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Gamma astronomy from space(*)

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Summary. — In this contribution I will review the status of γ-astronomy at energies larger than ~ 30 MeV from satellites. The measurements of the instruments aboard the Compton Gamma Ray Observatory have given a tremendous boost to this field of research, with γ-rays observed from a wide range of galactic and extra-galactic sources. The missions planned for the near future will be briefly summarized.

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1. – Introduction

Four "messengers" tell us about the Universe outside the solar system: i) light (photons), ii) cosmic rays, iii) neutrinos and iv) gravity waves. Light has been historically the "cornerstone" of astrophysics, with an expansion from the optical band to new wavebands. The study of the shortest wavelength (or highest energy) has received a dramatic boost in the last decade, with the most important contribution obtained with satellite experiments, and γ-astronomy has emerged as a a mature, vital, and highly interesting field (for recent reviews see [1-4]).

High energy photons ($E_\gamma \gtrsim$ few MeV) do not penetrate deeply in the atmosphere, therefore their direct detection is only possible from space with detectors placed on satellites. This of course put serious limitations on the area, weight, and power of the detectors, and only relatively small ones are possible. This limits the measurements to energy not too high, when the γ flux is still large. At larger energies, when photons can generate a large electromagnetic showers, it is possible to have detectors at ground level, as Cherenkov telescopes or Air Shower arrays. In this contribution I will only consider detectors in space.

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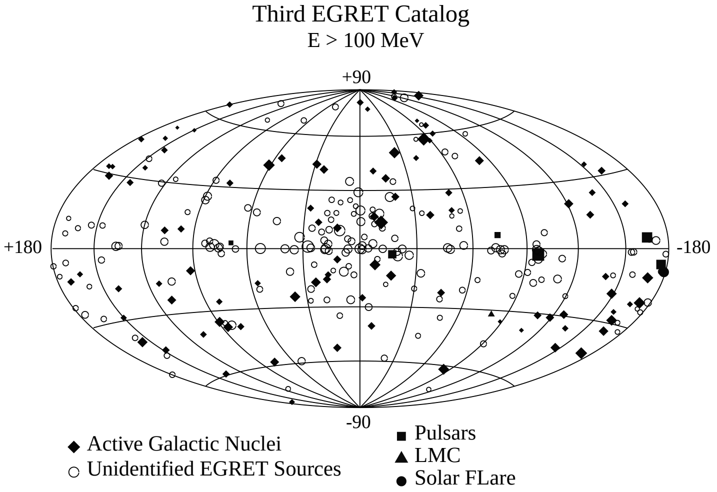

Fig. 1. – Point sources detected by EGRET at > 100 MeV (Third EGRET Catalog) [6].

2. – The results of EGRET

The most significant development in this decade has been the launch in 1991 of the *Compton Gamma Ray Observatory* (CGRO) with aboard its four instruments. The satellite remained active until June 2000 when it was deorbited.

The four instruments aboard the CGRO were: EGRET a spark chamber plus calorimeter instrument with sensitivity in the energy interval 30 MeV to 30 GeV; COMPTEL, a Compton telescope in the interval 0.1 to 30 MeV; BATSE, an omnidirectional X-ray and soft γ-ray "burst" detector consisting of large NaI scintillators sensitive to 30 keV to 2 MeV photons (with smaller spectroscopic NaI crystals for measurements up to 110 MeV); and OSSE, consisting of Nai-CsI phoswiches detecting photons of 0.1 to 10 MeV.

The highest energy detector EGRET (detecting photons in the energy range $\sim$ 30 MeV-30 GeV) has produced a wealth of astrophysical results. Prior to EGRET, two other successful satellite experiments, SAS-2 and COS-B, pioneered the field of high energy γ-rays, and were able to make some of the first maps of the γ-ray sky and produce the first γ-ray source catalogs [5].

The γ-ray sky in the 30 MeV to 30 GeV range comprises both diffuse radiation as well as point sources. The diffuse radiation constitutes the bulk of the received photons, and is found to have a Galactic component arising from cosmic-ray interactions with the local interstellar gas and radiation, as well as an almost uniformly distributed component believed to originate outside the Galaxy [7]. The average spectrum of the extragalactic diffuse emission is well-described by a single power-law with an index $-(2.10 \pm 0.03)$ in the 30 MeV to 30 GeV range. The precise origin of the extragalactic diffuse emission is not well-known, and possibly includes both diffuse origin as well as contributions from unresolved point sources, for example unresolved blazars.

The point sources detected by EGRET above 100 MeV are shown in fig. 1. Several types of sources are present as listed in table I. In addition to these sources EGRET has also detected 5 γ-ray bursts, the X-ray binary Cen X-3, and 1 solar flare.

