



Very High-Energy Gamma Ray

by GAURANG B. YODH

THE VERY HIGH-ENERGY GAMMA RAY WINDOW ON THE UNIVERSE

A *new generation of gamma ray telescopes being built throughout the world using air Cerenkov and air shower techniques will be able to detect rare, very high-energy gamma rays from distant celestial sources, thus enhancing our understanding of cataclysmic astrophysical events.*

THE EARTH IS CONTINUOUSLY BOMBARDED by cosmic rays whose energy spectrum extends from a few GeV to 10^{11} GeV. After almost eighty years, since the discovery of cosmic radiation by Hess in 1912, the origin of cosmic rays is still not well understood. Understanding the nonthermal processes and the environments that generate these high-energy particles is a fundamental problem in astrophysics. Gamma rays produced by the energetic collisions of particle beams in these sources can be rare messengers that provide important clues to understanding these energetic electromagnetic and nuclear processes. In this view, the sources of gamma rays of energies above about 100 GeV must be beams of charged particles that have been accelerated to still higher energies. Some of the possible sources for energetic gamma ray production include jets emerging from active galactic nuclei, the catastrophic collisions that seem to be responsible for gamma ray bursts, special radio galaxies, and the environments of rapidly spinning neutron stars or supernova remnants. Even more exotic sources for these energetic gamma rays have been proposed, such as the annihilation of weakly interacting massive particles producing monochromatic gamma rays, and also the decay of cosmic strings left over from the Big Bang.

Very high-energy (VHE) gamma ray astronomy is the observational science of measuring their flux, point of origin, energy spectra and temporal variations. These measurements provide the test bed for theoretical models of the astrophysical sources generating high energy particle beams, the nature of the medium in which they generate the gamma rays, and the

Detectors



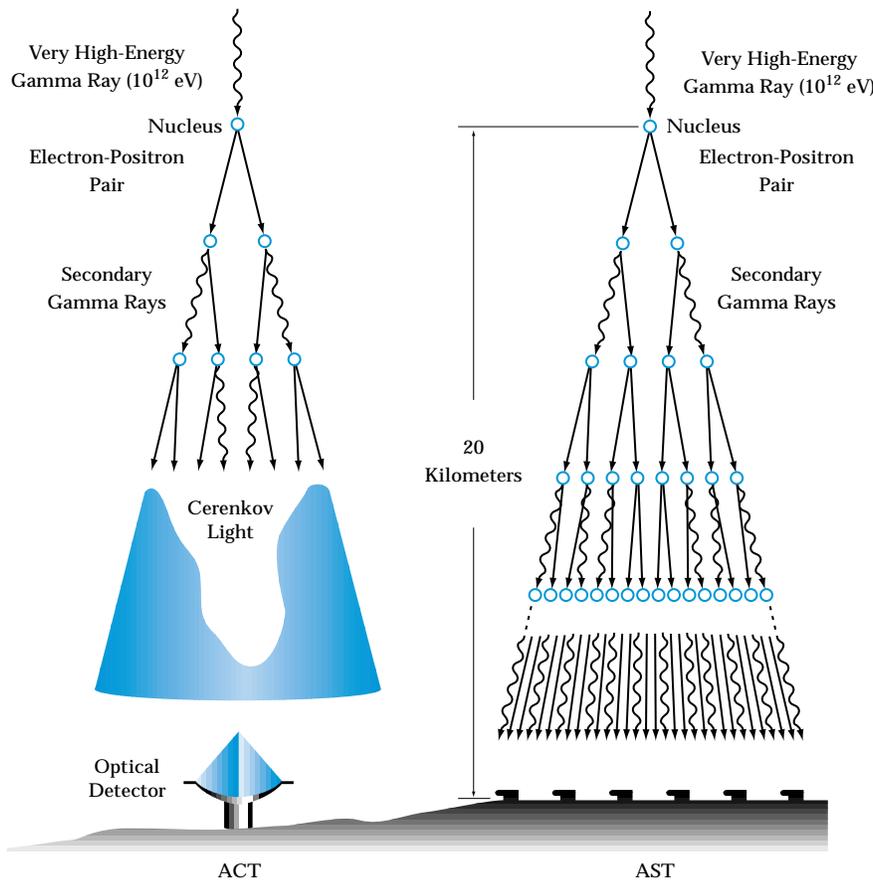
properties of the background photons that can modify the source spectra of gamma rays during their transit to Earth. Specifically, VHE refers to energies above a few hundred GeV, which corresponds to wavelengths smaller than about 6×10^{-9} nanometers. The telescopes that are used to study VHE gamma rays have to be sensitive to very small fluxes, typically 6×10^{-4} photons per square meter per hour. Considerable ingenuity is thus needed in designing telescopes to achieve believable detection of this very small flux.

