Spaced Based Gamma Ray Detection

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Gamma rays are high energy photons which are produced in a variety of astronomical phenomena. Optical techniques can not be used to detect gamma rays, since they are so energetic that they pass right through conventional optical instruments. Furthermore, the atmosphere is opaque to a large part of the gamma ray spectrum, requiring the use of space based platforms. Several methods for the detection of gamma rays are summarized and a few examples of recent and current space based gamma ray telescopes are presented.

I. INTRODUCTION

Gamma rays are photons from the high energy region of the electromagnetic spectrum. Their energy ($\gtrsim$ 100keV) and associated wavelength ($\lesssim 10^{-11}$m), make their detection process exceptionally challenging. Because they are absorbed by the earth's atmosphere, detectors must be placed on balloons or spacecraft (ground based detection is possible, however in a limited energy range only). Furthermore, gamma rays can not be deflected by mirrors and lenses like ordinary light, since they pass right through such optical devices. Because of the large energy associated with each photon, the total number of photons produced in a gamma-ray event is small. Such a weak signal is further obscured by cosmic ray contamination.

Despite the inherent difficulties in detecting gamma rays, they are of great scientific value. Gamma ray detection can enable us to probe nuclear transitions or matter-antimatter annihilation processes. Super massive black holes, pulsars, active galaxies, merging neutron stars and hypernovae are just some of the gamma ray sources in the universe. Several detected gamma ray bursts (GRBs) remain of unknown origin, and constitute an active field of investigation.

II. GAMMA RAY DETECTION TECHNIQUES

In addition to ground based detection involving Cherenkov radiation, there are four leading methods for detecting gamma rays from space: Scintillator-based detectors, solid state detectors, Compton scattering detectors and pair production detectors. A summary of the methods used in some recent and current gamma ray telescopes can be found in table I.

Table I: The most prominent recent and current space based gamma ray telescopes.

Telescope/ Platform	Energy Range	Detection Method	Years of Operation
CGRO			
BATSE	200 – 600keV	scintillator	1991-2000
OSSE	50keV – 10MeV	scintillator	1991-2000
CompTel	750keV – 30MeV	Compton	1991-2000
EGRET	20MeV – 30GeV	pair production	1991-2000
INTEGRAL	20keV – 8MeV	sold state	2002-
Swift	15 – 150keV	solid state	2004-
Agile			
Super-AGILE	10 – 40keV	solid state	2007-
GRID	30MeV – 60GeV	pair production	2007-
Fermi			
LAT	30MeV – 300GeV	pair production	2008-
GBM	15keV – 30MeV	scintillator	2008-

A. Scintillator Detectors

A scintillator is a material the emits low energy photons when struck by a high energy charged particle. Scintillators are usually made of non-organic materials like NaI or CsI, together with an impurity (called an "activator") such as Tl or Na. Although a gamma ray is not charged, it can produce charged particles in the scintillator when it interacts with it (via Compton scattering, photo-absorption or pair production). These charged particles cause the scintillator to emit low energy photons, which are then detected using photomultiplier tubes (PMTs).

The energy of the charged particles can be deduced from the PMT readings and thus the energy of the incoming gamma-ray can be found. However, the direction of the incoming gamma-ray can not be determined, and thus such detectors do not have imaging capabilities. Several methods exist to overcome this problem, the most notable of which is the use of a coded mask.

A coded mask is a plate of opaque areas and holes which is positioned at the opening of the telescope (fig. 1). By measuring the shadow that is cast on the detector, the direction of the incoming gamma rays can be determined. If there is more than one source, different shadows of the mask overlap. The detected pattern of light and shadows is then analyzed in order to assess the observed

