THE PROJECT EGRET (ENERGETIC GAMMA-RAY EXPERIMENT TELESCOPE) ON NASA'S GAMMA-RAY OBSERVATORY GRO

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Abstract. The Gamma Ray Observatory (GRO) is currently planned for a launch from the space shuttle in 1990. After the long hiatus in high-energy gamma-ray astronomy since the end of the COS-B mission in 1982, the Soviet missions Granat and Gamma-1 and the NASA mission GRO will resume observations in the energy range from below 100 keV and extending to above 10 GeV. GRO will carry four instruments designed to cover this range of over five decades in photon energy. It is planned to perform a complete sky survey above 1 MeV in the first year of the GRO mission. Data from this survey will be used to study galactic and extragalactic sources of gamma radiation as well as the galactic and extragalactic diffuse emissions. Additionally, measurements of gamma ray bursts will be performed. The angular and spectral resolution of the GRO instruments is significantly improved with respect to previous experiments. The sensitivity for point sources will be better by an order of magnitude, and the location of strong, high energy sources will be determined to about 0.1°–0.2°. After a brief description of the complement of GRO instruments, a detailed discussion of the high-energy telescope EGRET, its design and scientific objectives, is presented in this review.

1. Introduction

High-energy gamma-ray astronomy is a discipline that depends on the technical resources of the space age. The surface of the Earth is shielded from cosmic gamma radiation by roughly 20 mean free paths of attenuation in the atmosphere; furthermore the charged cosmic radiation generates a high level of secondary gamma-ray background in the atmosphere. Therefore one has to expose instruments which observe cosmic gamma-ray sources on stratospheric balloons or satellite platforms. Except for strong gamma-ray sources, e.g., the Crab pulsar, a balloon exposure is generally too short and the cosmic ray induced background in the residual atmosphere is too large to obtain a significant measurement.

The first extensive observation in space was achieved with a scintillation detector on the orbital NASA Mission OSO-3 in 1967–1968. The galactic disk was revealed as a strong source of high-energy gamma rays although the detector only had an angular

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resolution of $\sim 25°$. The breakthrough at energies above about 35 MeV was possible with the spark chamber telescopes on SAS-2 (NASA, 1972–1973) and COS-B (ESRO/ESA, 1975–1982). These instruments provided for the first time adequate exposures, sensitivities and angular as well as spectral resolution to define the general features of the gamma ray sky. Exposures of typically 3×10^7 cm^2 s (SAS-2) and 10^8 cm^2 s (COS-B) and angular resolutions in the degree range allowed mapping the distribution of the diffuse galactic emission as well as to detect pointsources. Two galactic sources could be clearly identified with young radio pulsars (Crab and Vela). For several strong sources identifications have been proposed (Cyg-X3, X-ray counterpart of 2CG195 + 04) but are not yet undisputed. Many of the other unresolved gamma-ray sources might be explained by structures in the interstellar medium, but the nature of a good fraction of the galactic sources detected by COS-B remains mysterious. By positional coincidence the gamma-ray emission from the second closest known QSO, 3C273, could be detected in the COS-B data. The low systematic background characteristic of the SAS-2 mission allowed a good determination of the intensity of a diffuse cosmic background radiation in the 100 MeV range. Figure 1 displays the coverage of the sky that was achieved with the SAS-2 and COS-B missions.

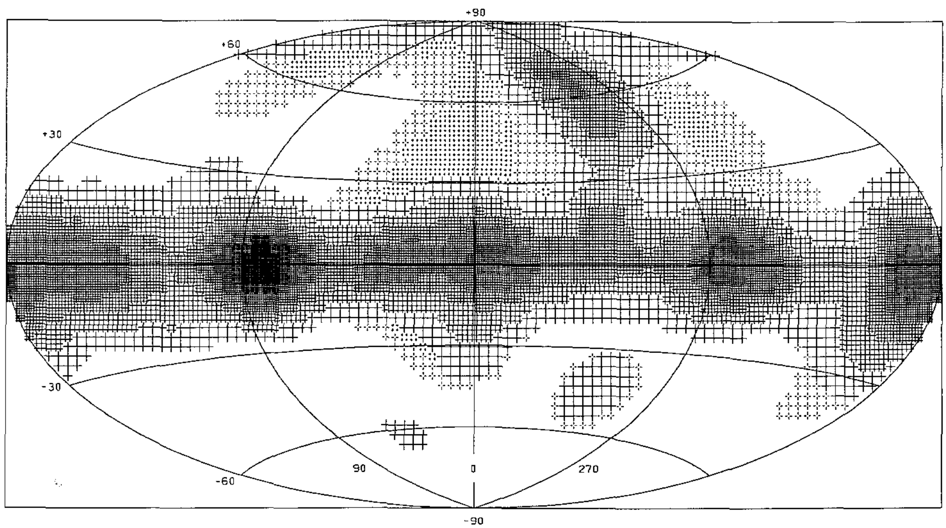

Fig. 1. Coverage achieved with SAS-2 and COS-B (galactic coordinates).

It is apparent that the observations were concentrated on the galactic disk. About a third of the sky was not observed with these missions. Observations in this energy range, where the most energetic and nonthermal cosmic processes become visible, should continue in the near future with the Soviet mission Gamma-1 and NASA's Gamma Ray Observatory. GRO is planned for launch in 1990.

