Gamma-Ray Telescopes

Gamma-rays are the highest-energy photons in the ELECTROMAGNETIC SPECTRUM and their detection presents unique challenges. On one hand it is easy to detect γ-rays. The interaction cross-sections are large and above a few MeV the pair production interaction, the dominant γ-ray interaction with matter, is easily recognized. Gamma-ray detectors were far advanced when the concept of 'γ-ray astronomy' was first raised in Phillip Morrison's seminal paper in 1958. Indeed it was the expected ease of detection and the early promise of strong sources that led to the large concentration of effort in the field, even before the development of X-RAY ASTRONOMY. Today the number of known γ-ray sources is well under a few hundred whereas there are hundreds of thousands of x-ray sources. What went wrong?

The answer is simple: the detection of cosmic γ-rays was not as easy as expected and the early predictions of fluxes were hopelessly optimistic. Below we consider the physical phenomenon whereby γ-rays interact with matter, the basic detector configurations and the detectors which have provided the bulk of the observational results; we conclude with a description of the techniques now under development.

First we provide a few definitions and a few caveats. The term 'γ-ray' is a generic one and is used to describe photons of energy from 100 keV (10^5 eV) to >100 EeV (10^{20} eV). A range of 15 decades is more than all the rest of the known electromagnetic spectrum. A wide variety of detection techniques is therefore necessary to cover this huge range. We will concentrate on the telescopes in the somewhat restricted range from 1 MeV to 100 TeV. The lower definition comes from the knowledge that the lower energies are better covered by the techniques used to cover hard x-ray astronomy and that many authors would define the γ-ray regime as starting at 0.51 MeV (the rest mass energy of the electron). There are no credible detections of γ-rays at energies much beyond 50 TeV and the 'γ-ray telescope' techniques used beyond these energies are really the same as those used to study charged COSMIC RAYS and hence are best discussed under that heading. We are left with some eight decades which we will, somewhat arbitrarily, define as the medium-energy (ME) range from 1 to 30 MeV, the high-energy (HE) range from 30 MeV to 100 GeV and the very-high-energy (VHE) range from 100 GeV to 100 TeV. These ranges are not defined by the physics of their production but by the interaction phenomena and techniques employed in their detection. Thus Compton scattering dominates the ME range necessitating the use of satellite-borne Compton telescopes. The HE and VHE ranges use the pair production interaction but in very different ways; HE telescopes identify the electron pair in balloon- or satellite-borne detectors, whereas VHE detectors detect the electromagnetic cascade that develops in the Earth's atmosphere.

GAMMA-RAY ASTRONOMY is still an observation-dominated discipline and the observations have been driven not so much by the astrophysical expectations (which have often been wrong) as by the experimental techniques, which have permitted significant advances to be made in particular energy ranges. Hence the most fruitful observations have come at energies of 100 MeV; these were originally inspired by the prediction of the strong bump in the spectra expected from the decay of π^0s that are created in hadron interactions. This energy region was exploited primarily because the detection techniques were simpler and more sensitive. In contrast the ME region has the potential for very interesting astrophysics with the predicted existence of nuclear emission lines but the development of the field has been slow because the techniques are so difficult.

Peculiarities of γ-ray telescopes

There are several peculiarities that uniquely pertain to astronomy in the γ-ray energy regime. These factors make γ-ray astronomy particularly difficult and have resulted in the slow development of the discipline.

In every band of the electromagnetic spectrum astronomical telescopes make use of the fact that the cosmic rain of photons can be concentrated by reflection or refraction, so that the dimensions of the actual photon detector are a small fraction of the telescope aperture. How limited would have been our early knowledge of the universe if the optical astronomer had not been aided by the simple refracting telescope which so increased the sensitivity of the human eye. The radio astronomer, the infrared astronomer, even the x-ray astronomer, depends on the ability of a solid surface to reflect and, with suitable geometry, to concentrate the photon beam.

