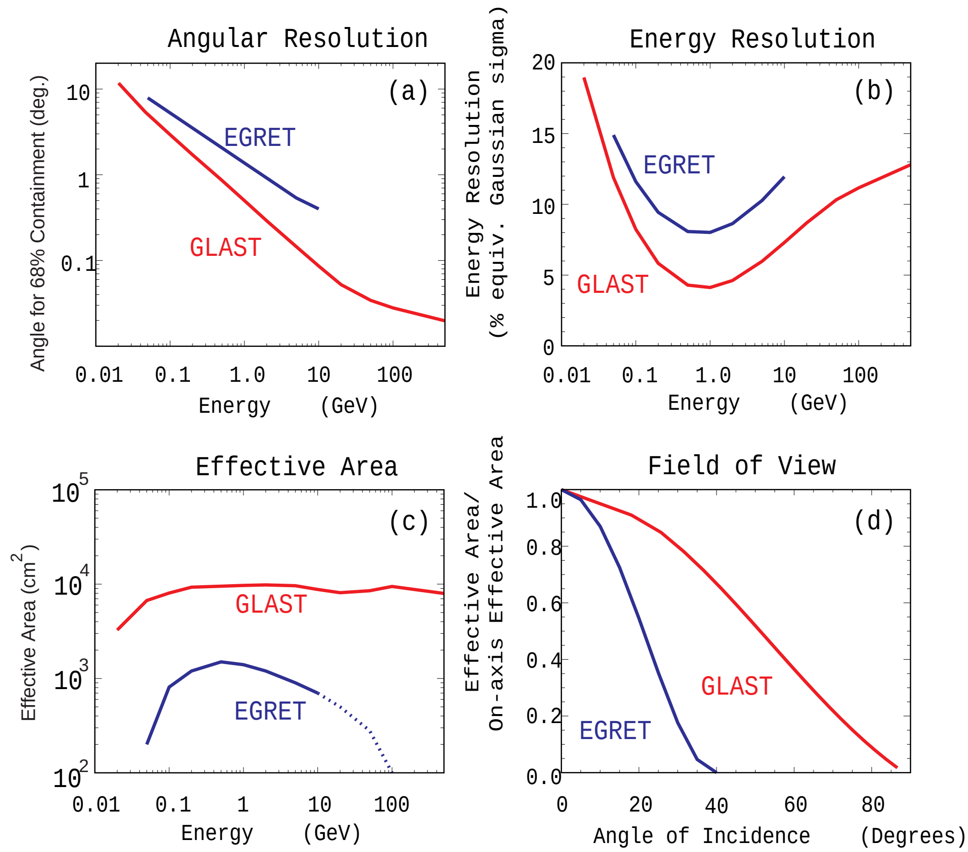

FIG. 2. Performance predictions for the GLAST instrument design, as obtained from detailed Monte Carlo simulations. The GLAST predictions are compared with corresponding plots for the existing EGRET instrument.

3. The field of view is greatly increased, as shown in Fig. 2d. The GLAST instrument is designed to be broad and thin in order to give it as large a peripheral vision as possible. With some sensitivity over nearly all of 2π steradians, the spacecraft can be operated in a scanning mode, always pointing away from Earth with a slow rocking motion toward the poles of the orbit. In that way, the view is never occluded by Earth, and the entire sky is visible every orbit. The result is maximum, uniform exposure for all objects in the sky and a continuous sensitivity to temporal fluctuations in the gamma-ray flux from all sources. The EGRET trigger relies upon time-of-flight counters for background rejection. That results in a long aspect ratio and narrow field of view, however, and is not appropriate for the GLAST design. Therefore, the GLAST tracker must be capable of self triggering. To avoid an excessively complex tracker trigger requires a detector system that is not only highly efficiency but also has very low noise occupancy. Again, silicon-strip detectors fit those requirements well.

