Gamma-Ray Astronomy

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In this paper, I present a summary of the status of γ-ray astronomy in the very high energy band (E>50 GeV), as of early 2007. It covers a selection of results obtained from observations made by ground-based detectors using the atmospheric Cherenkov or air shower techniques, together with short descriptions of some of the present and future experiments.

1 Introduction

γ-rays are only a very small fraction ($\approx 10^{-3}$) of the cosmic ray flux, however they are currently the best messengers of ultra-relativistic processes in the Universe. Since charged cosmic rays are deflected by the galactic magnetic fields and cannot be correlated with specific cosmic sites, γ-rays are important in searching for the cosmic accelerators. There are two categories of models for their emission:

1) leptonic models, in which γ-rays are produced via Inverse Compton scattering of low energy photons by relativistic electrons;

2) hadronic models, in which γ-rays are associated with π^0 decays resulting from the collision between accelerated hadrons and surrounding gas.

While leptonic models fit well the data obtained for different sources, the hadronic models are yet to be proved.

Two different kinds of instruments are used to detect γ-rays from space: satellite experiments and ground-based detectors. Since the γ-ray flux decreases with increasing energy, satellites can investigate only energies up to $\sim$100 GeV [1], while in the Very High Energy (VHE) band above 50 GeV ground-based detectors with much larger collection areas have to be used. Contrary to satellites, ground-based experiments detect γ-rays indirectly, exploting the fact that the interaction of a γ-ray with the Earth atmosphere results in the development of a cascade of electrons, positrons and photons, the so-called Extensive Air Shower (EAS). The Cherenkov telescopes detect the Cherenkov light radiated and beamed to the ground by the charged particles of the shower, while the EAS arrays detect a fraction of the shower particles that reach the ground. These two ground-based techniques are complementary: the advantages of the Cherenkov telescopes, that are high sensitivity, good angular and energy resolution, low energy threshold and good γ/hadron separation, are completed by the EAS arrays, which are favourable in their high duty-cycle and wide field of view, limited in Cherenkov telescopes. Together they permit the exploration of the VHE sky.

2 Present VHE experiments

The Cherenkov telescopes operating today include CACTUS (in USA), CANGAROO (Australia), HESS (Namibia), MAGIC (Spain), PACT (India), SHALON (Kazakhstan), STACEE (USA), TACTIC (India), VERITAS (USA) and Whipple (USA). The current EAS arrays include ARGO−YBJ (China), GRAPES (India), Milagro (USA) and Tibet ASγ (China). The altitude of the EAS experiments is important for the energy threshold, which lowers with increasing elevation. The site of Yangbajing, where both ARGO−YBJ and TIBET ASγ are located, is currently the highest for VHE experiments (4300 m).

Many observational results presented in the following section were obtained with HESS, a square array of four 12 m diameter Cherenkov telescopes which performs stereo imaging with an energy threshold of $\sim$100 GeV and a field of view of 5°. MAGIC is the largest imaging Cherenkov telescope with a mirror of 17 m diameter. Its energy threshold is $\sim$50 GeV, the field of view 3.5°, but its principal ability is the fast repositioning system. Concerning EAS arrays, Milagro is a water Cherenkov detector based on a large, deep (8 m) pond equipped with a dense grid of PMTs detecting the Cherenkov light of EAS particles. Its sensitive area has been later increased by adding external water tanks. ARGO−YBJ is a high altitude experiment with a full coverage by means of Resistive Plate Chambers (RPCs), that allows to detect individual EAS particles with very high space and time precision.

3 Observational results

3.1 Galactic Sources

In 2004 HESS carried out a survey of the central region of the Galactic plane, from the longitude l=-30° to l=30° and a coverage in latitude approximately b=±3°. This was a great success, resulting in the discovery of many new sources. Some of these can be associated to known astronomical objects, while other sources are not yet identified [2]. After this survey and subsequent follow-up observations, the list of Galactic VHE sources includes five pulsar wind nebulae (Crab Nebula, G0.9+0.1, MSH 15-52, Vela X and G313.3+0.1), three supernova remnants (RX J1713-3946, Vela Junior and Cas A), the two microquasars LS 5039 and LSI+61303, the binary pulsar PSR B1259-63 and the Galactic Centre (SGR A). Moreover, there are 19 not yet identified sources, with some tentative associations.

The Crab Nebula was the first source detected at TeV energies and is the standard candle for the field. Emission has been detected up to 80 TeV. MSH 15-52 contains a supernova remnant, a 150 ms pulsar, and a Pulsar Wind Nebula (PWN). This is the first evidence for an extended PWN at TeV energies, with a flux ~15% Crab. The HESS spectrum is fit by a single power law with a differential index $\Gamma = 2.27$ up to 40 TeV [3]. Although there is now clear evidence that PWN produce VHE γ-rays, there is no detection of pulsed emission from this kind of sources. EGRET on CGRO detected pulsed emission from eight pulsars in the GeV range, whose origin is still mysterious. Theoretical models predict cutoffs in the 1-100 GeV range, and upper limits on the VHE pulsed flux from the Crab are given by HESS, MAGIC, PACT, STACEE and CELESTE.

RX J1713-3946 is a large ($\sim 1°$) supernova remnant first discovered by CANGAROO. Later HESS reconstructed the morphology of the VHE emission, which matches with the pattern seen in X-rays. The CO data on this source show density peaks coincident with the increased TeV flux from the northwestern side, and this may be an evidence for the interaction of protons with dense gas. Therefore this is a candidate source for neutrino telescopes. The energy spectrum is well reconstructed from 200 GeV to 30 TeV by an index $\Gamma = 2.2$ with some curvature. The quality of HESS data allowed to measure the spectrum in 14 different regions, finding no significant variation [4].