Above a few MeV there is no efficient way of reflecting γ-rays and hence the dimensions of the γ-ray detector are effectively the dimensions of the γ-ray telescope. (As we shall see in a later section this is not the case for ground-based VHE telescopes.) In practice to identify the γ-ray events from the charged particle background it is necessary to use detectors whose efficiency is often quite low. Hence at any energy the effective aperture of a space-borne γ-ray telescope is seldom greater than 1 m^2 and often only a few cm^2, even though the physical size is much larger. For instance the COMPTON GAMMA RAY OBSERVATORY (CGRO) was one of the largest and heaviest scientific satellites ever launched; however, its ME and HE telescopes had effective apertures of 1600 cm^2 and 5 cm^2 respectively. Beam concentration is particularly important when the background scales with detector area. This is the case with γ-ray detectors which must operate in an environment dominated by charged cosmic rays.

The problem of a small aperture is compounded by the fact that the flux of cosmic γ-rays is always small. At energies of 100 MeV the strongest source (the Vela pulsar) gives a flux of only 1 photon min^{-1}. With weak sources long exposures are necessary and one is still dealing with the statistics of small numbers. It is small wonder that γ-ray astronomers have been frequent pioneers in

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the development of statistical methods and that γ-ray conferences are often dominated by arguments over real statistical significance.

As it is to photons in many bands of the electromagnetic spectrum the Earth's atmosphere is opaque to all γ-rays. The radiation length is 37.1 g cm^{-2} and the total vertical thickness at sea level is 1030 g cm^{-2}. Even the highest mountain is many radiation lengths below the top of the atmosphere so that it is virtually impossible to consider the direct detection of cosmic γ-rays without the use of a space platform. Large balloons can carry the bulky detectors to near the top of the atmosphere and much of the pioneering work in the field was done in this way. However, the charged cosmic rays constitute a significant background and limit the sensitivity of such measurements.

The background can take many forms. In deep space it is the primary cosmic radiation itself, mostly protons, heavier nuclei and electrons. This background can be accentuated by secondary interactions in the spacecraft itself. Careful design and shielding can reduce this effect, as can active anti-coincidence shields. However, at low energies induced radioactivity in the detector and its surrounds can be a serious problem. In balloons the secondary cosmic radiation from the cosmic ray interactions above the detector seriously limit the sensitivity and were the initial reason for the slow development of the field. Huge balloons that carry the telescopes to within a few grams of residual atmosphere are a partial solution, but it is still impossible to trust the measurement of absolute diffuse fluxes.

Physics of γ-ray interactions

In the energy region above 1 keV there are basically three processes by which the γ-rays can interact with the matter in the detector: these are the photoelectric effect, Compton scattering and pair production. The relative cross-sections, or, more practically, the mass absorption coefficients peak in different energy ranges. The cross-section has the same functional form for all materials, although the actual values and relative strengths of the three processes may differ somewhat. As the photoelectric effect, the interaction of the γ-ray with bound electrons in atoms, is only important at low energies (<1 MeV), we shall not consider it here.

Compton scattering

This is the most complex of the three interactions, and hence detectors which depend on it are the most complicated and the most difficult to interpret. It is important primarily in the energy range from 100 keV to 30 MeV and hence γ-ray astronomy in this range has been the slowest to develop.

In Compton scattering the electron is unbound and it alone must take up the energy and momentum of the γ-ray. In practice the γ-ray may undergo one or more Compton scatterings, losing energy to the electron in each case, until eventually it may undergo a photoelectric reaction. In each scattering the electron will take up some of the energy as kinetic energy and the γ-ray will change direction.

The relationship between the incident energy of the γ-ray, E, and the resultant energy, E', where both are expressed in units of E_e, the rest mass of the electron, is given by

$$E' = E/(1 + E[1 - \cos\theta)]$$

where θ is the scattering angle of the γ-ray. The maximum energy loss comes for backward scattering at which the scattered energy is

$$E' = E/(1 + 2E).$$

For $E > 0.51$ MeV, E' is close to 0.5 (or 0.255 MeV) which is the typical energy loss per scattering, independent of E.

At low energies the cross-section is given by the Thomson cross-section

$$\sigma_c = \sigma_T = (8\pi/3)e^2/m_e c^2 = 0.665 \text{ barns}$$

and at high energies

$$\sigma_c = (3/8)E(\ln 2E + 1/2)\sigma_T.$$

Hence Compton scattering is almost independent of the incident energy so that the cross-section decreases only slowly with energy.