This paper will describe briefly the overall characteristics of GRO and its payload of instruments and then in more detail the high energy telescope EGRET and its scientific goals.

2. The Gamma-Ray Observatory GRO

The Gamma Ray Observatory mission is currently scheduled for a launch in early 1990. After the Hubble Space Telescope, now planned for 1989, GRO will be the second mission of NASA's sequence of great observatories. GRO is shown in Figure 2.

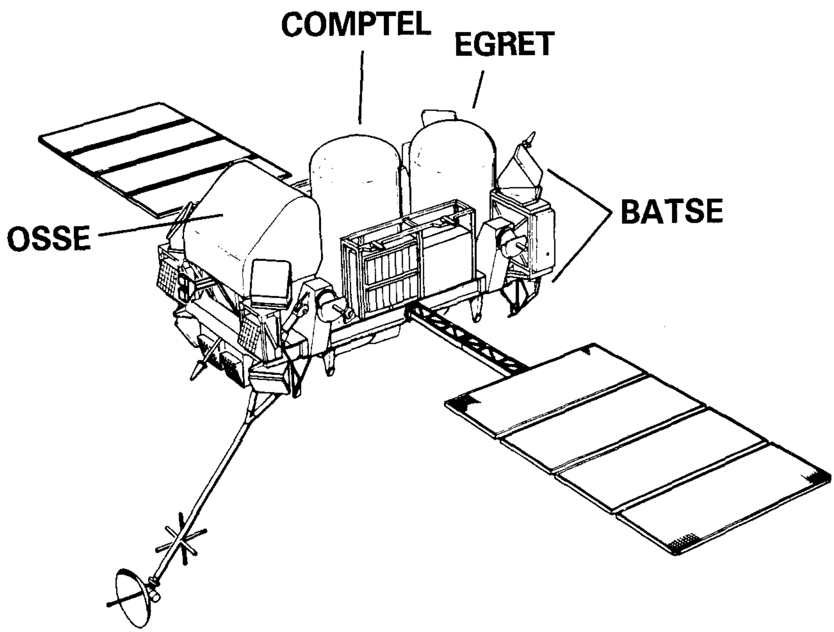

Fig. 2. Schematic view of the Gamma Ray Observatory.

GRO will be launched by the space shuttle and placed into a circular orbit of about 450 km altitude with an inclination of 28.5°. The mission's orbital altitude constitutes a compromise between the requirements of avoiding the radiation belts, which generate instrumental background, and the desired orbital lifetime. GRO is equipped with a propulsion system to maintain the orbital altitude and to enable either the recovery by the shuttle or a controlled re-entry into the atmosphere at the end of the mission. GRO will have a nominal 2-year science mission lifetime with possible extension of at least another year.

The GRO platform can be pointed in any direction with an accuracy of $\pm 0.5°$ and the attitude will be measured to within $\pm 2'$. Absolute timing of events will be possible to within 0.1 ms. The mass of the science instrumentation is about 6000 kg out of the total GRO mass of 17000 kg. The dimensions of the satellite body are $7.7 \times 5.5 \times 4.6$ m^3 and the deployed solar panels span 21 m. Telemetry of the experimental data will be maintained at a rate of 23 kbit s^{-1} through geostationary relay satellites of the TDRSS network.

Four instruments, capable of covering an energy interval from 20 keV to 30 GeV, will be carried on the GRO mission. The sensitivity of observations over these six decades of energy will be improved with respect to previous experiments by typically an order of magnitude. We give short summaries of the instruments in order of increasing energy. A more extensive description can be found in the Gamma Ray Observatory Science Plan (Kniffen *et al.*, 1988).

2.1. BATSE: BURST AND TRANSIENT SOURCE EXPERIMENT

BATSE is the smallest instrument on GRO. It consists of eight modules, each containing a large area detector (NaI, 51 cm diameter, 1.3 cm thick, 50 keV–1 MeV) and a spectroscopy detector (NaI, 12.7 cm dia., 7.6 cm thick, 20 keV–20 MeV). The BATSE modules with their large fields-of-view are oriented like the faces of an octahedron on the corners of GRO and permit monitoring of the full celestial sphere for transient gamma-ray phenomena. Directions of incidence can be reconstructed to within about a degree and the timing of events will be accurate to 0.1 ms. The sensitivity limit for a 10 sec burst is at 6×10^{-8} erg cm^{-2}. One important function of BATSE for the other GRO instruments will be the generation of a trigger signal when a solar flare or a cosmic gamma-ray burst is detected. The other instruments can then be commanded into a special burst mode. The Principal Investigator for BATSE is Dr. G. Fishman from the Marshall Space Flight Center/NASA in Huntsville, Alabama, U.S.A.