4. The background rejection capability is improved over the already-powerful EGRET capability. The anti-coincidence scintillator detectors are segmented to allow them to be used effectively with minimal self veto. The fine segmentation of the silicon-strip detectors allows nearly all cosmic ray events to be recognizable as such, no matter from which direction they enter the apparatus. The fine segmentation of the CsI calorimeter similarly allows stringent requirements to be placed upon the shower profile and on matching between calorimeter and tracker, which are powerful in rejecting cosmic-ray events. Detailed simulations of millions of cosmic ray

events have demonstrated that the GLAST design should achieve a signal-to-noise ratio of better than 20-to-1 even for the extragalactic diffuse gamma-ray signal.

The GLAST instrument design offers several improvements over previous missions in other respects, as well. For example, the EGRET spark chambers have a large dead time, which can easily be improved upon by the use of modern detectors and electronics—the GLAST dead time will be under 20 μs per trigger. The energy resolution can also be improved by taking advantage of extensive recent experience in particle-physics experiments that employ large arrays of CsI crystal detectors, as shown in Fig. 2b. The EGRET calorimeter is monolithic, but much can be gained by finely segmenting the calorimeter: for example, better triggering and background rejection and the ability to correct for shower leakage at high energy. In addition, in the GLAST design, by orienting the long crystals horizontally and reading them out from both ends, we gain the ability to measure the direction of high-energy photons that fail to convert within the tracker (although with about 10 times worse resolution compared with tracker conversions).

Division of the instrument into tower modules is necessary for instrumentation of the silicon-strip detectors and CsI crystals, but it also offers some important advantages. In the R&D phase, it is possible to construct complete prototype modules to verify the design in nearly all aspects before committing to production of the full instrument. The modules are all identical, so they can be produced and tested in an assembly-line fashion, facilitating construction and integration of the overall instrument. Finally, the modules offer redundancy, since each module contains a complete data acquisition system. If one or more modules break, the others will be able to continue to collect data.

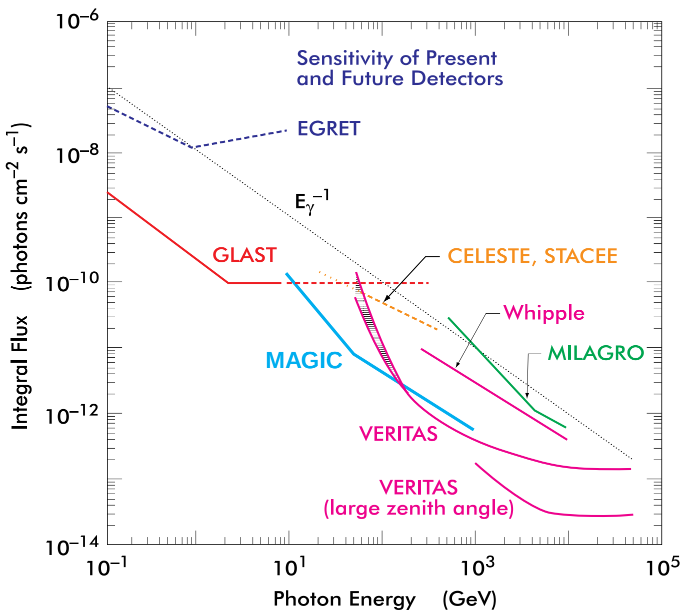

FIG. 3. Sensitivity to gamma-ray sources as a function of energy, comparing several existing and planned experiments, both terrestrial and space-based. The GLAST and MAGIC sensitivities are added to the figure from Ref. [2].

TABLE I. Performance characteristics of the GLAST instrument design.