Pair production

In the pair production interaction, the γ-ray is completely annihilated with its energy transferred to an electron–positron pair which is created, i.e.

$$h\nu \rightarrow e^+ + e^-.$$

The interaction takes place in the electric field of a nucleus which takes up some of the momentum. Obviously the threshold for the interaction must be >1.02 MeV (i.e. $2m_e$). The interaction can also occur in the field of an electron, but the cross-section is much less and the threshold is higher. The energy of the γ-ray is taken up by the electron–positron pair as rest mass and kinetic energy. The positron will generally annihilate with an electron to produce two γ-rays, which can Compton scatter or suffer photoelectric absorption. These secondary products at moderate energies can be totally absorbed in the detector; by measuring their energy plus the rest mass of the pair, the energy of the γ-ray is estimated.

The cross-section for pair production rises rapidly and becomes dominant above energies of about 30 MeV, after which it rises slowly to an asymptotic value. This value is given by

$$\sigma_{pp} = \sigma_0 Z^2[(28/9)\log(183/Z^{1/3}) - 2/27] \text{ cm}^2/\text{atom}$$

where $\sigma_0 = (1/137)e^4/m_e^2 c^4$.

The mean distance that a γ-ray travels before it undergoes pair production is given by

$$\lambda_{pp} = 1/N\sigma_{pp}$$

where N is the number of target nuclei per unit volume.

The mean free path for pair production is related to the radiation length, X_0:

$$\lambda_{\rm pp} = (9/7)X_0.$$

A critical factor is the degree to which the electron–positron pair retain the trajectory of the γ-ray. The root mean square angle between the trajectory of the secondary electron of energy $E_{\rm e}$ and that of the primary γ-ray of energy E_γ is about 4° at $E_\gamma = 30$ MeV, 1.5° at $E_\gamma = 100$ MeV and 0.2° at $E_\gamma = 1$ GeV. The value of observations at high energies is thus apparent.

Unfortunately it is not possible to measure the electron trajectory precisely as it will inevitably undergo Coulomb scattering as it passes through the material of the detector.

Measuring the energy of the γ-ray is essentially measuring the energy of the electron–positron pair and their secondary products. This requires that the detector have sufficient mass to absorb all these products. In practice this usually calls for a calorimeter with as much absorber as the spacecraft can carry.

ME and HE telescopes

Compton telescopes

The basic detector of γ-rays in the difficult 100 keV–10 MeV energy range is the scintillation detector, which consists of a solid or liquid material, in which light is produced by charged secondary particles resulting from the photoelectric or Compton scattering γ-ray interaction, and a phototube, in which light is converted into an electrical signal. A common material is thallium-activated sodium iodide, NaI(Tl). Charged particles are rejected by surrounding the detector by another plastic scintillator detector. If the outer detector is shaped like a well with small opening then it can serve as a collimator with crude angular resolution. Many of the early detectors worked on this principle.

A more sophisticated detector is the Compton telescope in which two detectors are operated in series (figure 1). In the front detector a primary γ-ray, which Compton scatters in the forward downward direction, is selected (based on the energy registered by the first detector from the recoil electron); the γ-ray is then absorbed in another Compton scatter in the lower detector. The lower detector is surrounded by an anti-coincidence scintillator to veto charged particles coming up from below. Of necessity because of the wide range of angles that the scattering may have, the efficiency of these simple detectors is poor, typically less than 1%. However, the energy and angular resolutions are improved over the simple one-stage detector.

The upper detector should have a large cross-section for Compton scattering over the desired energy range. In the 1–10 MeV region the best material is one with low Z; hence the detector should be a relatively thin liquid or plastic scintillator so that a single Compton scattering occurs with good efficiency. The second, lower, detector should totally absorb the product of the second Compton scatter and hence should be thicker and composed of high-Z material.

