VERY HIGH-ENERGY GAMMA-RAY ASTRONOMY

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Very high-energy (VHE) γ-ray astronomy is an exciting and rapidly developing field. A new generation of telescopes using the atmospheric Cherenkov technique has yielded outstanding results - an unprecedented number of new astrophysical sources have been discovered in the last two years. Many of the new sources are concentrated in the Galactic plane and have a direct bearing on the question of the origin of the cosmic rays; the galactic sources include pulsar wind nebulae, supernova remnants and microquasars. In terms of extragalactic sources, more than ten VHE blazars are now known and the discovery of blazars at increasing values of redshift indicate that the universe is more transparent to TeV photons than originally thought. VHE gamma rays can also be used to search for dark matter annihilations in, or nearby, our Galaxy. As yet, no compelling evidence for dark matter has been presented, but continued observations and new telescopes coming on line soon will continue to explore the remarkable universe as revealed at very high energies.

1 Introduction

The scientific motivation for VHE astronomy is rich and multi-faceted. First, the origin of the cosmic rays is an important outstanding question even ninety years after their discovery. The cosmic-ray spectrum exhibits an unbroken power-law form over an enormous range of energies, from 10^9 eV to 10^{20} eV, and the energy density of the cosmic rays in our Galaxy is large and comparable to the energy density in starlight or in the cosmic microwave background. The fact that the bulk of the cosmic rays are charged particles that bend in the magnetic field of the Galaxy has hampered our ability to deduce their origin. However, VHE gamma rays point back directly to their sources and can directly reveal the production sites of energetic cosmic rays.

Second, the history of astronomy during the last 100 years is one of continual exploration into new wavebands: from optical to radio, to infrared, to X-ray, and finally to γ-ray. VHE astronomy represents the latest new waveband to be opened up. Exploring the universe with VHE gamma rays allows us to see astrophysical TeVatrons - powerful non-thermal sources that

Table 1: VHE γ-ray source counts. The number of established VHE γ-ray sources in shown, indicating the rapid discovery rate in recent years.

Source Type (includes likely associations)	1996	2003	2006
Pulsar Wind Nebulae (e.g. Crab)	1	1	6
Supernova Remnants (e.g. RX J1713-3946)	0	2	6
Microquasars (e.g. LS 5039)	0	0	2
Binary Pulsar (B1259-63)	0	0	1
Diffuse emission (Gal Center, Cygnus)	0	0	2
Active Galactic Nuclei (e.g. Mrk 421)	2	7	11
Radio Galaxy (M87)	0	0	1
Unidentified	0	2	6
TOTAL	**3**	**12**	**35**

accelerate particles to TeV energies and beyond. Table 1 shows a compilation of the number of VHE γ-ray sources by type. In our Galaxy, these sources include pulsar wind nebulae (PWN), supernova remnants (SNRs), microquasars, and the Galactic Center region. Active galactic nuclei (AGN) of the blazar type and the radio galaxy M87 constitute the presently known extragalactic sources. As the field expand, with new telescopes starting observations, we except the discovery of more sources and more source classes as we complete a sensitive survey of the TeV universe.

Third, VHE gamma rays can be used to probe physics beyond the standard models of particle physics and cosmology. As an example of this, we consider the study of the extragalactic background light (EBL) that is poorly understood at the present time. The EBL is the cosmic IR/optical/UV light produced from normal star formation and dust re-radiation. VHE gamma rays from distant sources (such as AGN or gamma-ray bursts) will interact with EBL photons through the pair-production process, and spectral measurements of these sources in the VHE band provide a way to constrain the density and spectrum of the EBL. Searching for cold dark matter represents an example of exploring beyond the Standard Model. If supersymmetric weakly-interacting massive particles (WIMPs) comprise the bulk of the dark matter, their self-annihilations could lead to a measurable VHE γ-ray signal. We expect VHE γ-ray telescopes to provide important complementary information to direct-detection dark matter experiments and to accelerator-based experiments searching for supersymmetry.

2 Experimental Technique

Gamma rays entering the Earth's atmosphere interact with air molecules to produce an electron-positron pair. This pair radiates photons via the bremsstrahlung process and an electromagnetic cascade develops, creating an air shower in the atmosphere. Charged particles (mostly electrons) in the air shower radiate Cherenkov light that is beamed to the ground with a cone opening angle of $\sim 1.5^\circ$. *Atmospheric Cherenkov Telescopes* detect VHE γ-rays by capturing the rapid ($\sim 5\,\mathrm{ns}$) Cherenkov flashes amidst the background of night sky photons. These telescopes use large optical mirrors to focus the mostly blue Cherenkov radiation onto fast photomultiplier tubes (PMTs).