2.2. OSSE: ORIENTED SCINTILLATION SPECTROMETER EXPERIMENT

This experiment features four modules of NaI-CsI Phoswich detectors (each 33 cm diameter) which are mounted on single-axis orientation control systems providing offset pointing over a range of 192 deg. The field-of-view of the units is collimated to $4° \times 11°$ and each detector is enclosed in an active anticoincidence system. The units are normally operated in pairs such that one detector observes the source and the other monitors the background. In programmable intervals the roles are exchanged. The main objective of OSSE will be spectroscopy of cosmic gamma-ray sources and solar flares in the range of 100 keV to 10 MeV with a typical energy resolution of between 8% and 3%. Secondary goals are the detection of gamma- and neutron radiation up to energies of 150 MeV from solar flares. The independent pointing system of OSSE allows it to observe off-axis targets such as transient sources and the sun without influencing the overall GRO attitude. The Principal Investigator for OSSE is Dr J. Kurfess of the Naval Research Laboratory, Washington D.C., U.S.A.

2.3. COMPTEL: IMAGING COMPTON TELESCOPE

Incoherent scattering of photons on electrons in light elements (Compton scattering) is the dominant interaction process for the energy range from below an MeV to several 10 MeV. The Comptel instrument utilises such a scattering in a first detector plane (liquid scintillator, NE213) followed by the total absorption of the scattered photon in a second layer of detectors (NaI). The spatial resolution of the points of interaction in the two detector planes defines the trajectory of the scattered photon and the measurements of the deposited energies give the total energy of the incident photon as well as the scattering angle in the first interaction. The analysis of the ensemble of events detected allows source resolution of a few degrees over a field-of-view of about 1 sr. Sources can be located with an accuracy of 5–30 arc min and spectroscopy will be achieved with an energy resolution of 5–8% over the range 1-30 MeV. The sensitivity for sources lies at a level of 2% of the expected total emission of the Crab. Effective background suppression results from the relatively complex logic of the telescope in combination with large area anticoincidence domes enclosing the system. The Principal Investigator in a collaboration of four institutes is Dr V. Schönfelder of the Max-Planck-Institut für extraterrestrische Physik, Garching, FRG.

2.4. EGRET: ENERGETIC GAMMA-RAY EXPERIMENT TELESCOPE

The high-energy instrument EGRET will cover the range from 20 MeV to 30 GeV. EGRET continues the tradition of the spark chamber telescopes on SAS-2 and COS-B such that celestial photons are detected via the pair creation process and measured in a digital wire spark chamber. Energy resolution of about 15% in the central part of the energy range will be achieved with a 20 cm deep NaI spectrometer. The location of strong, high energy gamma ray sources can be determined with about 10′ accuracy. In order to reject charged particle background a plastic scintillator dome in anticoincidence surrounds the spark chamber. The sensitivity for high-energy gamma-ray sources will be improved with EGRET by about an order of magnitude against the previous experiments. The EGRET collaboration consists of scientists from

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- Max-Planck-Institut für Extraterrestrische Physik (MPE), Garching, F.R.G. (Co-PI: Prof. K. Pinkau)
- Stanford University, Stanford CA., U.S.A. (Co-PI: Prof. R. Hofstadter)
- Grumman Aerospace Corporation, Bethpage N.Y., U.S.A.

The first year of the GRO mission will be devoted to a complete sky survey. Besides improving the coverage of previously observed regions, large parts of the sky will then be observed for the first time at gamma-ray energies (about 80% in COMPTEL's range and about 40% for EGRET). In the following years observations of selected sources or regions are planned. An increasing part of the observation time will then be made available to the scientific community in a guest investigator program.

3. The EGRET Instrument

The schematic arrangement of the EGRET instrument is shown in Figure 3. The design exemplifies the typical components of spark chamber telescopes used in high-energy astronomy:

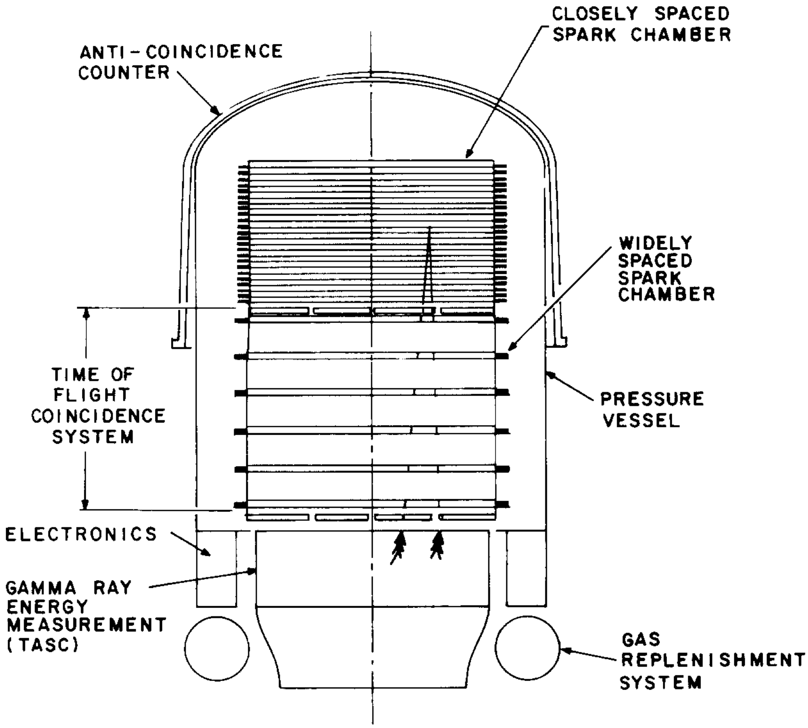

Fig. 3. Schematic arrangement of the EGRET instrument.