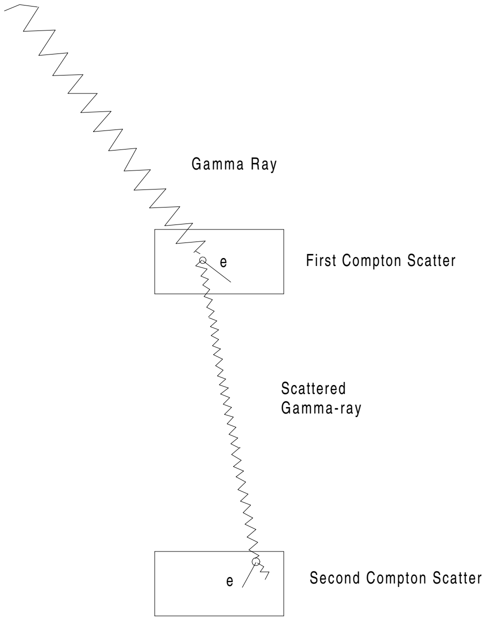

Figure 1. Schematic of double Compton scatter. In the upper scintillator the primary γ-ray Compton scatters in the downward direction; the γ-ray is then absorbed in another Compton scatter in the lower detector. In each case the energy of the recoil electron is measured and thence the energy and arrival direction of the primary are determined.

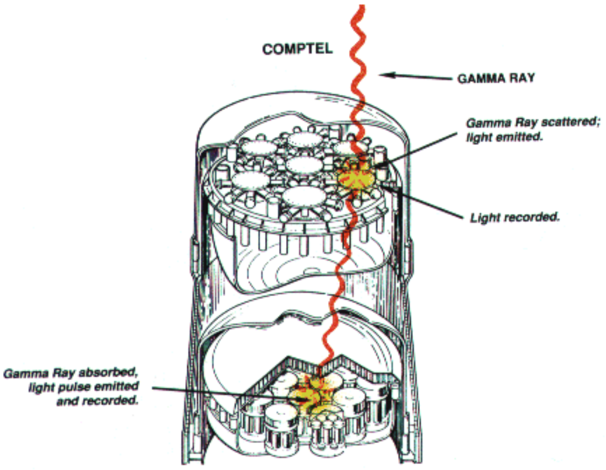

Figure 2. An example of a Compton telescope: COMPTEL. It is sensitive from 1 to 30 MeV. The angular resolution is 3–5°.

A double Compton scattering is also the basic principle used in the most sophisticated 1–30 MeV telescope flown to date, COMPTEL on the CGRO (figure 2). The primary γ-ray incident within ±40° of the telescope axis first Compton scatters in the upper detector which is a

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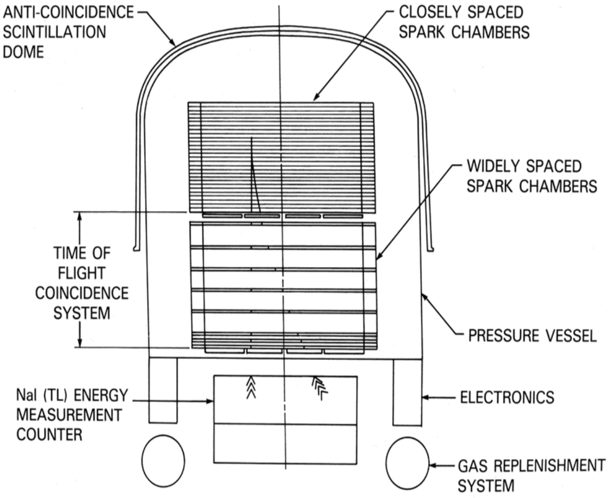

Figure 3. Example of a spark chamber telescope: EGRET. The telescope is sensitive from 30 MeV to 30 GeV. The field of view ±20° and the energy resolution is about 20%.

low-Z liquid scintillator; the second scattering takes place in the lower detector which is a high-Z NaI(Tl) scintillator. Each detector actually consists of seven modules and the separation between the two layers is 1.5 m. Hence time of flight can be used to discriminate against upward-going particles. In addition, all of the detectors are surrounded by thin plastic anti-coincidence scintillators which respond to charged particles. If the energy deposited in the upper and lower modules is measured, then the direction of the incident γ-ray can be determined to be within a narrow ring on the sky and its energy estimated to about 5–10%. A source then is apparent as the locus of intersections of a number of such rings.

Pair production telescopes

The spark chamber, long obsolete for HE physics experiments, has been the workhorse detector for γ-ray astronomy in the energy range 30 MeV–10 GeV from the early 1960s through the end of the century. The three experiments, which provided almost all the results during this period, all used the spark chamber as their principal detector. These were the USA's SAS-II (1973), Europe's COS-B (1975–82) and the joint European– USA EGRET on the Compton Gamma Ray Observatory (1991–).