It is interesting to note that more than 60% of the EGRET sources are unidentified, with no firmly established counterparts at other wavelengths. Some of these sources have

Table I. – *Sources in the Third EGRET (3EG) Catalog.*

Source Class	Number
Blazars	67 (94)*
Pulsars	6
Unidentified	170
Normal Galaxy	1 (LMC)
Radio Galaxy	1 (Cen A)

* 27 AGN have been marginally identified.

remained unidentified since the first surveys of the γ-ray sky with the COS-B satellite [5], and are one of the outstanding mysteries of the EGRET mission.

The majority of the sources away from the galactic plane have been identified as active galactic nuclei (AGN), essentially all of them of the "blazar" class. AGNs are currently understood as objects where the gravitational energy of material accreting on a massive black hole powers the emission of jets where plasma is emitted with relativistic speed. The blazars are those objects where one of the jets points close to the direction of the line of sight. A review on the blazars observed by EGRET may be found in [8].

Gamma-ray emission models for blazars are generally divided into two broad classes: leptonic and hadronic. A method to discriminate between the two could naturally be the detection of neutrinos.

3. – Gamma-ray bursts

One of the most exciting results in high energy astrophysics is undoubtedly the detection of γ-ray bursts (GRB). These events, first recorded by the VELA satellites in 1967, are bright transients in the γ-ray sky, with a typical duration of few seconds. More than 2500 bursts have been recorded by BATSE [9], they showed a distribution perfectly isotropic, but dishomogeneous, pointing to a cosmological distribution. Five of the BATSE bursts were also detected by EGRET [10], demonstrating that the emission extends to high energy.

The relatively poor angular resolution of BATSE of a few degrees has made the detection of GRB counterparts (*i.e.* sources at optical or radio wavelengths) difficult. The lack of counterparts has hindered efforts to pin down the distance scale of GRBs. In 1997, a major breakthrough was achieved with the first detection of optical counterparts. This work was accomplished by the Beppo/SAX [11] satellite detector in conjunction with powerful optical telescopes, both on the ground (Keck) and in space (HST). By using a combination of wide and narrow-field X-ray telescopes, Beppo/SAX can determine the positions of some bursts with an accuracy of several arc minutes. This excellent localization allowed the detection of fading optical counterparts for several dozen bursts [12]. Redshift values have been determined for approximately 15 counterparts; they indicate that the correlated bursts are cosmological in origin (typical $z \sim 1$). For reviews of the afterglow see [13]. The typical inferred energy outputs of the bursts range between 10^{51} and 10^{53} ergs (assuming isotropic emission). For one event, GRB990123, it has also been possible to obtain a contemporaneous optical detection with the telescope ROTSE-I [14] that can slew in an automated fashion upon receiving an alert from the GRB Coordinate network. At its peak brightness, the optical magnitude was 8.95 which, when combined with the measured redshift value of 1.60, meant that this burst was the most luminous object ever detected. GRB990123 was brighter than the brightest quasar by several orders of magnitude. Assuming isotropic emission, the inferred energy release of GRB990123 exceeds 10^{54} ergs.

A wide range of theoretical models have been proposed to explain gamma-ray bursts. The basic difficulty is to construct a physical mechanism that can produce and extract the intense high energy emission we observe. The general picture calls for a cataclysmic event which produces a relativistic fireball of material with Lorentz factors approaching 1000 [15]. The relativistic material escapes from the region of high energy density along a collimated jet. High energy radiation results when the jet collides with nearby ambient material. The nature of the original cataclysmic event is not fully understood. Generally favored pictures include merging of neutron stars and hypernovae ("failed supernovae" of heavy stars) [16].

All we know about GRBs has been obtained from the electromagnetic radiation they produce, but there are also speculations that they are the source of the highest energy cosmic rays [17] and that they produce a detectable neutrino flux [18]. We can expect GRB research to remain exciting for years to come.

4. – Future missions

In this section we will briefly discuss the missions of γ-astronomy that are planned for the near future.

4˙1. *INTEGRAL.* – INTEGRAL [19] is a medium-size ESA mission with contribution from Russia (the launcher) and NASA, with the launch programmed for April 22, 2002. The detector will cover the "low energy" range E_γ = 15 keV–10 MeV. The instrument will have very good energy resolution, that is needed for the detection of nuclear lines, and also very good angular resolution (12 arcminutes). The Integral payload consists of two main gamma-ray instruments the Spectrometer SPI (SPectrometer on INTEGRAL), and the Imager IBIS (Imager on Board the Integral Satellite). Each of them has both spectral and angular resolution, but they are differently optimised in order to complement each other and to achieve overall excellent performance. These instruments are supported by two monitor instruments which will provide complementary observations at X-ray and optical energy bands: The X-ray monitor JEM-X, will detect X-rays in the energy range E_γ = 3 keV–35 keV, while the Optical Monitoring Camera OMC will detect photons in the V band around 550 nm. The three main instruments of INTEGRAL (Spectrometer, Imager and X-ray detectors) share a common principle of operation: they are all coded-mask telescopes. The spectrometer will use an array of 19 hexagonal high-purity germanium detectors cooled to 85 K, and a hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view = 16 degrees) with a relatively modest angular resolution of 2 degrees and an angular resolution of 2.2 keV (FWHM) at 1.33 MeV.

