Current Status of VHE Astronomy

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Very-high-energy astronomy studies the Universe at energies between 30 GeV and 100 TeV. The past decade has seen enormous progress in this field. There are now at least seven known sources of VHE photons. By studying these objects in the VHE regime one can begin to understand the environments surrounding these objects, and how particle acceleration is realized in nature. In addition the photon beams from the extragalactic gamma-ray sources can be used to study the electromagnetic fields in the intervening space. This recent progress can be traced to the development of a new class of detector with the ability to differentiate between air showers produced by gamma rays and those produced by the much more numerous hadronic cosmic-ray background. Much more sensitive instruments are currently in the design phase and two new types of instruments are beginning to take data. In this paper we will discuss the physics of these sources and describe the existing and planned detectors.

I. INTRODUCTION

The first telescope sensitive to TeV radiation was an air Cerenkov telescope built in the 1950's by J.V. Jelley [6]. It would take over three decades to convincingly detect a cosmic source of TeV photons [12]. Real progress did not occur until a second generation of telescopes was built that could differentiate between air showers produced by gamma rays and those produced by protons and heavier nuclei. We now know of at least seven sources of TeV gamma rays, from the Crab nebula, to the distant active galaxies. There are several experiments now in the design phase that promise a sensitivity more than an order of magnitude better than current instruments. In addition there are two entirely new classes of detectors being brought online. One of these is sensitive to very low energy gamma rays (30-50 GeV) and the other capable of continuously monitoring the entire overhead sky. The next decade will be an exciting one for VHE astronomy.

II. THE DETECTION OF VHE GAMMA RAYS

When a high energy cosmic ray (photon or nucleus) enters the atmosphere it loses energy through interactions with the nuclei in the atmosphere. At high energies the energy loss is dominated by processes that create particles (nuclear interactions, bremsstrahlung, and pair creation). The result is an extensive air shower - a swarm of particles traveling towards the ground at nearly the speed of light. The number of particles in the swarm increases until the average energy per particle falls below $\sim$80 MeV. At that point the dominant interactions do not lead to particle production, and the air shower begins to die. For sufficiently energetic cosmic rays enough particles reach the ground to be directly detected.

There are two well developed techniques for detecting $\sim$TeV gamma rays. The first detects the Cherenkov radiation from the electromagnetic particles as they traverse the atmosphere. This radiation is beamed forward with an opening angle of $\sim$1 degree. When the Cherenkov light reaches sea level it is in the shape of a pancake, roughly 200 meters across and 1 meter thick. The photon density at sea level is roughly 200 photons m^{-2} TeV^{-1} of primary gamma-ray energy. This light must be detected over the night-sky background, $\sim$4000 photons m^{-2} ns^{-1} sr^{-1}. Air Cherenkov telescopes consist of one or more large mirrors which focus the Cherenkov light onto a camera placed at the focal plane. Present cameras consist of an array of photomultiplier tubes (PMTs). Since these are pointed optical instruments, they view only a small piece of the sky ($\sim 4 \times 10^{-3}$sr), and they can only operate during clear moonless nights. (Recently progress has been made in the ability to operate with a partial moon [11].) Table I gives the important characteristics of some of the air Cherenkov instruments now in operation.

The second technique is to directly detect the particles that survive to the ground. Until recently the dominant detector material was plastic scintillator. Recently, water has been used as a detection medium. Since the particles also travel in a pancake and are beamed forward, the plane of the particle front is perpendicular to the direction of the primary cosmic ray. Thus, by measuring the relative arrival time of the shower front on the ground, one can reconstruct the direction of the primary cosmic ray. Typical scintillation arrays deployed between 100 m^2 and 1000 m^2 of scintillator dispersed over 10^4 m^2 to 10^5 m^2 of land. With such a sparse sampling of the surviving particles they are only sensitive to much higher energy primary gamma rays ($\sim$100 TeV). Recent advances, such as the use of water as a detection medium (which allows for a dense sampling of the air shower) and the move to very high altitudes has led to energy thresholds near or below 1 TeV for particle detection arrays. These particle detector arrays view the entire overhead sky and can operate continuously.

The current set of available instruments may be divided into three categories based on both the experimental techniques employed and the physics goals of the instruments: high sensitivity instruments, low-energy threshold instruments, and open aperture/high duty cycle instruments.