Although the basic principles of the pair production telescope are simple, the detailed design is complex and accounts for the fact that the effective collection area is far smaller than the geometrical cross-section of the telescope. This is illustrated by EGRET, the pair production telescope on the CGRO. As with most pair production spark chamber telescopes, this consists of four distinct components which are shown schematically in figure 3.

(i) A spark chamber usually consists of a series of parallel metal plates in a closed container; the alternate plates are connected together electrically with one set permanently connected to ground. On an indication that a charged particle has passed through the chamber, a high voltage is applied to the second set of plates. The chamber contains a gas at a pressure such that the ionization left behind by the passage of the charged particle causes an electric spark discharge between the plates. The gas is a mixture of neon and ethane. An electron–positron pair created by a γ-ray interaction in one of the plates is then readily apparent as a pair of sets of sparks that delineate the path of the electron and positron. In practice the tracks are disjointed as the electrons suffer multiple scattering within the plates of the chamber. This limits the thickness of the plates (which should be as thick as possible to ensure that the γ-rays interact effectively, but not so thick that the electrons undergo excessive Coulomb scattering in the plate material). Multiple plates ensure that the tracks are effectively mapped. The collection area and angular resolution of the telescope are determined by the spark chamber geometry. In EGRET the spark chamber 'plates' consist of 28 wire grids interleaved with interaction plates of 0.02 radiation lengths thickness in which the γ-ray interacts. Each wire is threaded through a magnetic core memory, which is read out and reset after each event.

(ii) At least one electron must emerge from the spark chamber to ensure that it initiates a trigger that causes the application of the high-voltage pulse to the second set of plates to activate the spark chamber. A permanent high-voltage difference cannot be maintained between the plates, as the spark discharges will take place spontaneously. EGRET is triggered by a coincidence between two thin sheets of plastic scintillator with a 60 cm separation (sufficient to recognize and reject upward-going charged particles). It is the need for this trigger which limits the lower-energy threshold of the spark chamber telescope. The trigger detection system effectively defines the field of view of the telescope.

(iii) The electrons must be completely absorbed if their energy is to be measured; to achieve this there must be a calorimeter that is some radiation lengths thick. In EGRET, as in most spark chamber telescopes, this is an NaI(Tl) crystal, whose sole function is to measure the total energy deposited. At the low end of the sensitivity range the energy of the electrons can also be determined by the amount of Coulomb scattering in the plates of the spark chamber.

(iv) Finally the entire assembly is surrounded by an anti-coincidence detector which signals the arrival of a charged particle, but which has a small interaction cross-section for γ-rays. This consists of a very thin outer shell of plastic scintillator viewed by photomultipliers.

EGRET is the largest and most sensitive HE γ-ray telescope flown to date; it is the flagship instrument on

CGRO. Approximately the size of a compact car and with a total mass of 1900 kg, the telescope has an effective collection area of 1600 cm^2. The characteristics of the telescope are listed in table 1.

The telescope was designed for a 5 yr lifetime. The gas which fills the chamber gradually becomes poisoned and must be replenished. It was expected that a filling would last 1 yr. Hence only four gas canisters were attached to the instrument for replenishment at yearly intervals. In practice the unprecedented and unexpected success of CGRO meant that the mission was extended as were the replenishment intervals so that, for a considerable fraction of the 9 yr lifetime of the mission, EGRET operated at less than optimum efficiency.

VHE telescopes

Air Čerenkov telescopes

When an HE γ-ray strikes the upper atmosphere, it produces an electron–positron pair (as it does in a spark chamber). However, if the energy of the γ-ray, and hence of the electron–positron pair, is large enough, an electromagnetic cascade will result which will continue down through the atmosphere with secondary γ-ray and electron production by bremsstrahlung and pair production. The cascade will continue along the axis of the trajectory of the original γ-ray and the total energy of the secondary particles will be a good representation of its energy.

For γ-rays of energy 100 TeV and above, sufficient particles can reach ground level for the shower to be detected by arrays of particle detectors spread over areas of 0.1 km^2. As the secondary particles all move at nearly the speed of light and retain the original trajectory of the primary γ-ray, the shower front arrives as a disk which is only a meter thick. Differential timing between the detectors can then determine the arrival direction and hence the source of the γ radiation.