Energy Range	20 MeV to 300 GeV
Energy Resolution	$<$ 10% above 100 MeV
Effective Area	$>$ 8000 cm^2 above 1 GeV
Field of View	2.6 steradian FWHM
5σ source sensitivity (1 yr)	3.5×10^{-9} ph/cm^2/s ($>$ 100 MeV)

In addition to the graphs shown in Fig. 2, some characteristics of the GLAST instrument design are listed in Table I. Figure 3 shows how the GLAST projected sensitivity compares with EGRET and a number of existing and planned ground based experiments. Since the spectrum of a typical gamma-ray source falls roughly as $1/E^2$, the number of photons above a given energy typically falls as $1/E$. By that measure, it is evident from the figure that the EGRET sensitivity matches fairly well the existing ground-based experiments, but an instrument like GLAST will be necessary in order to complement effectively the next generation of ground-based Cerenkov telescopes, such as the Veritas observatory. In fact, it is anticipated that a very important component of the GLAST science effort will involve close collaboration with ground-based gamma-ray telescopes in order to maximize the spectral coverage at very high energies.

III. GLAST SCIENCE TOPICS

The scientific program of GLAST will follow closely along the lines of those subjects studied by EGRET. The large increase in sensitivity of GLAST with respect to EGRET raises the distinct possibility of discoveries of new phenomena and new types of gamma-ray sources. While that is characteristic of all previous high-energy gamma-ray missions and is the most exciting aspect of the GLAST mission, the discussion here is necessarily restricted to the scientific topics that are already familiar from previous studies.

The most recent catalog of EGRET point sources is Ref. [3]. Of 271 sources, 170 are as yet unidentified. Those that are identified with known objects fall into only a few classes, most notably active galactic nuclei (AGN) at high galactic latitudes and pulsars within the plane of the galaxy.

The AGN observed by EGRET are blazars, thought to be powered by accretion of material into supermassive black holes located in the centers of galaxies, with jets of relativistic particles directed approximately along our line of sight. Such blazars are highly variable gamma-ray sources, and their energy output is often dominated by gamma-ray emmission [4]. Therefore, to understand these objects and the associated physics under extreme conditions, it is crucial to detect the gamma rays. Furthermore, they must be monitored over long periods in order to observe and understand their flaring behavior. GLAST, operating in a scanning mode, will have nearly every source within its large field of view on every orbit and will be capable of detecting a bright flare in a single 90 minute orbit.

AGN are also interesting as distant sources of gamma rays that can be used as cosmological probes. Observations of cutoffs in the spectra of gamma-rays from many distant sources at various red shifts can be used to infer the amount of extragalactic background light, as illustrated in Fig. 4. Cutoffs in the TeV range are particularly sensitive to infrared light produced in the era of galaxy formation. With the exception of the most distant sources, the cutoffs will be beyond the energy range of GLAST, but data from GLAST will be important when combined with those from the ground-based detectors, in order to fill in the lower energy part of the spectrum. Data from those sources with cutoffs within the range of GLAST will be sensitive to the "initial stellar mass function" (IMF) and can thus provide information about star formation in the early galaxies [5].

An extrapolation based on EGRET results predicts that during four years of operation GLAST will detect about 5000 AGN, nearly a factor of 100 increase over the present sample. If distributed uniformly over the sky, there would be only about a 3° separation between adjacent sources. Allowing for galaxy clustering and random clumping, it is evident that source confusion will be an issue even far from the galactic plane. Because of multiple scattering, the angular resolution of GLAST is only slightly better than 3° at 100 MeV, the energy typically used as a cutoff for EGRET maps. Evidently GLAST will often be source confused at that energy—photons in the GeV energy range will be needed to resolve many of the sources, both galactic and extragalactic.