The Milagro EAS array discovered TeV emission from the Cygnus Region of the Galaxy. This is the brightest extended region of the entire northern sky, and the observed TeV emission is correlated with matter density. Inside this region the source MGRO J2019+37 is observed at 10.9σ, with a median energy $\sim$12 TeV, and results to be the second brightest source of the northern sky after the Crab Nebula. The location of MGRO J2019+37 is consistent with two EGRET sources, and an analysis of the arrival directions of the higher energy photons (with a better angular resolution) indicates that it is most likely an extended source or multiple unresolved sources. Another source in this region is consistent with an EGRET source and the unidentified HEGRA source J2032+413. Comparison of data indicates that the Milagro flux exceeds the HEGRA flux, as expected from an additional contribution due to the diffuse flux in this region [5].

3.2 Extragalactic Sources

In the catalogue of extragalactic VHE sources there are 17 objects: the nearby radio galaxy M87 and 16 blazars, whose redshifts z range from 0.031 to a possible 0.3 for PG 1553+11. Blazars are therefore the most common VHE sources, and they are thought to be those active galactic nuclei whose jets are pointing towards the Earth.

Because of the pair production process, VHE photons from extragalactic sources interact with infrared/optical/ultraviolet photons of the Extragalactic Background Light (EBL), which is the total radiation from stars and dust re-emission integrated over the luminosity history of the Universe. This interaction will result in an exponential cutoff of the intrinsic power law spectrum, $\exp(-\tau(E,z))$, where the optical depth $\tau(E,z)$ depends on the EBL photon density and on the cosmological parameters. Since the EBL density is still poorly known, the spectra of VHE blazars at different redshifts could put constraints to this background. Upper limits provided by the most distant VHE blazars are very close to the lower limits set by counting resolved galaxies, thus the Universe is more transparent to VHE photons than previuosly thought [6]. On the other hand, assuming a minimum density for the EBL, an upper limit can be set to the redshift of the VHE blazar PG 1553+11, whose combined HESS and MAGIC spectrum is very soft (mean $\Gamma = 4.1$). Considering the absorption, at the redshift $z = 0.42$ a broken power law, resulting in a convex intrinsic energy spectrum, becomes statistically preferred over a single power law. Since none of the other VHE blazars show such a spectral break, this redshift value should represent an upper limit. Alternatively, this would be the first time that a second emitting component is detected in a VHE blazar spectrum [7].

Blazars are sources with extremely variable fluxes, and thus their possible VHE emission could be also discovered serendipitously during sky surveys. On July 28, 2006, during its monitoring of PKS 2155-304, which was the first extragalactic source detected in the southern hemisphere, HESS detected a giant TeV flare, with an average flux above 200 GeV of ~ 7 times the Crab, and one-minute variability up to more than twice this value [8].

The cosmological origin of Gamma Ray Bursts (GRBs) was determined in 1997 thanks to the first redshift measurement of an optical counterpart, and was thus realized that they are the most energetic explosions in the Universe. EGRET detected emission above 1 GeV from 3 GRBs, with photons up to 18 GeV (GRB940217), however VHE emission from GRBs is still debated. Moreover, $\gamma\gamma$ pair production in the EBL prevents their observation, unless the GRB is at low redshift. Up to now, Cherenkov telescopes were able to set upper limits only to delayed emission, while the EAS arrays ARGO−YBJ, INCA, EAS−TOP and Milagro have set upper limits with data simultaneous to the GRB prompt emission in the wide energy range 1 GeV-1000 TeV. The best upper limits in the 1-100 GeV range were obtained by ARGO−YBJ with the “scaler mode”: the 4σ values for the fluence (flux integrated over GRB duration) go down to $\approx 10^{-5}\ erg/cm^2$ [9].

4 Upgrades and Future Experiments

In the future VHE astronomy will take advantage of both upgrades to the present experiments and new detectors. In the area of Cherenkov telescopes, VERITAS started operating with four 12 m telescopes, MAGIC-II will work with a second 17 m diameter reflector, and HESS-II will have a 28 m diameter telescope at the centre of the current square array. The new Cherenkov Telescope Array (CTA) should consist of a northern and southern observatory, each made of ~10 huge and ~100 small telescopes, for a sensitivity ~10 times better than HESS and MAGIC between a few tens of GeV and 100 TeV.

In the area of EAS arrays, the ARGO−YBJ carpet of RPCs will be covered by a 0.5 cm layer of lead to convert the more numerous EAS photons ($N_\gamma \approx 7N_e$). The new High Altitude Water Cherenkov (HAWC) experiment should consist of a 150 $m \times 150$ m pond of water instrumented with a large number of PMTs (the same 900 used by Milagro) and located at an elevation >4000 m for a substantial lowering of the energy threshold of Milagro.

5 Conclusions

The new generation of VHE experiments has yielded outstanding results, including the discovery of many more VHE sources, for a total of ~50. The Galactic plane is rich in number and type of VHE sources, and a number of new sources do not have obvious counterparts at other wavelengths, suggesting that we are starting the investigation of a new class of astrophysical objects, bright in the VHE region but faint in other wavebands. The discovery of new blazars at greater redshift values, with unbroken power law spectra up to the highest energies detected, makes the Universe more transparent to VHE photons than previously thought, giving also a larger window for the first detection of VHE emission from GRBs. Future experiments should continue the rapid development of VHE astrophysics: the quest for cosmic ray accelerators is still open!

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