At lower energies the cascade will die out as the average energy of the secondary particles drops to the point that ionization losses become the major loss process (figure 4). For a primary γ-ray of energy 1 TeV, few secondary particles will reach even mountain altitude. However, as the relativistic particles traverse the atmosphere, they excite the atmosphere to radiate Čerenkov light with high efficiency. Although the fraction of energy that goes into this mode is small (less than 10^{-6} of the primary energy), it permits a very easy way to detect the cascade and thence the γ-ray. A simple light detector (mirror, plus phototube, plus fast pulse counting electronics) provides an easy way of detecting the cascade. Early telescopes consisted of ex-World War II searchlight mirrors with phototubes at their foci, coupled to fast pulse counting electronics.

The observations are best made from a dark mountain top observatory. Since the Čerenkov angle in air is about 1° and the amount of light is proportional to the number of particles in the cascade (and hence to the energy of the γ-ray), the measurement of the atmospheric Čerenkov component provides a good measure of the energy and arrival direction of the γ-ray. Because the light spreads out as it traverses the atmosphere, the collection area for γ-ray detection is as large as the lateral dimensions of the light pool at detector altitude; this can be as much as 50 000 m^2.

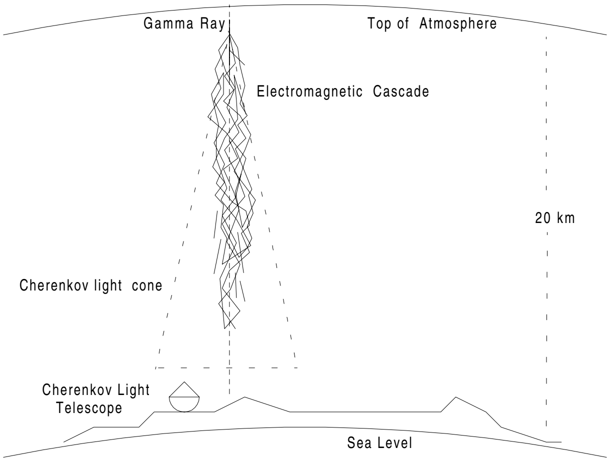

Figure 4. Schematic of atmospheric air shower detection. The γ-ray interacts with an air molecule high in the atmosphere and produces an electron–positron pair. These electrons subsequently interact and produce an electromagnetic cascade. The passage of relativistic particles through the atmosphere causes the emission of Čerenkov light which reaches ground level as a disk of diameter 200 m and thickness 1 m. The light can easily be detected by optical Čerenkov light telescopes (not to scale).

This is one of the few astronomical techniques in which the Earth's atmosphere plays an essential positive role. However, the technique has its drawbacks. Although the atmosphere comes cheap (and the gas does not need to be replenished), the observer has no control over it; the telescope is wide open to the elements and the detector is susceptible to a troublesome background of light from Sun, Moon and stars, from the airglow, from lightning and meteors, and from a variety of man-made light sources, from satellites and airplanes to airport beacons and city lights. These limit the sensitivity for γ-ray source detection. However, the most troublesome background is that from air showers generated by charged cosmic rays of similar energy to the γ-rays under study. These air showers are cascades of particles which are superficially very similar to a pure electromagnetic cascade but contain penetrating particles (mostly muons) which reach ground level (see COSMIC RAYS: EXTENSIVE AIR SHOWERS). These showers are thousands of times more numerous and their light flashes are difficult to distinguish from those from γ-rays. Because of interstellar magnetic fields, the arrival directions of the charged cosmic rays are isotropic; hence a discrete source of γ-rays can stand out only as an anisotropy in an otherwise isotropic distribution of air showers. Unfortunately a γ-ray source would have to be very strong (a few per cent of the cosmic radiation) to be detectable in this way.