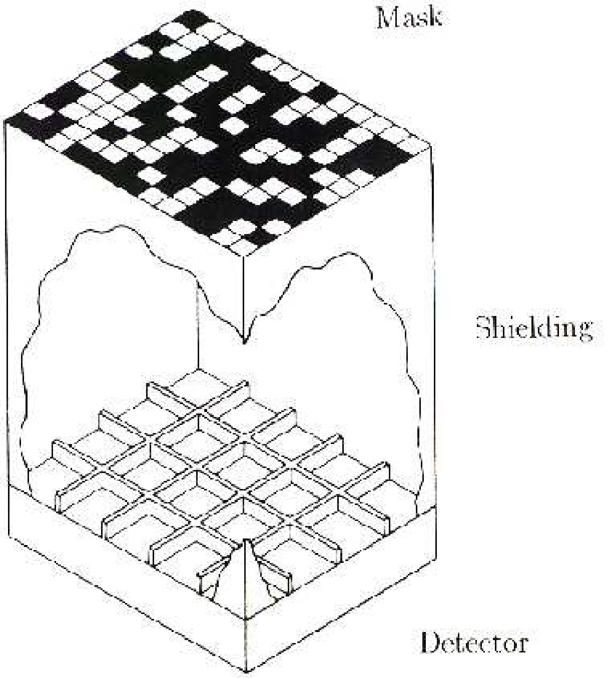

Figure 1: A schematic view of a coded mask placed above a detector. The shadow cast on the detector can be used to deduce the direction of an incoming gamma ray.

image of the sky, in a procedure called image deconvolution. Such methods have the disadvantage of blocking some of the incoming photons, and they usually require the use of sophisticated software and data processing. Nevertheless they are being used, for example, on board the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and on Swift (a NASA mission dedicated to detecting GRBs), achieving angular resutions of a few arcminutes.

An alternate way of determining the direction of the incoming gamma rays was used in the Burst and Transient Source Experiment (BATSE) launched on board the Compton Gamma Ray Observatory (CGRO) in 1991. The idea behind the estimation of the arrival direction is as follows: If the arrival direction is normal to the detector, then the collecting are is large, and many gamma rays are absorbed. If the arrival direction is slanted, at an angle removed from the detector normal, then the projected area of the detector is less, and fewer gamma rays are absorbed. Comparing the number of absorbed gamma rays from several detectors located on the eight corners of the spacecraft, a rough estimate of the arrival direction (often within several degrees) could be achieved.

B. Solid State Detectors

When a gamma ray encounters a semiconductor such as Ge or CdZnTd it can knock out an electron, leaving an electron-hole pair in the semiconductor. By applying a voltage, a current will be produced and can be measured. The current intensity is an indication of the incoming gamma ray energy. Imaging can be performed by the use of a coded mask as described above.

Solid state detectors offer better energy resolution, less noise, and better spatial resolution than the standard scintillators. However, such materials are more expensive and require greater care. They are thus quite limited in size, reducing the collecting area of the telescope (since no focusing elements can be used for gamma rays, the collecting area of the telescope is the same as the area of the detector).

A Ge based detector is installed on board INTEGRAL and a CdZnTd is being used aboard Swift.

C. Compton Scattering Detectors

For energy ranges where Compton scattering is the dominant physical process ($1-30$MeV), the use of multiple scintillators can produce imaging telescopes without the need for coded masks. A gamma ray which undergoes Compton scattering in a first scintillator, is later absorbed by a second scintillator. By measuring the light produced in both scintillators, the total energy of the incoming gamma ray can be deduced. As for the direction, using the Compton scattering formula:

$$\Delta\lambda = \frac{h}{m_e c}\left(1-\cos\theta\right)$$

together with the energy of absorption in both scintillators, the scattering angle θ can be found. From this, and the location of absorption in the each scintillator, the angle of the incoming gamma ray can be calculated. However, the azimuthal direction can not be determined, giving a ring of possible incoming directions. By comparing several such rings, a source location can be estimated.

Such a mechanism was implemented on the Imaging Compton Telescope (COMPTEL) on board the CGRO (fig. 2), which measured direction accuracies of 1° and energies up to an error of 5%.