It is particularly important at the outset to emphasize a fundamental difference between particle showers that are initiated by gamma rays and those initiated by cosmic rays (mostly protons). Protons and other electrically charged particles have their motion affected by galactic and intergalactic magnetic fields, which means that their arrival direction on Earth does not “point back” toward their source. This is not the case with the electrically neutral photons of gamma radiation, for which arrival direction does in fact correlate with source direction.

Since about 1987, VHE astronomy has achieved the status of credible observational science with the unambiguous detection of two galactic and two extragalactic sources in the few hundred GeV to few TeV energy range by the atmospheric (or air) Cerenkov telescope (ACT) technique. These observations have provided excellent challenges to theoretical modelers of these sources.

Typical energetic extragalactic sources observed by air Cerenkov telescopes are the two active galactic nuclei (AGN) blazars Markarian (Mrk) 421 and Mrk 501. Mrk 421 is at a distance of about 120 Mpc; its intrinsic luminosity in TeV gamma rays, if it is all beamed into a solid angle of

The longitudinal and lateral development of a gamma ray shower in Earth's atmosphere, which spreads the influence of the single incident gamma ray over a large area at the surface of the earth. The left illustration is the spread of the Cerenkov light pool, and at the right is the spread of air shower particles. The Cerenkov light is collected by an optical light collector, and the air shower is sampled by a set of detectors spread out on the ground.



0.01 steradians, corresponds to a relativistic mass conversion rate of more than one millionth of a solar mass per year! It is extremely efficient in generating nonthermal gamma radiation. Trevor Weekes of the Whipple Observatory in Arizona has described these observations as if “we are looking down the barrel of a gun, or a powerful cosmic jet, to see how it works.”