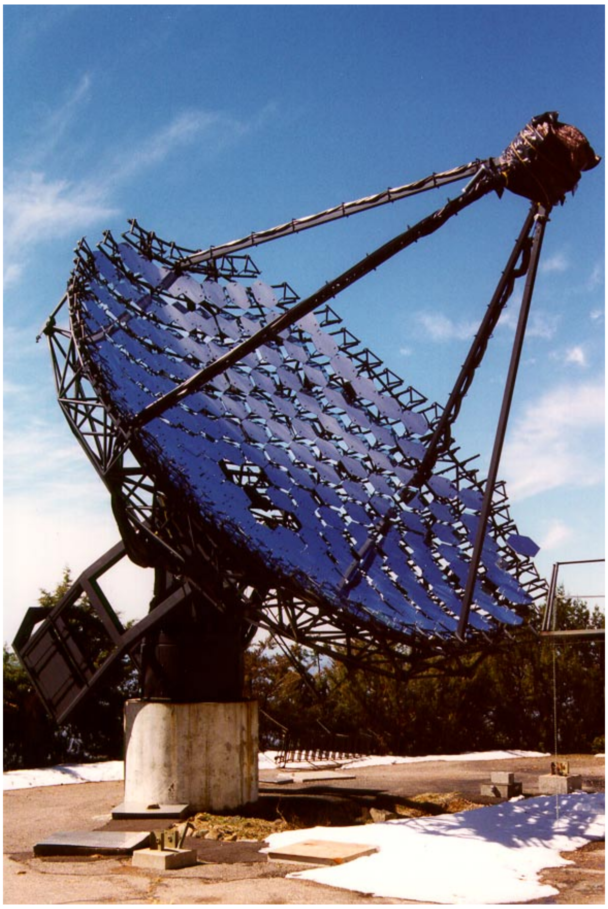

Figure 5. The Whipple 10 m γ-ray telescope. Note the '10 m' refers only to the aperture of the optical reflector; the effective collection area is $>$50 000 m^2 so that the γ-ray 'aperture' is 120 m.

Imaging detectors

Early attempts to discriminate the electromagnetic showers initiated by γ-rays from air showers initiated by charged particles were unsuccessful using either the ground-level arrays of particles detectors or atmospheric Čerenkov detectors. The development of the Čerenkov imaging technique gave the first effective discrimination; an array of photomultipliers in the focal plane of a large optical reflector was used to record a Čerenkov light picture of each air shower. Monte Carlo simulations of the development of air showers from photon and hadron primaries predicted that the images of the former would have somewhat smaller angular dimensions and thus could be identified. The largest optical reflector built for γ-ray astronomy is the Whipple Observatory 10 m optical reflector (built on Mount Hopkins in southern Arizona in 1968) (figure 5); in 1984 this was equipped with a photomultiplier camera with 37 pixels which was used to detect the CRAB NEBULA. This first detection led to a rapid development of the imaging technique, with significant improvements in flux sensitivity.

There are currently nine observatories around the globe using variants of this technique and the detection of some 13 sources has been claimed, both in the Galaxy and beyond. Background rejection of cosmic rays is now in excess of 99.7%, and the technique is effective from energies of 250 GeV–50 TeV. The energy resolution is typically 30–40%. A signal with significance of (5–10)σ can be detected from the Crab Nebula in just an hour of observation. Because of the very large collection area associated with the technique ($>$50 000 m^2), it is particularly powerful for the detection of short transients in TeV γ-ray sources (see also VERY-HIGH-ENERGY GAMMA-RAY SOURCES). In fact the shortest flare ever seen from a known γ-ray source at energies greater than 1 MeV was recorded from the blazar, Markarian 421; the duration of the TeV flare was 15–20 min. In some cases the telescope is an array of small reflectors operated in a stereo mode, e.g. the German–Spanish HEGRA experiment in the Canary Islands.

Table 1. Comparison of EGRET and GLAST.

Parameter	Units	EGRET (achieved)	GLAST (desired)
Energy range	GeV	0.02–30	0.02–300
Effective area	cm^2	1500	8000
Field of view	sr	0.5	2
Angular resolution (at 100 MeV)	deg	5.8	3.0
Energy resolution	%	10	10
Source sensitivity ($>$100 MeV) $\times 10^{-7}$	cm^{-2} s^{-1}	1	0.04

There are also two air shower particle detectors which have successfully detected γ-rays of a few TeV from the strongest sources. One is a large water Čerenkov detector, MILAGRO near Los Alamos, New Mexico, USA, at an elevation of 2.6 km. The other is a densely packed array of scintillation detectors in Tibet, which operates at an elevation of 4.3 km. Although these telescopes are somewhat less sensitive, they have the advantage over Čerenkov telescopes in that they can operate continuously and hence monitor a large section of the sky.