The primary advantages of the atmospheric Cherenkov technique are high sensitivity, excellent angular resolution and energy resolution, and relatively low energy threshold. The disadvantages are moderate duty-cycle ($\sim 10\%$) and small field-of-view (FOV). The Cherenkov telescopes operating today include CACTUS, CANGAROO-III, HESS, MAGIC, PACT, SHALON, STACEE, TACTIC, VERITAS. and Whipple. CACTUS, PACT, and STACEE are examples of wavefront-sampling telescopes that use an array of mirrors to gather the Cherenkov radiation and to measure the arrival time and amplitude of the Cherenkov pulse at many distributed locations on the ground. The other telescopes are examples of the more established imaging Cherenkov technique where the Cherenkov radiation is focused onto an imaging camera at one or more locations on the ground.

Some fraction of the charged particles and photons in VHE air showers reach the ground level and can be detected by *Air Shower Arrays.* These arrays typically consist of charged particle detectors (scintillators or resistive plate counters) spread out on a grid or water Cherenkov detectors in which a large tank of water is viewed by a number of fast PMTs. The primary advantages of the air shower technique are high duty-cycle and very wide FOV. Disadvantages are moderate sensitivity, poor energy resolution and angular resolution, and relatively high energy threshold. Thus, the two major ground-based techniques for detecting VHE γ-rays are fully complementary – both techniques have proven essential in exploring the VHE sky. The air shower telescopes operating today include ARGO-YBJ, GRAPES-III, Milagro, and Tibet.

3 Scientific Highlights

Many new exciting results have been reported during the last several years, especially by the new atmospheric Cherenkov telescopes HESS and MAGIC. The most compelling results are the following:

1. **Galactic Plane Survey:** HESS reported results from a deep survey of the Galactic plane, that led to the discovery of a significant number of new VHE γ-ray sources. Some of these sources are well correlated with known astronomical objects but other sources cannot be easily identified. An important new source whose γ-ray processes are not understood is the Galactic Center.

2. **Detailed Studies of Galactic Sources:** For the first time, a number of VHE sources have been well studied in terms of their spectra, spatial extent, and variability. Considerable progress has been made on the theoretical side to understand these galactic TeVatrons. Among the galactic VHE objects studied are SNRs, PWN, microquasars, and several diffuse sources.

3. **New Extragalactic Sources:** A number of new AGN have been reported by HESS and MAGIC. Three of these new sources are in the redshift range of 0.15-0.20, making them the most distant extragalactic objects yet detected at very high energies. The fact that AGN are detected with relatively hard and continuous spectra at TeV energies has implications for our understanding of the EBL. The radio galaxy M87 has also been studied by HESS with much better sensitivity than previous instruments, revealing interesting short-term dynamics.

4. **Dark Matter Searches:** Searches for dark matter signals have been made from observations of Galactic Center and nearby dwarf galaxies. So far, no compelling signals have been presented, but the limits are beginning to probe interesting regions of parameter space.

4 Galactic Sources

4.1 Galactic Plane Survey

HESS reported results from their survey of the central region of the Galactic plane.[1] The survey was carried out in 2004 with the completed four-telescope array, and it covered a region in Galactic longitude from l = -30° to l = 30°. The coverage in Galactic latitude was approximately b = ±3°. The average flux sensitivity of the survey was 3% of the Crab Nebula at energies above 200 GeV. Eleven sources were detected with a post-trials statistical significance greater than six standard deviations ($> 6\sigma$). Of these sources, only two (Galactic Center and RX J1713) had been reported previously at very high energies.

There are several strong indications that the sources detected by HESS have a galactic, rather than extragalactic, origin. First, the sources are concentrated along the galactic plane with a mean Galactic latitude of -0.17°. Second, the width of the Galactic latitude distribution is consistent with the distribution of young pulsars and supernova remnants in the Galaxy. Finally, all of the sources are extended beyond the size of the HESS point spread function, a result that would rule out, for example, an AGN component.

It is obviously essential to correlate the VHE sources detected in the Galactic plane with known objects in order to establish the various source classes and to search for new, and unexpected, types of VHE γ-ray emitters. The HESS group has made a systematic study of possible counterparts for the sources detected in their survey. A number of the sources from the survey are firmly identified with known objects, including SNR RX J1713-3946, the Galactic Center (SGR A), SNR G0.9+0.1, and the microquasar LS5039. Of the remaining sources, five have plausible associations with supernova remnants or pulsar wind nebulae, one (HESS J1837-069) has a possible association with an unidentified ASCA X-ray source, and two sources (HESS J1614-518 and HESS J1804-216) do not have any well-motivated association.