- An anticoincidence system to discriminate against the primary charged particle cosmic radiation.
- A spark chamber with interspersed conversion material to materialize the incident photons and to determine the trajectory of the secondary electron-positron pair.
- A triggering telescope that detects the presence of charged particles with the correct direction of motion and initiates the recording of the tracks in the spark chamber.
- An energy measuring device, which for EGRET is a total absorption spectrometer crystal (TASC) made of NaI.

These active components of the telescope are integrated above and below a circular baseplate, which also carries the necessary electronic equipment and a gas supply system to refill the spark chamber four times. The overall physical characteristics of EGRET are listed in Table I.

TABLE I

EGRET physical characteristics

Mass:	1830 kg
Length/Diameter:	2.25 m/1.65 m
Power (incl. heater):	190 W
Data:	6859 bits s^{-1}

The EGRET subsystems will now be described in more detail with an emphasis on the functional aspects of the design.

The anticoincidence system is an integral, dome-shaped plastic scintillator (NE 110) which is mounted on the upper enclosure (pressure vessel) of the spark chamber. NE 110 is a scintillator with good light efficiency and high transparency so that the passage of particles through the 2 cm thick plastic can be detected with a probability that exceeds the design goal of $1\text{–}10^{-6}$. The dome is viewed by 24 photomultiplier tubes which are coupled to its lower perimeter in order to keep the field-of-view of EGRET free of any irregular mass distributions which might lead to instrumental background. The pressure vessel, a seamless aluminium dome of 2 mm thickness, and the anticoincidence detector were developed under the direction of the Max-Planck-Institute collaborators in the EGRET project.

The conversion of the high-energy photons into electron-positron pairs occurs in an upper stack of 28 spark chamber modules interleaved with tantalum foils of an average thickness of 90 μm (= 0.02 radiation lengths). The total depth for axial radiation is thus about 0.54 radiation lengths which leads to a conversion efficiency of about 30% at 100 MeV. The volume of the upper chamber is approximately $80 \times 80 \times 45$ cm^3 so that effective areas approaching 2000 cm^2 can be expected for the center of the field-of-view. The spark chamber is filled with a gas mixture of neon, argon, and ethane at 1.1 atmosphere pressure. During the flight operations the gas filling of the spark chamber can be replaced four times from a gas replenishment system. The gap width is 4 mm and the electrodes are formed by two crossed wire planes each containing 992 precisely spaced wires for the required resolution of the particle tracks.

Below the conversion chamber, a two-layer scintillation detector (separation 60 cm) registers the passage of charged particles. The direction of the radiation is determined by a time-of-flight delayed coincidence. The signal from this trigger telescope together with the absence of a detection in the anticoincidence system generates the command to apply the high voltage to the spark chamber and to register an event. A refinement on the event acceptance logic comes from the tile structure of the trigger telescope layers. The signals from the individual scintillator tiles (4×4 in each of the two layers) can be combined such that the effective field-of-view of EGRET can be shifted away from potential sources of dominating background e.g. the earth's atmosphere. For a better definition of the tracks of the electron-positron pair the space inside the trigger telescope contains six additional widely spaced spark chamber modules with little scattering material. Further, there are two spark chambers with wires at 45° to uniquely correlate between the x- and y-projection points. The spark chamber, trigger telescope and the connected electrical and mechanical systems have been developed by the group at the Goddard Space Flight Center.

The fourth major detector subsystem of EGRET is the total absorption spectrometer crystal (TASC) which was developed under the direction of the co-investigators at Stanford University. The NaI spectrometer measures $77 \times 77 \times 20$ cm^3 and has a mass of 435 kg. Its thickness corresponds to about 8 radiation lengths and enables the determination of photon energies up to several tens of GeV. The expected energy resolution for this spectrometer is about 15% FWHM over a wide range of energies from 100 MeV to several GeV. The scintillation light from TASC is collected by 16 photomultiplier tubes of 12.7 cm diameter.

A further scientific goal of EGRET will be the spectroscopy of high-energy cosmic gamma-ray bursts and solar flares. For this purpose the pulse height of signals from the TASC will be stored in a 256-channel spectrum that spans the range from 0.6 to 140 MeV in a pseudo-logarithmic manner. For solar events the accumulation time for one spectrum is 32 seconds and is repeated regularly. For cosmic bursts the accumulation time for four sequential spectra can be adjusted by command. Telemetry transmission of a cosmic burst will take about half an hour. A readout trigger can either be generated internally by EGRET by the detection of a count rate increase in the anticoincidence detector or by an external burst signal from the BATSE experiment. The internally generated burst signal can also be used to initiate a special mode for the spark chamber. In this mode the spark chamber is triggered and read out whenever a specified number of counts is registered in the anticoincidence scintillator within an interval of about 2 μs. This mode and its trigger level can be enabled and adjusted by command.