The Imager IBIS is optimized for angular resolution. This in a coded mask telescope is limited by the spatial resolution of the detector array (since diffraction is negligible at gamma-ray wavelengths).

4˙2. *HETE-2.* – The High Energy Transient Explorer [20] is a small scientific satellite designed to detect and localize gamma-ray bursts. The detector was launched from a Pegasus rocket in November of 2000. The coordinates of GRBs detected by HETE will be distributed to interested ground-based observers within seconds of burst detection, allowing detailed observations of the initial phases of GRBs. The "2" in the name of the mission is a remainder of the sad story of the HETE-1 satellite that was launched on November 4, 1996. The rocket failed to release the satellite, that died for lack of solar power within a day. HETE-2 is the successor quickly built with spare hardware from the first satellite. The instruments of HETE will be: one gamma-ray detector (0.5–400 keV) and two X-ray detectors 2–25 keV and 0.5–10 keV (coded-aperture imagers). The expected angular resolution will be ~ 10 arc-minutes for a "typical" burst, and as low as 10 arc-seconds for the most powerful ones; the solid angle covered ~ 1.5–2 str.

Sophisticated on-board processing software will allow the location to be calculated on board in real time, and ground post-burst analyses will provide refined localization. In addition to the study of GRBs, the HETE instruments will conduct a survey of the X-ray sky, and study X-ray transients (sensitivity of few milliCrab in a day's observation).

On orbit, the HETE spacecraft will always point in the anti-solar direction for optimal exposure of the solar panels to the Sun. As a result, the HETE instruments monitor a ~ 2 steradian field centered roughly on the ecliptic. During the course of a year, HETE will survey a region of the sky along the ecliptic which covers about 60% of the celestial sphere. Because of the anti-solar orientation of HETE, ground observers will always know approximately where HETE is observing. In addition, all bursts detected by HETE will be at least 120 degrees from the Sun and, therefore, in prime position for observations by ground-based optical observers. The scientific instruments operate during orbit twilight and night, when the Earth is not blocking their view.

When a GRB is detected by HETE, a summary of the collected burst data is sent to a series of listen-only ground stations distributed around the equator. These data are forwarded to MIT, where they are distributed to ground observers via the GRB Coordinates Network (GCN). Subscribers to GCN or visitors to the GCN web site can receive notification of HETE GRB coordinates within seconds of burst onset.

4˙3. *SWIFT*. – Swift [21] will be the next satellite dedicated to the study of GRB's after HETE-2, with a launch programmed for 2003. Three instruments will be on board: i) a γ-ray camera, ii) an X-ray telescope, iii) an UV and optical telescope.

The strategy of the SWIFT mission will be unique. After the detection of a burst with the γ-ray cameras, that will be approximately 5 times more sensitive than BATSE and have an angular resolution of $\sim$ few arc-minutes, Swift will have the unique ability to rotate in orbit and repoint its gamma X-ray telescope, and ultraviolet/optical telescope at the GRB with a delay of only 20–70 seconds. The combination of a smaller field of view and a better sensitivity should result (depending on the extrapolation of the $\log N$-$\log S$ curve) to an event rate of order 1/day. If an X-ray afterglow is observed (and this should happen for around 1/3 of the events, that is for ~ 100 burst/year), the X-ray telescope should be able to give a new position with a resolution ~ 2.5 arc-seconds (sharp core of $1''$) within ~ 10 seconds, allowing the ground-based instruments to start the study.

4˙4. *AGILE*. – The AGILE γ-ray astronomy satellite [22] has been selected as the first Small Scientific Mission of the Italian Space Agency. With a launch in 2003, AGILE will provide an important new tool for high-energy astrophysics in the 30 MeV–50 GeV range before GLAST. Despite the much smaller weight and dimensions, the scientific performances of AGILE are comparable to those of EGRET. The AGILE scientific payload is based on the state-of-the-art and reliably developed technology of solid-state silicon detectors. The instrument is very light (~ 60 kg) and effective in detecting and monitoring gamma-ray sources (30 MeV–50 GeV) within a large field of view. The instrument