4.2 Supernova Remnant: RXJ 1713-3946

Before 2005, there was evidence of VHE γ-ray emission from four supernova remnants (SNRs): SN 1006, RX J1713-3946, RX J0852-4622, and Cassiopeia A (Cas A). HESS and CANGAROO have confirmed emission from RX J1713-3946 and RX J0852-4622 and have been unable to detect SN 1006. HESS has also detected others sources in the Galactic plane that can be plausibly associated with supernova remnants, including HESS J1640-465, HESS J1813-178, and HESS H1834-087. We can now say with confidence that shell-type SNRs are general sources of VHE γ-rays.

RXJ 1713-3946 is a large ($\sim 1°$) SNR that has been well studied by a number of X-ray instruments (ROSAT, ASCA, Chandra, and XMM-Newton). The source was detected earlier by CANGAROO and by HESS (using two telescopes in the construction phase). The current measurements by HESS are part of a very strong detection taken with the full four-telescope array.[2] As shown in Figure 1, HESS well reconstructs the spatial morphology of the γ-ray emission; the SNR shell has been clearly resolved and the VHE emission strongly maps the pattern seen in X-rays. Even more, by dividing the data into three bands of energy ($E < 0.6\,\mathrm{TeV}$, $0.6\,\mathrm{TeV} < E < 1.4\,\mathrm{TeV}$, and $E > 1.4\,\mathrm{TeV}$) HESS is able to show that the VHE morphology does not change appreciably with energy. The energy spectrum is well reconstructed from 200 GeV to 30 TeV; the spectral index is hard ($\alpha \sim 2.2$), but the spectrum exhibits curvature and does not well fit a single power-law form. The quality of the HESS data is sufficient to allow spatially-resolved spectral determination - the spectrum measured in 14 different regions of the remnant are not found to vary significantly.

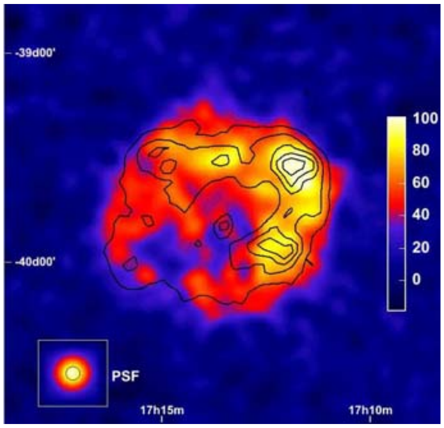

Figure 1: VHE γ-ray excess map of the SNR RX J1713-3946 from HESS. The black contour lines show the surface brightness in 1-3 keV X-rays as measured by ASCA.

4.3 Microquasars

Microquasars generally exhibit strong emission across a broad range of wavelengths, with jets observed in radio and rapid variability in X-rays. The standard picture of a microquasar is one of a binary system in which a normal star orbits around a compact object. Mass lost from the star falls into an accretion disk where it can be heated and ejected or can fall into the compact object. In some ways, microquasars can be considered active galaxies in miniature, and so there is the hope that by understanding microquasars we can shed light on the mechanisms that power AGN.

HESS earlier reported the clear detection of the microquasar source LS 5039.[3] This object consists of a massive star orbiting an unknown compact object with an orbital period of 3.9 d. The source was detected during the galactic plane survey in 2004 and then extensively observed by HESS in 2005. The new data show clear evidence for a periodic VHE γ-ray signal, with a period of 3.9078 ± 0.0015 d and a maximum in the light curve at the point of inferior conjunction (i.e. when the star and compact object are aligned relative to Earth). This is the first established periodic source at TeV energies. HESS measures a hard spectrum (spectral index $\alpha \sim 1.9$) near the point of maximal VHE flux emission and a much softer spectrum (spectral index $\alpha \sim 2.5$) near the point of minimal VHE flux emission. The model for the VHE γ-ray emission is complicated and involves production in the disk or in the jet, along with substantial absorption.