D. Pair Production Detectors

For photons with energies above 30MeV the dominant process is pair production, whereby the photon is converted into an electron and a positron. This process can

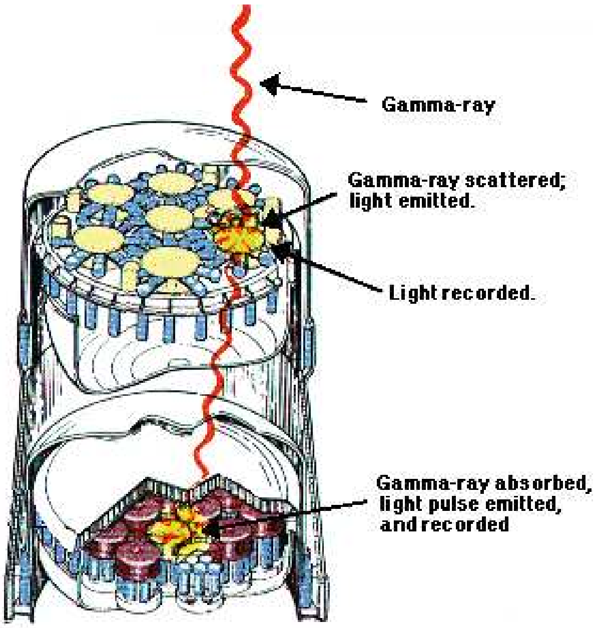

Figure 2: The COMPTEL apparatus. Combining Compton scattering in the first scintillator and complete absorption in the second, the energy and direction of an incoming gamma ray can be determined.

not happen in vacuum, since it would violate energy-momentum conservation, however, if a sufficiently energetic gamma ray encounters a high-Z material, which has a large cross section for pair production, it will produce an electron positron pair. Since the electron mass is approximately 0.5MeV, the electron and positron produced will have large kinetic energy. If they are directed into a gas chamber, they will leave an ionization path in their wake. By crisscrossing the gas chamber with wires, a voltage can be applied, creating sparks along the ionized paths. The paths can then be used to deduce the direction of the incoming gamma ray. The electron and positron are later absorbed, and their energy is registered, allowing the gamma ray energy to be found as well. Such a spark chamber was put to use in the Energetic Gamma-Ray Experiment Telescope (EGRET) which was launched aboard CGRO. It measured arrival direction accuracies of 5.5° (it should be noted that this number is highly energy dependent, with bright gamma ray sources being localized with approximately 10' accuracy) and could determined the energy to about 20%.

An alternate method for determining the paths of the electron and positron involves the use of Si solid state detector layers playing the role of the spark chamber. The Large Area Telescope (LAT) on board Fermi, as well as the Italian light imaging detector for gamma-ray astronomy (AGILE) utilize this technique, achieving approximately 1° directional accuracies and less than 10% errors in energy determination (for LAT).

III. NOISE REDUCTION

As mentioned earlier, cosmic rays are a major source of noise in gamma ray measurements. However, since cosmic rays are usually comprised of charged particles they can be separated from gamma rays using the following mechanism. The entire detection apparatus is enveloped in a scintillator material. If a cosmic ray passes through the scintillator, it will create a flash of light which can be detected using PMTs. The scintillator is arranged in a thin layer so that only charged particles interact with it, and gamma rays do not. We thus have a signal only if a cosmic ray entered the detector, which can be used to eliminate false readings in the rest of the apparatus. This is called an anti-coincidence technique.

In addition, detectors with multiple layers, like the Compton and pair production schemes, can utilize time-of-flight techniques to eliminate false readings from stray light or particles entering the detector from the opposite direction.

IV. CONCLUDING REMARKS

Because gamma rays are absorbed in the earth's atmosphere, their study had to await the availability of observing platforms in space, or near the top of the Earth's atmosphere. Thus significant work on these photons has only been possible since the 1960s, and many of the detectors and observing techniques are still under development. The quest for better angular resolution (and therefore source identification) and spectral resolution (for more information on source behavior) is a continuing activity. Gamma-ray detectors are meant to measure the same things detectors at other wavelengths measure, but the challenge of working in this difficult energy range places more demands on instrument developers than most other fields. Future detectors are beginning to use more advanced solid-state technology to overcome some of these problems and provide large, sensitive detectors which will further establish gamma-ray astronomy as an integral part of astrophysical research.

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