3.1. Angular and Energy Resolution

The incident direction of a detected gamma ray is derived from the information in the spark chamber picture. The characteristic electron-positron pair will be reconstructed in 3 dimensions and an appropriately weighted bisection of the tracks close to the vertex or origin of the pair is used to estimate the direction of the photon. Several physical and technical factors limit the accuracy of this estimate:

– The kinematics of the pair creation process is not measured completely. The recoil of the target nucleus remains unknown and the division of the kinetic energy among electron and positron can only be estimated from the scattering characteristics of the particles.

– Small angle Coulomb scattering changes the original direction of the pair particles. This effect is particularily noticeable at low energies where the angular resolution deteriorates as one approaches the lower limit of EGRET's sensitivity.

– The spatial resolution of a digital wire spark chamber is limited. This limits the angular resolution at the higher energies, when the electrons' trajectories are no longer affected by scattering.

Following Thompson (1986) the position of a celestial point source, which is determined by the ensemble average of the effective number of counts detected from the source, can be reconstructed to within 10–20 arc min for strong, high energy sources.

The energy resolution of the 8 radiation lengths thick TASC is influenced by two effects which become dominant at opposite ends of the energy range of EGRET:

– The inert material between the conversion point of the gamma ray and the upper face of TASC (typically 0.5 r.l.) extracts ionisation energy from the kinetic energy of the pair. At low energies this can be a significant fraction of the total energy. Scattering of low energy electrons can also lead to the complete removal of a particle out of the normal path of the telescope. If the tracks of the particles are defined well, one can reconstitute the ionisation losses and the kinetic energy of a lost particle to a certain degree from the traversed material and from the scattering characteristics.

– At high energies (above several GeV) the resolution is expected to degrade slowly due to the fluctuations in the energy leakage out of the TASC crystal. Hughes *et al.* (1980) estimated that this effect will decrease the resolution to about 25% FWHM at the upper end of the EGRET range.

The overall energy resolution of EGRET is expected to be around 15% FWHM for the major part of the energy range (from 100 MeV to several GeV). These estimates were borne out by measurements performed with the TASC subsystem in a positron beam at SLAC (Hughes *et al.*, 1986).

Table II summarizes the parameters of the EGRET telescope as they are expected on the basis of calculations and preliminary measurements.

TABLE II

EGRET parameters

Energy Range:	20 MeV–30 GeV
Energy Resolution:	~15% (~100 MeV–several GeV)
Effective Area (≥200 MeV):	~2000 cm^2
Sensitivity (≥100 MeV):	~5 × 10^{-8} cm^{-2} s^{-1}
Angular Resolution:	0.1°–0.4°
Field of View:	~40° FWHM
Timing:	0.1 ms

3.2. The calibration of EGRET

The experimental verification of the sensitivity and the determination of the resolution functions in energy and direction is of course an essential requirement in the course of the EGRET project. The largest part of the EGRET calibration was performed at the Stanford Linear Accelerator Center (SLAC) in the period April 26 to June 30, 1986. At SLAC an appropriate gamma-ray beam was developed: quasi-monoenergetic electrons from the accelerator with an adjustable energy in the range 650 MeV to 30 GeV collide with a pulse of laser photons (2.34 eV) and produce gamma-ray photons in the range 15 MeV to 10 GeV (inverse Compton scattering). The pulsed gamma-ray beam was operated with a repetition frequency of 15 Hz, pulse width of about 40 ns and an average intensity of 0.1 ≃ 0.5 photons pulse^{-1}. The photon beam was collimated to a cross section of 1 cm^2 at a distance of about 170 m from the intreraction region and thus had a negligible angular dispersion. A more detailed description of the calibration beam and its operation has been given by Mattox *et al.* (1987).

The sensitive area of EGRET was sampled with the gamma-ray beam in a regularily spaced raster scan (spacing 5 cm) which was executed by a computer-controlled positioning fixture. Figure 4 shows EGRET in this fixture during the calibration.

Ten discrete gamma-ray energies (15, 20, 35, 60, 100, 200, and 500 MeV, 1, 3, and 10 GeV) and 13 directions of incidence (inclination: 0°, 10°, 20°, 30°, and 40°, azimuth: 0°, 22.5°, and 45°) were measured in the available time and roughly 760,000