A new microquasar source, LSI +61 303, was reported this year by the MAGIC telescope based on 54 h of data taken in 2005 and 2006. This source is a high-mass X-ray binary at a distance of ~ 2 kpc and an orbital period of 26.5 d.[4] Radio observations have revealed compact jets that lead to this object being classified as a microquasar. Period outbursts are seen in both the radio (near apastron) and X-ray bands (approximately 10 days before the radio). MAGIC detected a point-like source with a statistical significance greater than $9\,\sigma$ at position coincidence with LSI +61 303 and consistent with the EGRET source 3EG J0241+6103. As shown in Figure 2, the VHE γ-ray flux is high (up to 16% Crab) near phases [0.5,0.7], but is low near periastron passage. The energy spectrum at TeV energies is well fit by a single power-law form with spectral index $\alpha \sim 2.6$, and the TeV luminosity exceeds that seen in X-rays. Emission models tend to favor a picture of a binary pulsar where the γ-rays are produced by the interaction of the winds of the pulsar with those of the massive star, as opposed to a microquasar picture. However, more multi-wavelength observations are needed, along with more complete VHE γ-ray observations, in order to elucidate the nature of this fascinating source.

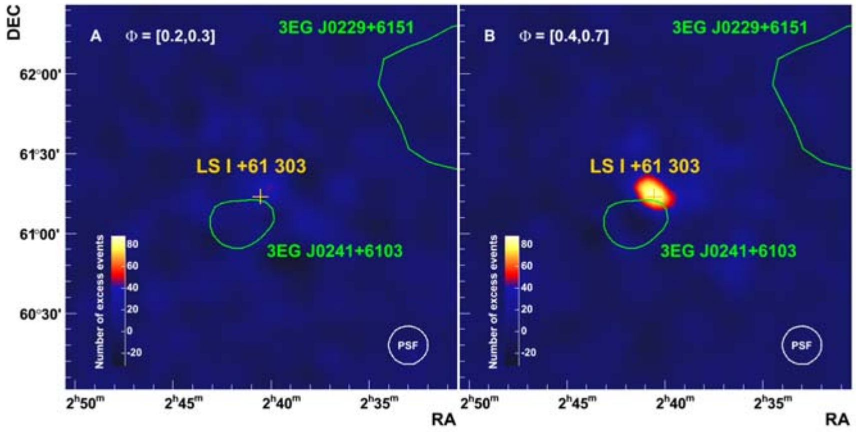

Figure 2: Observations of the microquasar LSI +61 303 by MAGIC. The map of excess γ-ray counts is shown for two different intervals of the orbital phase: [0.2,0.3] on the left and [0.4,0.7] on the right.

4.4 Diffuse Sources

Diffuse γ-ray sources are important to detect and map out for a number of reasons. In our Galaxy, diffuse emission usually signals the interaction of VHE cosmic rays with galactic material such as molecular clouds. The γ-ray emission can thus be used to trace the density of material and to uncover sites of energetic particle acceleration.

Two diffuse VHE γ-ray sources in the Galactic plane have been recently reported. As part of their all-sky survey at TeV energies, Milagro discovered a bright and extended source in the Cygnus region.[5] The source, MGRO J2019+37, appears spatially consistent with the distribution of Galactic material in the region, but its γ-ray flux exceeds that predicted from a conventional model of cosmic-ray production. HESS has discovered diffuse γ-ray emission in the region of the Galactic Center (after removing the contributions two detected point sources).[6] A strong correlation is seen between the VHE γ-ray distribution and that of the molecular clouds, as traced by their CS emission. This result provides strong evidence for γ-ray emission resulting from interactions of cosmic rays with molecular clouds and is consistent with a rather uniform cosmic-ray density in the region.

5 Extragalactic Sources

With the advent of HESS and MAGIC in the last three years, the number of known extragalactic VHE sources has increased significantly. There are at least eleven TeV AGN, all of the blazar type. The general paradigm for these sources is that the gamma rays are produced in a relativistic jet that is oriented along our light of sight. These AGN generally exhibit spectra that have two broad peaks: one at lower energy due to synchrotron radiation and one at higher energy due to inverse-Compton radiation. The VHE emission is highly variable, presumably resulting from changes in the jet or in the beaming geometry, or both.

An important recent result is the detection of several blazars (H2356-309, 1ES1218+304, and 1ES 1101-232) at redshifts beyond $z = 0.15$.[7,8] The fact that TeV photons can reach us from sources this distant argues that the opacity of the universe is less than anticipated. Indeed, the VHE spectral measurements for the most distant blazars have been used to constrain the EBL density to lie just above that predicted from galaxy counts. Figure 3 illustrates the general relation between the redshifts of the known VHE blazars and the expected cutoff energy due to EBL absorption. The new sources at higher redshift values were detected by HESS and MAGIC which have significantly better sensitivity at γ-ray energies below 200 GeV than previous experiments.