Future telescopes

INTEGRAL

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is primarily a European mission which will be launched in 2001. It will operate in the 15 keV–10 MeV region with two prime objectives: good angular resolution (12 arcmin) and good energy resolution ($E/\delta E) = 500$). To achieve these objectives two instruments are used: the spectrometer SPI based on solid-state germanium detectors with coded aperture masks to define the field of view and the imaging IBIS which used cadmium telluride and cesium iodide detectors. These detectors are supplemented by small x-ray and optical telescopes for the monitoring of transient sources over a broad range of wavelengths. The detector design is based on the assumption that broad lines are emitted from point-like sources and narrow lines come from extended sources as indicated by earlier missions.

GLAST

The next-generation pair production telescope will replace the spark chamber with solid-state detectors which will be more compact, more efficient and have better angular and energy resolution. However, the general principle of the telescope will be the same, with an anti-coincidence scintillator shield, an interaction region with three-dimensional imaging system and a calorimeter; only the triggering system is unnecessary, as the imaging system can be active all the time. There are no expendables and no noisy pulsed high voltage and sparks.

NASA envisages the next-generation telescope as operating in the range 20 MeV–300 GeV, with a scheduled launch date of 2005. With the somewhat unimaginative acronym, GLAST (Gamma-Ray Large Area Space Telescope), GLAST will surpass EGRET by a factor of 10–40 in most parameters. A comparison of the two missions is given in table 1.

There are two competing technologies for the central pair production detector on GLAST. One (fiber GLAST) uses crossed planes of silicon fibers coupled to multi-anode photomultipliers, separated by thin layers of high-Z converter plates. The calorimeter uses the same kind of detector but with thicker plates. The fibers are 1.3 m long and the whole detector is 1.8 m high; they have a square cross-section of side <1 mm. This technology has already been used in cosmic ray particle experiments and is thus favored by space scientists. The other technology (silicon GLAST) uses the silicon strip technology that has been used in HE particle accelerator experiments for a number of years; it has not so far been used in space science applications. Again the layers of ionizing-particle-sensitive detectors are alternated with thin layers of lead converter. The calorimeter will be made of bars of cesium iodide, with individual read-outs to give spatial resolution.

Both technologies seem to address equally well the physical demands of GLAST, so it will be a difficult choice to select just one of them. Remarkably both technologies can achieve the dramatic improvement over EGRET, outlined in table 1, with an instrument that will only be twice as heavy.

Next-generation VHE telescopes

The success of the atmospheric Čerenkov imaging technique has led to plans for next-generation VHE telescopes (NGVHETs) of increased collection area and complexity. One of the most ambitious of these is the Very Energetic Radiation Imaging Telescope Array System (VERITAS), first proposed to the Smithsonian Institution in 1996. An international collaboration has been formed to build this array of 10 m aperture Čerenkov telescopes in southern Arizona.

Similar NGVHETs are now under construction in the southern hemisphere: the High Energy Stereoscopic System (HESS) is a European collaboration based in Heidelberg, Germany, which plans to build an array of four 12 m telescopes in Namibia and the Collaboration of Australian and Nippon for a Gamma-Ray Observatory in the Outback-IV (CANGAROO-III) is an Australian–Japanese collaboration which will add three more 10 m telescopes to their existing 10 m telescope in Woomera, Australia.

VERITAS will consist of six telescopes located at the corners of a hexagon of side 80 m with a seventh at the center. The telescopes will be similar to the design of the Whipple 10 m reflector, which is the most sensitive telescope of its kind. By employing largely existing technology in the first instance and stereoscopic imaging, VERITAS will achieve the following:

- effective area >0.1 km^2 at 1 TeV;
- effective energy threshold <100 GeV with significant sensitivity at 50 GeV;
- energy resolution 10–15% for events in the range 0.2–10 TeV;
- angular resolution <0.05° for individual photons and source location to better than 0.005°.

Other designs are also under consideration. In the northern hemisphere a European collaboration centered in Munich, Germany, is building an advanced technology 17 m telescope called MAGIC. This will effectively bridge the energy gap between space- and ground-based γ-ray telescopes. There are also three groups using large solar arrays in an attempt to significantly lower the threshold of the technique. Although their optics are crude, such arrays can have very large mirror areas (>1000 m^2) and attain energy thresholds below 50 GeV. Two such experiments, STACEE in the USA and CELESTE in France, have already reported the detection of a signal from the Crab Nebula.

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