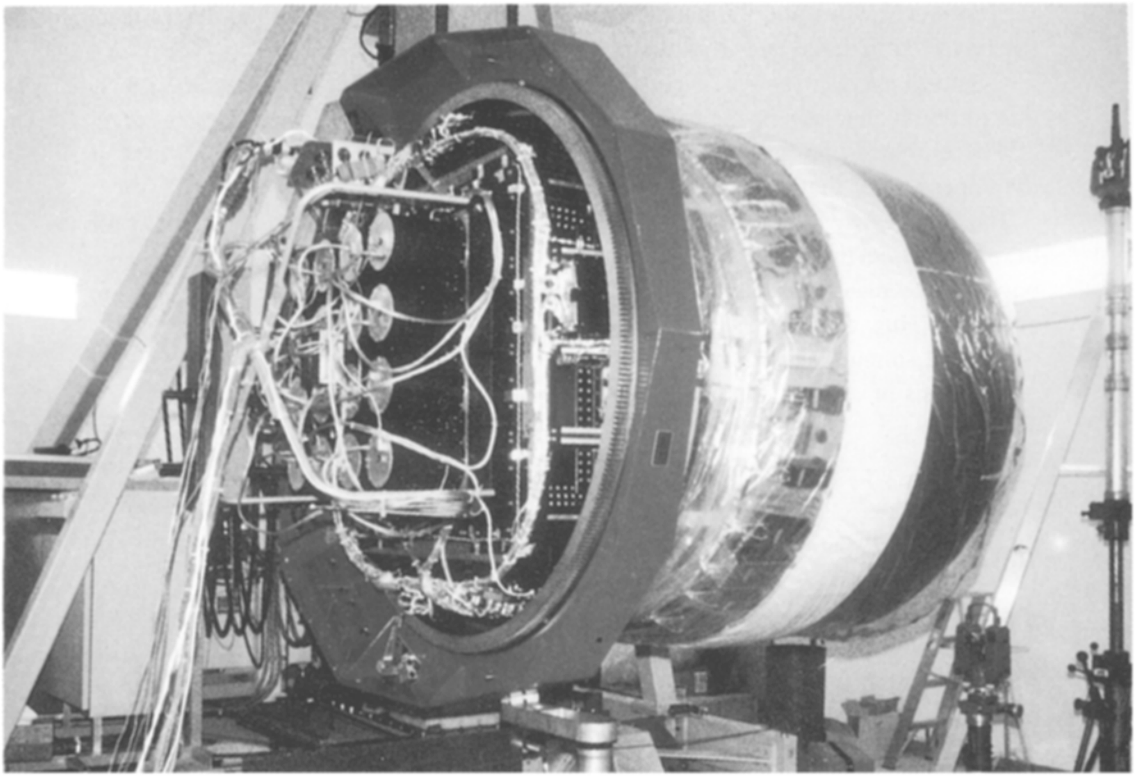

Fig. 4. Photograph of EGRET during the calibration at SLAC.

events were recorded. A more extensive description of the EGRET calibration has been given by Thompson *et al.* (1987).

The analysis of the calibration data is currently being pursued intensively in the institutes of the EGRET collaboration. The analysis requires that this large database be processed to a consistent level, i.e., the pattern recognition, direction, energy and beam monitor systems have to be refined and tuned to the experimental data before reliable results for the distribution functions and sensitivities can be obtained.

A further accelerator measurement with EGRET was performed at the Brookhaven National Laboratory to investigate the sensitivity of the instrument to charged cosmic ray background. The material external to EGRET's anticoincidence detector (about 160 mg/cm^2 of thermal blanket and light shield) can act as a source of instrumental background when high-energy nuclear interactions produce secondary photons in the field-of-view. The measurements involved the tangential irradiation of this external material with up to 10 GeV protons from the accelerator. The preliminary assessment of the measurements indicates, that the cosmic ray induced background will remain, as expected, significantly below the level of the diffuse cosmic gamma-ray background.

A final calibration measurement with EGRET is planned in 1988 at the MIT Bates Linear Accelerator Center in Middleton, Massachusetts, where a gamma-ray beam with appropriate energies (20 MeV to at least 830 MeV) is available. The primary purpose of this measurement will be the verification of improvements in the instrument which have been implemented since the SLAC calibration.

4. Scientific Objectives of EGRET

The first operational objective of the Gamma Ray Observatory will be a complete survey of the sky. The instruments with a large field of view, COMPTEL and EGRET, will achieve this survey with about 24 pointed observations of 2 weeks duration. The sensitivity of the instruments will allow detection of sources in the survey data that are about a factor of 10 weaker than the sources presently known. After the survey GRO will perform pointed observations of selected sources and measurements of galactic and extragalactic diffuse emissions.

From the design of the EGRET telescope with its wide field-of-view and good angular resolution at high energies the main scientific objectives follow directly:

- Observation of galactic and extragalactic point sources
- Measurement of the galactic and isotropic diffuse radiation.

As in any other discipline of astronomy the distinction between resolved (diffuse) and unresolved (point-like) emissions depends of course on the angular resolution of the instrument. Only if additional indications for the nature of the source, like time variations, are available a gamma-ray source, i.e., a localized significant excess of intensity over the background that is consistent with the point spread function of the instrument, can be called a genuine point source. The primary scientific goals and objects of investigation shall now be discussed in more detail.

4.1. Galactic Point Sources

4.1.1. *Pulsars*

Two of the brightest high energy gamma-ray sources were identified on the basis of their periodic emission with the young radio pulsars in the Crab nebula and in the constellation Vela. The standard model for the emissions of a rotating neutron star holds that the luminosity is supplied by the loss of rotational energy. If one assumes canonical values for the moment of inertia of a neutron star and a pencil beam model for the solid angle of emission, the efficiency of converting rotational energy into high energy gamma rays is 3×10^{-4} for the Crab and 5×10^{-3} for the Vela pulsar. These high efficiency values indicate the close connection between the basic radiation processes and the gamma-ray emission in pulsars. From the measurements of COS-B it is known that the gamma-ray emission of pulsars is subject to secular variations. With EGRET the emissions of the Crab and Vela pulsars will be investigated in unprecedented detail and it is hoped that the understanding of the source mechanism will be advanced. Taking into account the available 'braking-power' and the distances of other radiopulsars one can estimate which objects are the most likely to become observable with the increased sensitivity of the GRO instruments. If the efficiency of gamma-ray production in radio pulsars is similar to the values quoted above, EGRET should be able to detect about a dozen more pulsars in the high-energy range. For the resolution of the pulsed emission it is however mandatory to know the pulsar parameters (period and its derivative) with an accuracy commensurate with the long duration of a GRO observation. This information can only be provided by contemporary radio observations. Therefore a collaboration of GRO investigators and three radio observers who will use three different radio telescopes to cover the whole sky has been initiated to supply the necessary parameters for numerous selected pulsars.