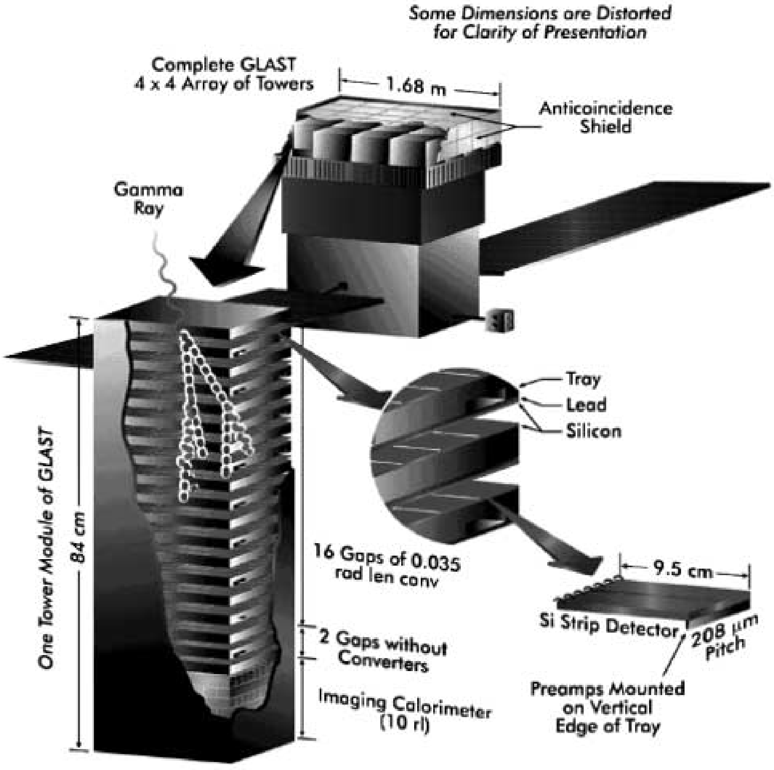

Fig. 2. – Artist's conception of GLAST, the next major satellite γ-ray telescope [24]. The main GLAST instrument will consist of interleaved Si-strip/absorber layers for tracking and an imaging CsI calorimeter for energy and position measurement.

consists of a silicon-tungsten tracker, a cesium iodide mini-calorimeter (1.5 radiation lengths), an anticoincidence system made of segmented plastic scintillators, fast readout electronics and processing units. In constrast with old generation instruments such as EGRET, AGILE does not require gas operations and/or refilling, and does not require high-voltages. Spectral information will be obtained from multiple scattering of created pairs in the silicon planes (for energies less than ~ 500 MeV) and by using the energy deposited in the tracker and the mini-calorimeter. The instrument is designed to achieve an optimal angular resolution (source location accuracy $\sim 5'$–$20'$ for intense sources), a very large field of view ($\gtrsim 2$ str), and a sensitivity comparable to that of EGRET for on-axis (and substantially better for off-axis) point sources. AGILE will also carry an imaging hard X-ray detector to simultaneously monitor in the 10–40 keV range the sources observed in the central part of the gamma-ray field of view.

4·5. *GLAST*. – The single most important new γ-ray telescope to be flown in space the next decade will be GLAST [23, 24], a state-of-the-art detector, based on several techniques developed for experimental particle physics, such as Si-strip tracking and CsI calorimetry. With a very wide field of view, and a suitable pointing strategy, GLAST will scan the entire sky on every orbit, offering unparalleled coverage of transient γ-ray phenomena, such as AGN flares and gamma-ray bursts. GLAST will have substantially improved characteristics (angular resolution, energy resolution, energy range, etc.) relative to its predecessor, EGRET. The resulting improvement in sensitivity of GLAST will enable the detection of up to two orders of magnitude more sources (*e.g.*, approximately 3000–4000 AGN). An artist's conception of GLAST is shown in fig. 2. The current plan calls for a launch sometime in 2005.

4˙6. *AMS*. – The Anti Matter Spectrometer AMS [25] is scheduled for a three-year mission on board the International Space Station Alpha (ISSA) from 2003 to 2006. AMS has as primary mission the search for cosmic ray antinuclei as well as the search for dark matter studying anomalies in CR spectra and composition (*e.g.*, e^+, $\bar{p}$), but has also an interesting sensitivity as a high energy (0.3 to 100 GeV) gamma-ray detector.

5. – Conclusions

The entire field of astrophysics using very high energy particles (γ-rays, cosmic rays, and neutrinos) is in a state of rapid developement, stimulated by the exciting results obtained in the last few years. Using γ-rays, we are probing remarkable and unexpected phenomena in objects such as active galaxies and gamma-ray bursts, we are also searching for the origins of the cosmic radiation. For the future, there is an expanding interest in this field, and next-generation experiments in space and on the ground will greatly expand our discovery horizon.

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