A. High Sensitivity Instruments

The Whipple gamma-ray telescope was the first instrument in this class. The mirror area is of moderate size and the camera is an array of 330 PMTs. Each PMT views 0.25° of the sky and the field-of-view of the camera is roughly 3°. More modern instruments have been built with finer resolution cameras. The CAT telescope in the Pyrenees has a camera with 0.1° pixel size. The finer camera resolution leads to better rejection of the background, however simulations indicate that resolution finer than 0.1° will not lead to an improvement in sensitivity.

This type of instrument is known as a high-resolution imaging detector. The shape and orientation of the image of the Cherenkov light pool is sensitive to the direction and type of the primary cosmic ray. The image induced by a primary gamma ray forms an ellipse. The semimajor axis of the ellipse points to the source position in the image plane. In contrast, the image of a proton initiated shower will be more chaotic and the larger transverse momentum of the hadronic interactions leads to a wider image. Also, in general the protons do not come from the source direction, hence the semimajor axis of a fit ellipse will not point to the source location.

The energy resolution of these instruments is limited by their ability to locate the "core" of the extensive air shower. (The core of an EAS is the location where the primary cosmic ray would have hit the ground in the absence of an atmosphere.) At present the HEGRA collaboration has an array of six telescopes operating in the Canary Islands. Multiple measurements the shower density allow one to reconstruct the core location with high precision. The energy resolution of this array is roughly 20% (ΔE/E), while the energy resolution of single telescope is $\sim$40%.

B. Low Energy Threshold Instruments

Huge mirror areas must be used to achieve energy thresholds well below 100 GeV. Since the Cherenkov light must be detected in the presence of the night-sky background, the energy threshold of an air-Cherenkov telescope is inversely proportional to the square root of the mirror area. In the early eighties the large mirror area afforded by solar power plants was suggested as an economical way of achieving very low energy thresholds ([23]). At present there are two such installations beginning operations, the CELESTE group operating in the Pyrenees and the STACEE collaboration in the United States. Both groups have achieved energy thresholds below 50 GeV.

C. Large Aperture/High Duty Factor Instruments

Despite the relatively high energy thresholds of these instruments they have several advantages over air-Cherenkov telescopes. They can be operated continuously and they view the entire overhead sky. There have been two efforts to lower the energy threshold of these instruments. The Tibet collaboration has built a small, dense scintillator array at very high altitude (4 km asl). At this altitude many more shower particles survive to the ground. They have achieved an energy threshold below 10 TeV. The second group has developed a water Cherenkov detector, known as Milagro [19]. Since the Cherenkov angle in water is $\sim 41°$, a sparse array of PMTs in a large pool of water can detect nearly every electromagnetic particle that reaches the pool. In addition the gamma rays in the air shower (which outnumber the electrons by ∼4:1) convert to electrons and/or positrons in the water and are detected with high efficiency. Using the dense sampling of the air shower the Milagro collaboration hopes to have an energy threshold below 1 TeV.

III. THE PHYSICS OF VHE GAMMA RAYS

A. Neutron Stars

Neutron stars are compact objects, measuring ∼10 km across with a mass of about 1.4 times the mass of our sun ($M_\odot$). The surface layer is composed of iron and the density near the core is $\sim 10^{15}$ gm cm^{-3}. They are the final stages of stellar evolution, being left behind after a massive star goes supernova. Conservation of angular momentum and magnetic flux lead to rotational periods of several milliseconds to 10s of seconds and magnetic fields around 10^{12} Gauss at the surface.

The region around the neutron star is known as the magnetosphere, which is composed of a charge separated plasma threaded by magnetic field lines. Charged particles escape the magnetosphere along the open field lines emanating from the poles of the star. This wind of particles terminates in a shock where electrons are accelerated to TeV energies. The energetic electrons enter the nebula, emit synchrotron radiation as they spiral in the magnetic field, and upscatter the synchrotron photons to TeV energies via inverse Compton scattering. This model is known as the synchrotron self-Compton (SSC) model [4].