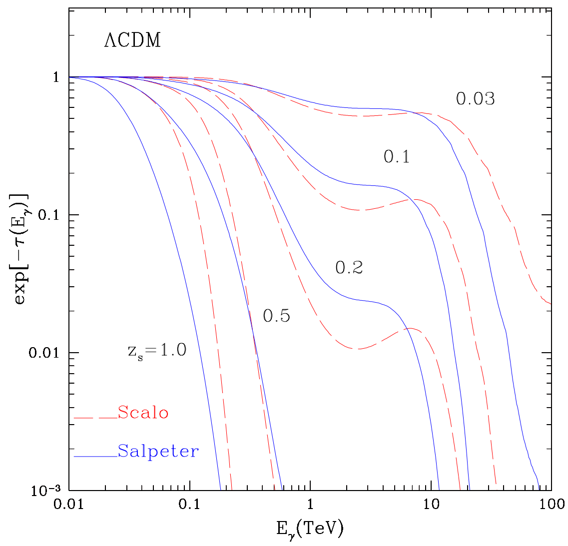

FIG. 4. The gamma-ray attenuation factor for ΛCDM models, for two different models of the initial stellar mass function [5].

In a pair conversion telescope, the multiple scattering contribution to the error falls as $1/E$, while the number of photons above a given energy E from a typical source also falls as $1/E$. Since our ability to distinguish a point source above background goes roughly as the gamma-ray flux divided by the square of the error in the space angle, we can expect that the high energy photons will be more important for detecting and localizing sources than the more abundant low energy ones. Indeed, a detailed maximum-likelihood analysis using simulated GLAST data shows that most of the power for source detection will come from photons in the 1 GeV energy range. Thus source detection, localization, and multiple-source resolution all underline the importance of optimizing the GLAST design to make the most of the much better resolution possible at GeV energies than near threshold. The silicon-strip detector pitch of 200 μm has been chosen with that in mind.

An important class of galactic point sources is pulsars. From EGRET observations we have good phase and spectral information on 7 pulsars. Of those, one has no radio or optical counterpart (Geminga). GLAST, with its factor of 20 improvement in sensitivity for sources in the galactic plane, is estimated to be capable of detecting about 300 pulsars at distances of up to 15 kpc, of which about 100 are expected to have phase and period information from radio detections. Another 10 could probably be analyzed for phase and period directly from the gamma-ray data. A few may be well-aged millisecond pulsars. All together, we expect to end up with a sample of the order of 30 pulsars with gamma-ray phase and spectral information of sufficient quality to be useful for constraining astrophysics models. It is remarkable that for many of the young and middle-aged pulsars, their energy output is dominated by gamma-ray emission. Clearly gamma-ray data will be crucial for understanding them. Models based on the EGRET sample of pulsars already make specific predictions that will be put to crucial tests using the large amount of data which GLAST's greater sensitivity will offer [6].

EGRET has seen gamma rays from a handful of gamma-ray bursts, including the highest energy photons ever observed from bursts [7]. Recent breakthroughs in finding optical counterparts for bursts and measuring their red shifts have greatly clarified our information on the locations of the bursts and their energy output [8]. The focus of efforts in this field is now on understanding the emission mechanisms, a task which will likely require full coverage of the energy spectrum. As part of a flotilla of missions being planned to study bursts, GLAST will play the unique role of measuring their high energy tail. In addition to increasing greatly the statistics on high-energy bursts, GLAST will also improve upon the EGRET observations by avoiding loss of data due to instrument dead time. GLAST should be able to measure nearly all high-energy photons within the most intense parts of bursts, which typically have a pulse width that is comparable to the EGRET 100 ms deadtime. With its wide field of view, GLAST will also serve as a powerful burst monitor, detecting from 100 to 300 bursts per year and acting as a real-time trigger for follow-up by other instruments. Simulations indicate that about a third of those bursts will be localized to better than 10 arc minutes, and the brightest few will be localized to 1 arc minute.

Supernova remnants have long been postulated to be the sites of acceleration of galactic cosmic rays. If supernova remnants do accelerate cosmic rays, then the interaction of the high-energy particles with the gas should be a source of gamma rays. Some EGRET gamma-ray sources appear to be associated with supernova remnants, but the identifications remain uncertain [9]. GLAST is expected to have sufficient sensitivity to detect gamma rays produced during cosmic-ray acceleration and will even be able to spatially resolve some supernova remnants. Hopefully this will provide the first clear evidence for cosmic ray acceleration in supernova remnants.