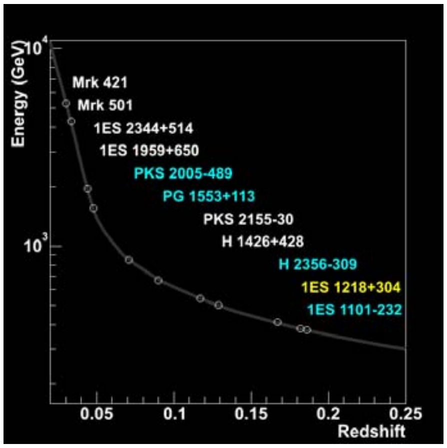

Figure 3: Approximate energy for EBL absorption as a function of redshift for the eleven known VHE blazars.

6 Dark Matter

Understanding the nature of dark matter is one of the most compelling issues facing physics and astronomy. The astrophysical evidence for dark matter is very strong, and it is now generally believed that to fully understand dark matter a variety of instruments and techniques will be needed, including direct and indirect-detection experiments and accelerator-based particle physics detectors. A good possibility for its discovery comes from GeV and TeV telescopes sensitive to gamma rays produced from WIMP annihilations in regions having high dark matter densities. Possible targets include the Galactic center, dark matter clumps in the Galactic halo, nearby dwarf galaxies, and selected extragalactic sources.

The Galactic Center is now well established as strong source of VHE gamma rays, with detections by CANGAROO, Whipple, HESS, and MAGIC. The HESS results are the most significant to date.[9] HESS sees steady VHE emission with a point-like core that is consistent with the location of SGR A* (the radio source linked to the putative black hole at the Galactic Center) and the emission spectrum is well fit by a single, unbroken power law with a hard spectral index of $\alpha \sim -2.0$. Astrophysical possibilities for this emssion include shock acceleration at a nearby supernova remnant or plerion (possibly obscured), the interaction of stellar winds or cosmic rays with ambient material, or non-thermal processes involving the black hole itself. Since the properties of the VHE emission (i.e. simple power-law form) are completely compatible with an astrophysical origin, there is, as yet, no clear evidence for a dark matter signal.

The Draco dwarf galaxy, a nearby satellite galaxy and part of the Local Group, is thought to contain a large amount of dark matter. Recently, CACTUS reported evidence for 100 GeV gamma rays from the direction of Draco; however this evidence was weakened by further analysis of the data.[10] The STACEE solar-array telescope reported preliminary results from 10.2 h of observations of Draco;[11] no γ-ray signal was seen and an upper limit on the flux was placed at < 0.07 Crab at energies above 200 GeV.

7 Upcoming Instruments

A number of new GeV and TeV γ-ray telescopes are coming on line soon or are in the process of construction. GLAST is a major space-borne γ-ray mission that has been constructed by an international consortium and is currently scheduled for launch in October 2007. The mission consists of two instruments, the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). The LAT will have greatly improved performance relative to EGRET on the CGRO

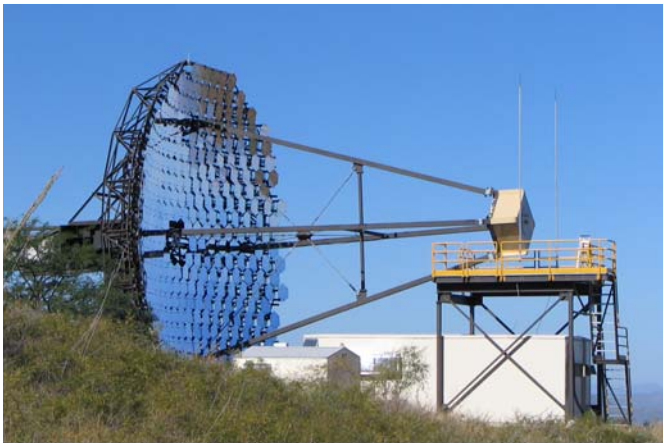

Figure 4: VERITAS Telescope 3 at the basecamp of Mt. Hopkins, Az, as of August 2006. VERITAS in an array of four 12m diameter imaging atmospheric Cherenkov telescopes starting scientific operation in January 2007.

and is likely to detect thousands of point sources at GeV energies and extend the spectra for many of them up into the hundreds of GeV.

On the ground, the capabilities of both the HESS and MAGIC telescopes will be significantly enhanced by major upgrades that should be completed over the next several years. Significantly, the construction of VERITAS in southern Arizona, USA, is now complete. VERITAS (see Figure 4), an array of four large-aperture, imaging Cherenkov telescopes, should have comparable capabilities to HESS. Science observations with VERITAS start in January 2007 and the key science topics include a sky survey, blazars, supernova remnants, and dark matter.

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