B. Active Galaxies

The heart of an active galaxy is a supermassive black hole ($10^6 - 10^{10}$ $M_\odot$). The black hole is surrounded by an accretion disk that is fed by the host galaxy. Radio loud AGN have jets of relativistic particles emitted along their rotation axes. Among the radio loud AGN it is believed that all the observed classes are simply the same type of object viewed from different orientations. Blazars are a special class of radio loud AGN that have their jets closely aligned with the line-of-sight. To date all of the AGN detected in the VHE regime are blazars.

There are two general models for the production of TeV gamma rays from AGN. In the first model, similar to the SSC model detailed above, electrons are accelerated by a shock front moving within the jet. These electrons emit synchrotron radiation which they then upscatter to TeV energies. Variants to this model exist, the main variation being the source of the upscattered photons.

In the second class of models protons are accelerated to extremely high energies, 10^{18} eV. These protons initiate a particle cascade through $p\gamma \to \Delta \to \pi's$ (the ambient $\gamma's$ come from synchrotron radiation emitted by accelerated electrons). The π^0's decay into photons which pair produce with the same synchrotron photons. The resulting electromagnetic cascade shifts the gamma-ray energy to ∼10 TeV [14].

Since electrons are light they can be accelerated quickly, though radiation losses make it difficult to accelerate them to very high energies. Conversely, protons can be accelerated to very high energies, but their acceleration rate is slower. Both models predict a characteristic two-humped energy spectrum. In the SSC model X-rays are produced by synchrotron emission from energetic electrons. TeV gamma rays are then produced via inverse Compton scattering of the X-ray photons and the same population of electrons.

C. Gamma-Ray Bursts

Gamma ray bursts are short intense bursts of gamma rays. They vary in duration from milliseconds to hundreds of seconds. While perhaps not universally accepted, the preponderance of evidence indicates that GRBs are distant phenomena, laying well outside of our galaxy. Most current models involve one or more highly relativistic shells (perhaps the aftermath of a neutron star-neutron star merger) interacting with each other or with an external medium. A highly relativistic shock forms at the interaction region, leading to particle acceleration [15,16]. Though no detections of GRBs have yet been made in the TeV regime, the EGRET instrument (on board the Compton Gamma Ray Observatory) has observed GeV photons from GRBs [9]. The Milagro and Tibet experiments (with their all-sky, all-time capability) will greatly increase our sensitivity to TeV emission from GRBs.

D. The Inter-Galactic Infra-Red Radiation Field

The interaction cross-section for $\gamma\gamma \rightarrow e^+e^-$ is large when the invariant mass of the two colliding photons is just above twice the rest mass of the electron. TeV photons interact with infrared and visible photons, leading to an apparent attenuation of the source at high energies [7]. The attenuation of high-energy photons depends on the distance to the source and the intensity of the inter-galactic infrared radiation (IGIR) field. Since most of this field has its origin in the early period of star formation, it should be sensitive to the details of structure formation in the Universe [13]. However, significant reprocessing of this radiation has occurred over the lifetime of the Universe. At present it is still a matter of debate if the initial conditions of structure formation can be extracted from a measurement of the IGIR field [20].

In principle one could use the observed spectra of AGN to measure the IGIR field. However, there is the complication that absorption of TeV photons may also occur at the source, and we do not know the intrinsic energy spectrum of these sources. To improve the models of particle acceleration in AGN, multi-wavelength campaigns (TeV, x-ray, and optical) of AGN in both their flaring and quiescent states are required. However, the observation of similar AGN at several redshifts will probably be required before a convincing measurement of the IGIR can be made. Since only weak AGN have been detected to date in the TeV regime, this implies the need for telescopes with sensitivities $\sim$10 times greater than current instruments. Several such instruments are planned.

IV. OBSERVATIONS OF VHE GAMMA-RAY SOURCES

A. Galactic Sources

The Crab nebula is powered by a pulsar spinning 30 times per second. The nebula is filled with relativistic electrons injected from the pulsar. Figure 1 shows the measured energy spectrum of the Crab out to almost 50 TeV. The high energy measurements have been made by the CANGAROO collaboration by observing the source at large zenith angles [22]. The data are well described by the SSC model outlined above [4]. The best fits to this model indicate that the magnetic field strength in the region where the TeV gamma rays are produced is roughly 16 nT [8]. The parameter σ in the figure is the ratio of magnetic energy to total energy in the pulsar wind. The bulk of the energy in the wind is the kinetic energy of the particles. To date, no pulsed emission from the Crab has been observed above 30 GeV.