NATURE'S GIFT

What makes it possible to detect such small fluxes? Most space-based

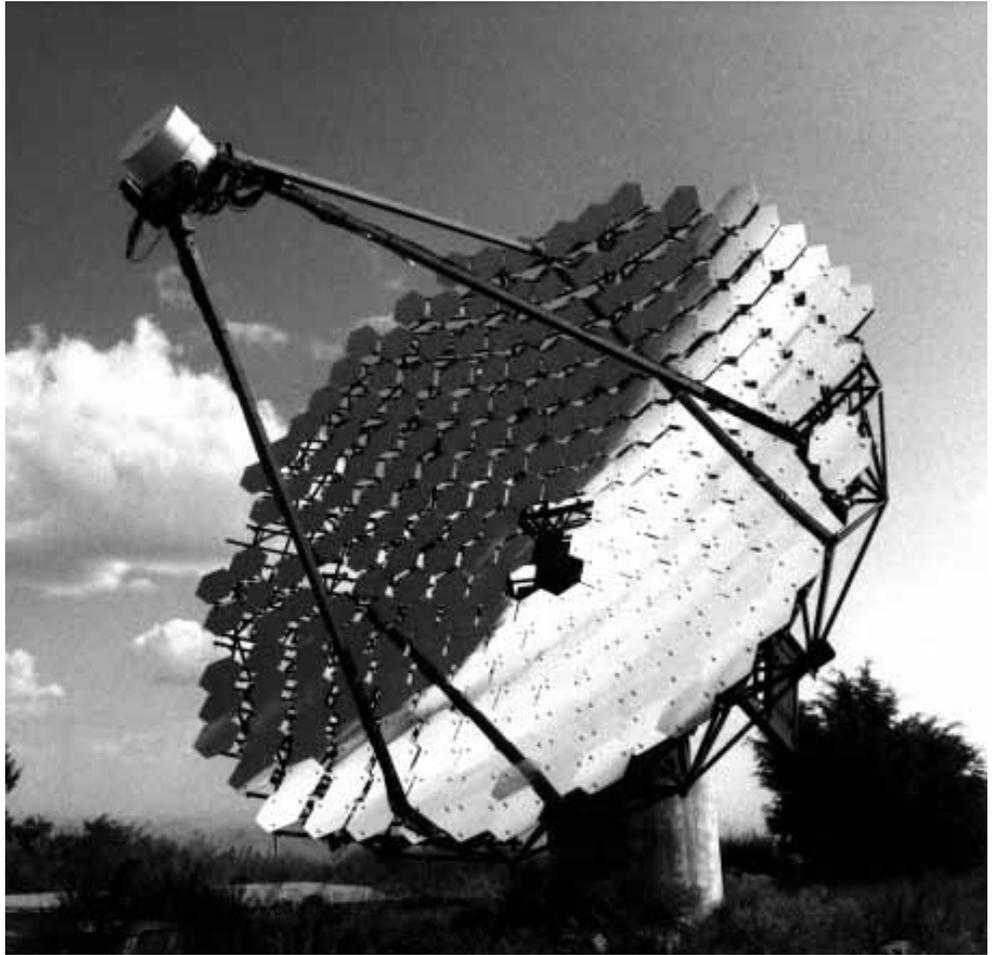
instruments are limited in size, having a collecting area of only few square meters, and hence they become insensitive to detection at energies above about 10 GeV, because the flux decreases so rapidly with energy. Instead, we have to rely on the atmosphere to spread out the influence of each individual gamma ray over a large area. The very high-energy gamma rays, coming from a distant source, interact in the upper atmosphere and in so doing generate a large splash or cascade of particles, consisting mainly of electrons and positrons and photons, which all move at or almost at the speed of light. This cascade process serves two purposes: first, it transforms a single high-energy gamma ray into a very large number of fast-moving charged particles; and second, it spreads these particles out over a huge area.

The relativistic particles generate a flash of Cerenkov light, an electromagnetic shock wave which air Cerenkov telescopes (ACT) can detect. Those particles, both charged and neutral, that manage to penetrate down to ground level can be detected by air shower telescopes (AST). Conversion of a single gamma ray into either a light flash or a particle swarm is shown schematically in the illustration on the left. The effective collecting area for Cerenkov light is greater than 25 acres and for an air shower is greater than 2.5 acres at energies around 1 TeV. Such large areas make it possible to detect the minute fluxes of these high energy gamma rays.

CERENKOV AND AIR SHOWER TELESCOPES

Cerenkov Telescopes. The Cerenkov light pool reflects mainly the longitudinal development of the particle cascade. This light is detected by a Cerenkov telescope, which has a large optical mirror that is typically five or more meters in diameter. The Whipple telescope shown on the right is 10 meters in diameter (33 feet) and produces an image of the cascade in a high speed camera. The camera needs to be very fast because the Cerenkov flashes last only a few nanoseconds. These telescopes, like other optical instruments, are currently restricted to operating on dark nights and can point only at one source at a time. Typical observation times are a few hours each night.