4.1.2. *Unidentified Galactic Point Sources*

Besides the sources identified with the Crab and Vela pulsars the data from SAS-2 and COS-B revealed two more bright sources: in the galactic anticenter the hard source 2CG195 + 04 ('Geminga') and a source in Cygnus.

Geminga is the second brightest known gamma-ray source; its error box with a radius of $\sim 0.4°$ is, however, large enough to make a certain identification with an object at other wavelengths difficult. A widely considered candidate for Geminga is a X-ray source discovered with the Einstein satellite. Recent reports on optical counterparts (Bignami *et al.*, 1987, Halpern and Tytler, 1988) keep the interest in the 'enigmatic Geminga' high.

For the Cygnus source the SAS-2 workers (Lamb *et al.*, 1977; Fichtel *et al.*, 1987) propose an identification with the periodic X-ray source Cyg-X3 that had undergone a major radio outburst before the SAS-2 observation. The COS-B measurements, several years after SAS-2, fail to show the characteristic periodicity of Cyg-X3 although a bright source 2CG078 + 04, significantly offset from Cyg-X3, is present in Cygnus (Hermsen *et al.*, 1987).

In the galactic plane one is faced with a superposition of possible high-energy point sources and structured diffuse gamma-ray background from the interaction of cosmic rays (CRs) and the interstellar medium (ISM). The long and repeated exposures achieved during the COS-B mission made it possible to discern sources in the Galaxy which were up to a factor of four fainter than the Crab source. This result was described in the so called 2CG catalogue (Swanenburg *et al.*, 1981). The acceptance criteria for unresolved sources that were applied in this work, revealed a total of 24 low galactic latitude objects. Except for the pulsars mentioned no undisputed identifications have been made until now. The new surveys of the interstellar medium, particularly for molecular gas at mm wavelengths, made it possible to construct refined background models for the analysis of the gamma-ray measurements. Preliminary results from such work by Pollock *et al.* (1985a, b) and Simpson and Mayer-Hasselwander (1987) has shown that some of the 2CG sources can indeed be explained by small scale concentrations in the ISM (4 sources out of a sample of 11 sources). But a set of unidentified unresolved sources remains visible above the background (7 sources of the sample) and in one case a new variable source was added to the list. The further observation of these sources will be one of the primary objectives of EGRET. The improved resolution at higher energies will restrict the areas of the error boxes (e.g., for Geminga we expect a reduction in solid angle by more than a factor of 10), so that positional coincidences with candidate identifications will be more meaningful. The extrapolation of the presently known number-brightness distribution of gamma-ray sources indicates that several tens of additional galactic sources will become visible with EGRET. The planned collaboration with radio observers of the interstellar medium will be very important, because the knowledge of the diffuse background is essential for point source studies.

4.2. Galactic diffuse emission

The study of the distribution and dynamics of the interstellar medium (ISM) is essential for our understanding of the structure and evolution of the Galaxy. It is well known that the ISM, which accounts for several percent of the total mass of the Galaxy, is distributed inhomogeneously in the space between the stars: extended low density regions contrast with neutral and molecular clouds where the density of the medium can be increased by factors of 10^4 to 10^7. High-energy cosmic rays (CRs) that penetrate the ISM, excite gamma-radiation from the ISM in electronic (bremsstrahlung) and nucleonic (π^0 production and decay) interactions. The first result of gamma-ray astronomy was the detection of the dominant emission from the Milky Way. This was immediately, at least qualitatively, explained as due to the above processes (Kraushaar *et al.*, 1972; Bignami *et al.*, 1975; Stecker *et al.*, 1975). The assumption of a pressure balance between the ISM, the CRs and the interstellar magnetic field was used in many of these studies and was generally justified by the results. Recent studies (Strong *et al.*, 1987, 1988, and references therein) of the final COS-B data in correlation with comprehensive radio surveys of the ISM over the complete galactic disk derive the overall distribution of CRs in the Galaxy. They show that, as the previous studies had indicated, the average densities of CRs and ISM are globally correlated, however the density increase of the CRs towards the inner Galaxy is rather moderate (about 1.5 compared to the solar environment). The consequences of this result for the sources and propagation of CRs are an ongoing topic of investigation. EGRET will be able to resolve the spatial and spectral distribution of the diffuse radiation to a degree that allows investigation of the local CR density in various places in the Galaxy, such as arm-interarm regions or possibly localized sites of CR production.