Three other galactic sources have been detected in the TeV regime: Vela [25], PSR1706-44 [10], and SN1006 [21]. The first two of these sources are filled supernova remnants similar to the Crab nebula, while SN1006 is a shell type supernova remnant (SNR). SNRs are the favored location for the acceleration of hadronic cosmic rays. The TeV emission emanates from one rim of the expanding shell. While this discovery at first appeared to be evidence of cosmic ray acceleration within supernova remnants, recent calculations indicate that the observed TeV emission is consistent with expectations from an inverse Compton component associated with the acceleration of electrons. Thus there is still no direct evidence for the acceleration of nuclei within supernova remnants.

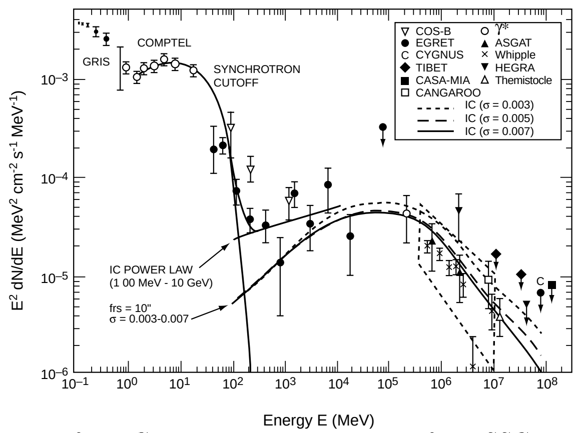

FIG. 1. The measured energy spectrum of the Crab nebula. Predictions of the SSC model are superimposed on the figure. The different model predictions correspond to different values for the ratio of magnetic energy to the total energy (σ) in the pulsar wind.

B. Extra-Galactic VHE Gamma-Ray Sources

To date two confirmed detections of AGN in the TeV energy regime: Mrk421 and Mrk501. There are also several unconfirmed AGN detections: 1ES 2344+514 and PKS 2155-304 [3]. Mrk421, Mrk501, and 1ES 2344+514 are relatively close with redshifts of order 0.03, while PKS 2155-304 lies at a redshift of 0.117. Mrk421 was the first extragalactic object to be observed in the TeV band. The average flux from this source is roughly 1/3 that of the Crab nebula [17]. However, in contrast to the emission from the Crab, the luminosity of Mrk421 varies wildly over a large range of timescales. This same variability has also been observed in Mrk501. The AGN 1ES 2344+514 was discovered during an apparent flare, however the quiescent emission is too low to monitor the long-term behavior of this source [2]. Observationally there are two important measurements made of the AGN, their variability and their energy spectra.

The observed minimum time scale of variability is related to the size of the source, the relativistic bulk motion of the source, and the acceleration timescale. The shortest variability timescale observed to date, from Mrk421 with the Whipple observatory [5], was fifteen minutes. A short variability timescale is more easily explained in electron models, although the proton model can explain the current observations if the bulk Lorentz factor of the source is increased. Also of interest is the long term flaring behavior of these sources. In Figure 2 we show the observed flux from Mrk501 over a three year period. The source exhibits long periods of inactivity followed by periods of intense flaring that may last for several years. The cause of this long term behavior is as yet unknown.

The upper range of the energy spectrum of an AGN is determined by the bulk Lorentz factor, the balance between acceleration and cooling of the particles, and the optical depth of the source to TeV gamma rays. The best measurement of the energy spectrum of an AGN above 5 TeV has been made by the HEGRA group [1]. While the HEGRA group has a measured a significant number of photons between 19 and 24 TeV, they establish a 2σ C.L. lower limit to the maximum energy of 16 TeV. Since electrons cool more efficiently than protons it is more difficult to accelerate them to very high energies. However, current measurements of the maximum energy are consistent with the SSC model.