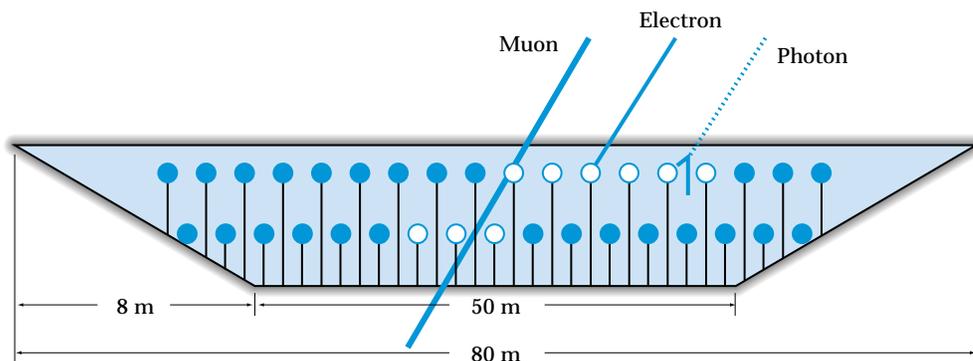
Cerenkov imaging telescopes have a powerful capability: they can discriminate against events generated by ordinary cosmic rays. Showers are produced not only by the gamma rays we desire to see but also by the much more copious cosmic rays. It is therefore imperative to discriminate against these cosmic ray background showers. This is done in imaging Cerenkov telescopes by requiring that the shape of the image correspond to a gamma-initiated shower and not to a cosmic ray shower. This was first achieved by the Whipple collaboration at Mt. Hopkins in Arizona. They are able to reject over 95 percent of cosmic ray showers. One other advantage of the Cerenkov technique is that it can measure the total light generated by



the shower, which is proportional to the energy of the primary gamma ray. Finally, the ACT technique has superior angular resolution, which also makes it possible not only to reject cosmic rays but also to study the spatial properties of sources that are not point-like. The Whipple telescope has established the Crab Nebula as a standard candle and has been the first to detect the two extragalactic sources, the Blazars Mrk 421 and Mrk 501, mentioned previously.

The limitations of imaging Cerenkov telescopes are that it is difficult for them to observe more than one source at a time, and they are not operative all the time as they require dark nights. These difficulties are being overcome through the use of a new AST technique that is ideally suited for continuous operation, day

The Whipple Observatory 10 m optical collector and its imaging camera on Mt. Hopkins in Arizona. The imaging camera consists of a cluster of photo-multipliers that make a fine-grained image of the sharp Cerenkov light pulse. (Courtesy Whipple Observatory)



Schematic cross section of the Milagro detector showing the two layers of photomultipliers (circles). The lighter circles represent tubes that have responded to the Cerenkov light emitted by air shower particles traveling through water. Three different kinds of air shower particles are indicated: electrons (positrons); MeV gamma ray photons; and penetrating muons. The signals from all responding PMTs are recorded—both time of hit and size of the pulse—from which the arrival direction can be reconstructed.

or night, and that can monitor the overhead sky.

Air shower telescopes. Conventional ground-based air shower telescopes consist of a collection of detectors, such as scintillation counters which respond to the passage of charged particles spread out over more than 2.5 acres. These counters typically provide an active area coverage of only about one percent. To be able to detect showers produced by TeV primaries, it is imperative to build arrays at high altitudes as the maximum number of shower particles occurs high up in the atmosphere. One small array has been operating at Mt. Chacaltaya, Bolivia, at 17,000 feet for many years, first started in the 1960s by George Clark of the Massachusetts Institute of Technology.

A modern shower array dedicated to searching the skies for very high-energy gamma rays is the Tibet Array, operating at about 14,000 feet at Yanbajing, a few hours from Lhasa. This array is shown on pages 12 and 13. It has a threshold energy of a few TeV. Particle showers from the air shower hitting the array are detected. These particles form a swarm that is a few nano-lightseconds in thickness. Hence by measuring the arrival time and pulse heights of the responding detectors one can reconstruct the content of the shower as well as its direction to an accuracy of about a half of a degree.

A new type of air shower telescope, called Milagro (or “miracle” in Spanish), is under construction at about 9000 feet in the Jemez mountains in New Mexico. It consists of a large pond (80m × 60m × 8m deep) of water that is instrumented with 840, 8-inch photomultipliers (PMTs). As the showers produced by the desired gamma rays as well as cosmic rays hit the pond, they contain electrons, positrons, MeV gamma rays, muons, and hadrons. Upon entering the water, all of these particles produce Cerenkov light, which is then detected by the photomultipliers. The pond is encased in a light-tight bubble (somewhat like a tennis court bubble but black), so that the pond is sensitive day and night. It is fully sensitive over its entire area of 5000 m² or the size of a typical football field. A schematic of the cross section of Milagro is shown in the illustration above left. The pulse height and time signals from these PMTs are recorded, and the event is reconstructed online to yield information about the energy of the shower and the direction of the originating particle.