Over half of the point sources seen by EGRET remain unidentified. GLAST will offer several improvements. The GLAST error boxes generally will be much smaller, greatly facilitating the search for optical, radio, or x-ray counterparts. The GLAST photon statistics for the EGRET unidentified sources will be much greater, allowing detailed timing studies to be completed, for comparison with candidate counterparts. Many of the sources are undoubtedly members of existing classes, such as radio quiet pulsars and unrecognized blazars, but it is likely that many sources that will be identified with the help of GLAST data will represent entirely new classes of gamma-ray sources. The likelihood of such discoveries is one of the most exciting aspects of the GLAST science program.

IV. GLAST TECHNICAL STATUS

The GLAST instrument development program is currently in an R&D and prototyping stage. The NASA ATD program and the D.O.E. SLAC laboratory are supporting the construction of a full-scale engineering prototype tower, which will be tested in electron and gamma-ray beams near the end of 1999. Smaller prototype assemblies representing each of the three detector subsystems (tracker, calorimeter, and anticoincidence system) were successfully tested in beams at SLAC in October of 1997. The results may be found in Ref. [10].

One important objective of the technology development program has been to demonstrate that readout electronics for the megachannel silicon strip tracker could be made which satisfy the stringent requirements imposed by a space-based experiment. Excellent progress has been made in that regard. Early prototypes performed well during the 1997 beam test, with the amplifiers and discriminators using only $140\,\mu$W of power per channel. The current prototype system, based upon two CMOS ASIC designs, achieves the needed signal-to-noise performance, as well as all data acquisition and redundancy requirements, with a per-channel power consumption of under $210\,\mu$W, including both digital and analog functions.

ASIC design has also been a central part of the calorimeter technology development. In this case, the main challenges arise from the need for a very large dynamic range, together with good energy resolution. A prototype front-end readout chip has already been tested and is to be used in the engineering prototype tower. In the 1997 beam test, much of the focus was on proving a novel concept for imaging the electromagnetic showers by reading horizontal stacked CsI crystals from both ends. In this way, GLAST will be able to measure the direction, with reduced accuracy, of high-energy photons that fail to convert in the tracker.

Much effort has also gone into engineering the light-weight structure necessary for supporting the silicon-strip detectors and electronics during the rocket launch. Perhaps even more challenging has been the engineering required for the calorimeter support structure, due to the large weight and poor mechanical properties of the CsI crystals. Thermal design has also been of critical importance, due to the large amount of electronics interspersed throughout the detector. A detailed design of the complete tower module now exists, and construction is in progress.

A sophisticated distributed data acquisition system has also been designed for GLAST, and a slightly simplified prototype is being built for the engineering prototype tower. A VME based prototype readout module has already been tested together with the tracker readout electronics. Thus the full-scale tower now under construction will include fully integrated prototypes of all four GLAST instrument subsystems: the silicon-strip tracker, the CsI calorimeter, the anti-coincidence system, and the data acquisition system.

V. CONCLUSIONS

NASA will release an Announcement of Opportunity for the GLAST instrument in the spring of 1999, with proposals due in September. Final selection is expected to be finished by the start of 2000, at which point Phase A of the mission will begin. The instrument design presented here, which utilizes a silicon-strip tracker and a CsI calorimeter, is ideally suited for the GLAST mission. It is being developed and proposed by a strong international collaboration with significant support from the Department of Energy and foreign agencies, as well as from NASA. The technology is robust and mature, with a rich heritage in particle physics and space science. Furthermore, the collaboration has demonstrated through prototyping and beam tests that the technology can exceed the instrument requirements and through extensive, detailed simulations that the instrument concept is well optimized and can exceed the mission requirements. Use of this modern technology will allow us to fly an instrument capable of improving by well more than an order of magnitude upon all previous high-energy gamma-ray missions. That not only will lead to great advances in the field of high-energy astrophysics, but also holds significant promise of exciting discoveries.

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