On a scale of individual molecular cloud complexes the emission of diffuse gamma radiation from the local system in Orion could be detected with COS-B. This observation was used to determine the total mass content of the complex and it agreed well with the radio results. If more observations become available with EGRET, the analysis of the mass and radiation contents of a sample of molecular cloud complexes will be an important objective.

EGRET will thus contribute to the study of the ISM from the smaller scale of clouds to the medium scale of galactic arms and other structures, to measurements of the large scale features of the Galaxy like a halo.

4.3. Extragalactic point sources

Up to now only one extragalactic object has been definitely detected in the 100 MeV range: the brightest QSO 3C273 was found in several COS-B observations. For other potential candidates no indications of high energy emission were found in the SAS-2 and COS-B data despite the fact that some Seyfert galaxies (NGC4151 and MCG 8–11–11) and the radio galaxy Cen-A have been seen at hard X-rays and up to the MeV gamma-ray range. This indicates that either temporal or significant spectral changes must be present in these sources between about 1 MeV and 100 MeV. The observation of this intermediate range with GRO might hold the key for the understanding of these objects, because gamma-ray emission can be a major factor in their radiation budget. The quasar 3C273 emits 2×10^{46} erg s^{-1} between 50 and 500 MeV, which exceeds the emission in any other decade of energy.

What are the prospects for EGRET to detect more extragalactic sources? Extrapolating our knowledge of the total galactic emission to the normal galaxies of the local group it has been shown that the Magellanic Clouds and the Andromeda galaxy (M31) should be detectable with EGRET (Houston *et al.*, 1983; Özel and Berkhuijsen, 1987). Their hard 'galactic' spectrum should contrast with the softer diffuse background especially at higher energies.

The closest giant elliptical galaxies with strong radio emission are possible candidates: Centaurus A, which has been seen in the MeV range, and the prominent member of the Virgo Cluster M87 (Vir A).

The only other class where a prediction on an empirical basis can be tried is quasi-stellar objects. If one scales the detected gamma-ray luminosity of 3C273 with the observed X-ray luminosities one can expect to detect 3C279, 3C263, and 3C446 with EGRET. All of these QSOs are located at high galactic latitudes.

Other active galaxies (Seyferts and BL Lac objects) are difficult to estimate with respect to their emission above 20 MeV. Extrapolating the observed low energy gamma spectra into the EGRET range can lead to detectable intensities but on the other hand the indicated spectral cut-off above several MeV might reduce them to an unobservable level (Fichtel, 1988).

4.4. Extragalactic diffuse radiation

The SAS-2 mission detected for the first time a diffuse gamma-ray intensity at high galactic latitudes (Fichtel *et al.*, 1978). The spectrum of this component is steeper than the galactic emission and it is isotropic at least on a coarse scale. The luminous veil of foreground galactic emission that exists even at high latitudes equals the intensity of the background radiation at about 300 MeV, whereas the isotropic component will dominate ($\sim 70\%$) at the lowest energies registered with EGRET. Isotropy of the diffuse radiation has been established to a level of 20% by comparing solid angle elements of ~ 1 sr in size. Based on the available evidence, the origin of this radiation is unlikely to be in a galactic halo; a cosmic origin seems more plausible even if a generally accepted theory has not yet been found. One proposal is that the superposition of QSOs and active galaxies generates this background. While this proposal seems to be the most viable, other more exotic theories propose that the radiation is produced in matter-antimatter annihilation in a symmetric universe or in exploding low mass black holes produced in the big bang. EGRET will be able to determine the intensity of the isotropic diffuse radiation with an accuracy of about 20% for pixel elements of 10^{-2} sr (= resolution element at low energies) in a deep exposure at high latitudes (1 month). For larger solid angle elements the accuracy will increase according to the counting statistics. Since the local galactic foreground is heavily structured, the EGRET analysis of the cosmic background will have to take into account all available information on the local ISM (e.g., from radio, infrared, ultraviolet and soft X-ray observations) to extract a meaningful result. The analysis of the diffuse background radiation can be expected to be one of the longest term projects of EGRET, but the cosmological implications make it also one of the most interesting topics.

4.5. Cosmic gamma-ray bursts and solar flares

From the measurements with the gamma-ray spectrometer on the Solar Maximum Mission (SMM) it is known that many cosmic gamma-ray bursts (GRBs) and solar flares have spectra that extend to well over 10 MeV (Matz *et al.*, 1985). In solar flares this hard component is generated by high energy ions that interact in the solar photosphere (π^0 decay), whereas for GRBs neutron stars with high magnetic fields and possibly pulsar-like activity may be responsible. The EGRET spectrometer, as described in Section 3, will record spectra of bursts up to 140 MeV with an adjustable integration time.

5. Concluding Remarks

After the end of the COS-B mission in 1982 we hope that the late 80's and early 90's will see the resumption of gamma-ray astronomy in space. The impending Soviet missions Granat and Gamma-1 will be followed by the Gamma-Ray Observatory. On GRO, a complement of four instruments with significantly more sensitivity and resolving power than previous experiments, covering the entire energy range from below 100 keV to above 10 GeV, will markedly improve our knowledge of the entire gamma-ray sky. With the wide field-of-view instruments COMPTEL and EGRET the first, and probably also last, sky survey of this century will be conducted at energies above 1 MeV in the first year of the GRO mission.

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