The performance of this instrument has been tested in its first phase, called Milagrato. It has been operated for about a year and a half. The photographs on the next page illustrate some of the features of this novel telescope.

The advantages of the Milagro telescope are that it is operational day and night; it views the entire overhead sky all the time; and it is particularly suited to observation of transients. When in full operation it will be sensitive down to a few hundred GeV, thus overlapping the

For readers wishing to pursue very high-energy gamma rays in more detail, the following URLs may be helpful:

Whipple Telescope

<http://egret.sao.arizona.edu/links.html>

MAGIC

<http://hegra1.mppmu.mpg.de:8000/MAGIC/>

Milagro

http://umdgrb.umd.edu/~milagro/project_summary

Veritas

<http://pursn3.physics.purdue.edu/veritas/>

STACEE

<http://hep.uchicago.edu/~stacee/>



Jordan Goodman

energy range of ACTs. With the addition of an array of water tanks outside the pond, Milagro will have sensitivity into the high energy range of 10 to 100 TeV as well. At these higher energies Milagro will have the unique capability of detecting the muons that are produced only in cosmic ray showers. This will provide for cosmic ray rejection at higher energies and a means of extending the energy spectrum into the region where a cutoff is expected to the absorption of gamma rays in transit from source to Earth by ambient background photons.

WHERE ARE WE GOING WITH THE ASTRONOMY?

The air Cerenkov and air shower telescopes described here are not the only ones that are currently being constructed or proposed. These instruments are intended to explore what we have currently defined as the very high-energy gamma ray region. There remains an energy gap, between 10 GeV and a few hundred GeV, that is still virgin territory. Satellite or space station-based instruments, such as GLAST and AMS, are currently under development; these will correspond to second generation versions of the Compton Gamma Ray Observatory and should explore the 10 to 100 GeV sky.

Certain ground based instruments are also being constructed to span this energy gap. One example, called STACEE, is being constructed in New Mexico using solar collectors at Sandia Laboratories. A new proposal from Germany, called MAGIC, would build a 17 m optical collector to image the Cerenkov light from showers in this energy range with an advanced camera. A multiple imaging Cerenkov telescope is being constructed on Mount Abu in India. A multiple mirror array of telescopes of the Whipple design, called Veritas, is being vigorously pursued in the U.S. under the leadership of the Whipple collaboration. A comparison of light flux sensitivity, collection areas, and energy thresholds for ACT telescopes coming into operation or whose proposals are actively being pursued is given in the table below. These instruments will

Above left: The Milagro pond is enclosed in a light-tight inflated cover that can withstand the weather. It is possible to work under the cover for installation or maintenance activities. Above right: A view of the Milagro volume under the cover. The structure is used to anchor the photomultipliers on a 3m x 3m grid. The photomultipliers are attached to the grid by strings and rise to their required position by buoyancy force.

increase the sensitivity for source searches by over two orders of magnitude and lower the energy threshold by a factor of about ten compared to those of currently operating ACT telescopes. This partial list of projects indicates that in the next decade we should have gamma ray coverage of the high-energy universe from a few hundred MeV to 100 TeV. We can look forward to providing much-needed clues to understanding non-thermal energetic processes in the Universe, and perhaps even the question of the origin of cosmic rays.

Light flux sensitivity, collection areas, and energy thresholds for some contemporary telescopes.

Telescope	Minimal Photon Flux (photons/m ²)	Collector Area (m ²)	Energy Threshold (GeV)
Whipple 98 ^a	16	74	100
Veritas ^b	10/telescope	9x74	60
MAGIC ^c	1-2	234	20
STACEE ^c	2-5	Large	30-80

^aThe upgraded Whipple telescope will be operating in 1998.

^bProjects in proposal stage.

^cCurrently under construction.