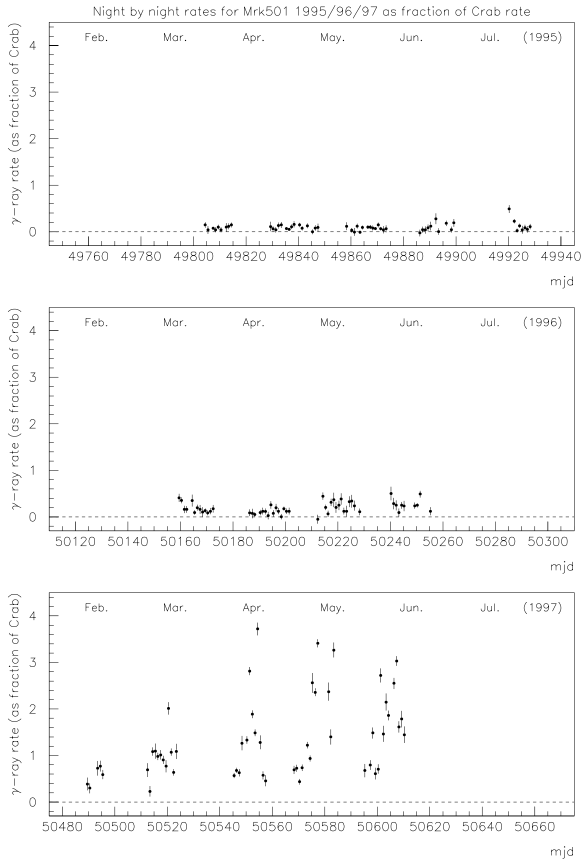

FIG. 2. The measured flux from Mrk501 over a three year interval [18].

V. THE FUTURE OF VHE ASTRONOMY

TeV gamma-ray astronomy has reached a productive stage of development. The 1970's and early 1980's were a period marked by controversy and conflicting results. The development of a second generation of imaging Cherenkov telescopes paved the way for convincing discoveries of sources of TeV gamma rays. Several new instruments just now coming online promise to open the field to new types of physics. All-sky instruments such as Milagro and Tibet will be sensitive to a TeV component of gamma-ray bursts. They also have the ability to provide long-term monitoring of AGN and perhaps discover new sources of TeV gamma rays. The solar array air Cherenkov telescopes will have very low energy thresholds, comparable to the upper energy range of space-based instruments. They could enable us to observe a pulsed component to the Crab, observe the more distant AGN, and/or AGN where absorption of TeV photons at the source is important.

Farther down the road there are several instruments planned that will achieve sensitivities over ten times better than current instruments. These include the Veritas array and MAGIC in the northern hemisphere and HESS and Super CANGAROO in the southern hemisphere. Veritas [24], HESS, and Super CANGAROO will consist of arrays of large high-resolution imaging telescopes. The MAGIC telescope will be one large 220 m^2 mirror with high quantum efficiency PMTs in the camera. Figure 3 shows the expected sensitivity of several current and planned instruments. These instruments should detect over 30 AGN and allow for a full exploration of the TeV Universe.

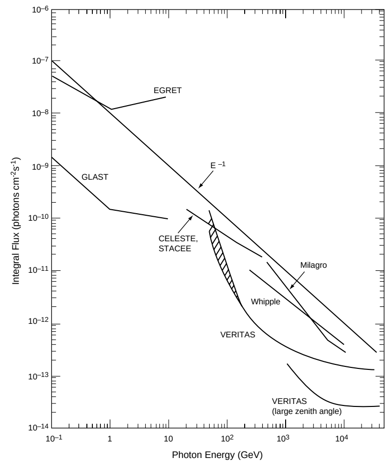

FIG. 3. The sensitivity of selected current and planned TeV gamma-ray observatories.

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TABLE I. Characteristics of current VHE air Cherenkov telescopes. Numbers given in parentheses are planned.

Detector	Mirror Area	Energy Threshold (GeV)	Number of Pixels	Number of Telescopes	Location
Whipple	75 m^2	200	330	1	Arizona, USA
CAT	17 m^2	190	534	1	Pyrenees, France
CANGAROO	11.3 m^2	1000	256	1	Woomera, Australia
HEGRA	8.5 $m^2 \times$ 5	1000	271×5	5	La Palma, Canary Islands
Telescope Array	6 $m^2 \times$ 7	600	256	7	Dugway, Utah
Durham	42 $m^2 \times$ 3	200	109	3	Woomera, Australia
CELESTE	1000 (2000) m^2	60(30)	18(40)	18(40)	Pyrenees, France
STACEE	1230 (2500) m^2	75(50)	32(64)	32(64)	New Mexico, USA