Gamma ray observation from ground

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Abstract. Nowadays the Gamma ray observation of the sky is opening an important window to understand the nature of high-energy phenomena in the Universe and provides important tools to test fundamental physics that is constrained in the production and propagation of high-energy photons. The observation of gamma ray from ground is playing an important role: the success of the running ground based experiments shows that the large collection area and the high sensitivity to the high energy domains makes the gamma ray observation from ground complementary to the satellite one, and in many cases fundamental for a large class of scientific investigation. In this paper the main ground based gamma ray running experiment are reviewed and a glance of the perspective in this field is given.

1. Introduction
Thanks to MAGIC [1] and VERITAS [2] (in the northern hemisphere), H.E.S.S. [3] and CANGAROO [4] (in the southern hemisphere) a new wavelength domain is opened for astronomy, the domain of very high energy gamma rays with energies between about 100 GeV to about 100 Tera electronvolts TeV, energies which are a millions times higher than the energy of visible light. The high-energy gamma rays probe a "non-thermal" Universe [5] [6], where mechanisms other than thermal emission by hot bodies allow the concentration of large amounts of energy into a single quantum of radiation.

High-energy gamma rays can be produced in a top-down fashion by decays of heavy particles such as the hypothetical dark matter particles or cosmic strings, both relics that might be left over from the Big Bang. In a bottom-up fashion, gamma rays can be generated when high-energy nuclei - accelerated for example in the gigantic shock waves created in stellar explosions - collide with ambient gas particles. The flux and energy spectrum of the gamma rays reflects the flux and spectrum of the high-energy nuclei. They can therefore be used to trace these cosmic rays in distant regions of our own Galaxy or even in other galaxies. The first images of the Milky Way in very high-energy gamma rays [7] were obtained in recent years, and reveal a chain of gamma-ray emitters lining the Galactic equator (Fig. 1.1) demonstrating that sources of high-energy radiation are ubiquitous in our Galaxy. Sources of this radiation include supernova shock waves, where atomic nuclei are presumably accelerated and generate the observed gamma rays.

Another important class of objects in this context are "nebulae" surrounding pulsars, where giant rotating magnetic fields give rise to a steady flow of high-energy particles. Some of the objects discovered are binary systems, where a black hole or neutron star orbits a massive star. Along the elliptical orbit, the conditions for particle acceleration vary and hence the radiation intensity is modulated with the orbital period. These systems are particularly interesting in that they allow probing how particle acceleration processes respond to the varying ambient conditions. One of several
surprises was the discovery of "dark sources", objects which emit high-energy radiation, but have no obvious counterpart in other wavelength regimes. In other words, there are objects in the Galaxy, which are so far only visible and detectable in high-energy gamma rays. Beyond our Galaxy, well over a dozen extragalactic sources of high-energy radiation have been discovered, located in active galaxies, where a supermassive black hole at the centre is fed by a steady stream of gas and is releasing enormous amounts of energy. Gamma rays are believed to be emitted from the vicinity of these black holes, allowing the study of the processes occurring in this violent and as yet poorly understood environment.

High-energy gamma rays trace populations of high-energy particles in distant regions of our own Galaxy or in external galaxies.

2. Ground based gamma ray experiments

Ground based detectors reveal Gamma rays by their interaction with the atmosphere that becomes an essential part of the detector itself. Because of this interaction, just high-energy photons (few tenth of Gev) can be detected. However thanks to the large effective area of the ground based experiments the ground installation are unique for the high sensitivity to the high-energy component of the gamma ray spectrum.

2.1. EAS detectors

The EAS detectors, such as MILAGRO and ARGO, are made by a large array of detectors sensitive to charged secondary particles generated by the atmospheric showers. They have high duty cycle and a large FoV, but a low sensitivity. Since the maximum of a photon-initiated shower at 1 TeV typically occurs at 8 km a.s.l., the energy threshold of such detectors is rather large. Direct sampling of the charged particles in the shower can be achieved:
- either by using an array of sparse scintillator-based detectors, as for example in the Tibet AS instrument (located at 4100 m a.s.l. to reduce the threshold). For an energy of 100 TeV there are about 50 000 electrons at mountain-top altitudes, so sampling is possible;
- or by effective covering of the ground to ensure efficient collection and hence lower energy threshold.
– The ARGO-YBJ [9] detector (see Fig. 2.1) at the Tibet site follows this approach. It is made of an array of resistive plate counters. Its energy threshold lies in the 0.5 TeV-1 TeV range. The first results show that ARGO can detect the Crab Nebula with a significance of about 5 standard deviations ($\sigma$) in 50 days of observation.

– MILAGRO [10] (see Fig. 2.2) is a water-Cherenkov based instrument near Los Alamos (about 2600 m altitude). It is made of photomultipliers in water. It detects the Cherenkov light produced by the secondary particles of the shower when they pass through the water.

The energy threshold of EAS detectors is at best in the 0.5 TeV-1 TeV range, and it also depends on where the first interaction of the atmospheric shower occurred, so such detectors are built to detect UHE photons as well as the most energetic VHE gammas. At such energies fluxes are small, so they need to have large surfaces, of order of $10^4$ m$^2$.

EAS detectors are possibly provided with a muon detector devoted to hadron rejection; otherwise the discrimination from the background can be done based on the reconstructed shower shape. The direction of the detected primary particles is computed by taking into account their arrival times, and the angular precision is about 1 degree. Energy resolution is also poor. The calibration can be performed by studying the shadow in the reconstructed directions caused by the presence of the moon. Thanks to an effective method of background rejection (based on a deep water Cherenkov light emission as a veto) MILAGRO made the discoveries of 3 extended sources, 4 less significant hot-spots, and evidence for diffuse emission along the Galactic plane[13][14].
2.2. Imaging Atmospheric Cherenkov Telescopes (IACT) detectors

The recent breakthroughs in very high-energy gamma-ray astronomy were achieved with Cherenkov telescopes. When a gamma ray enters the atmosphere, it interacts with atmospheric nuclei and generates a cascade of secondary particles, with electrons and positrons. Moving through the atmosphere at speeds higher than the speed of light in the gas, these particles emit a beamed bluish light, the Cherenkov light. On the ground, this Cherenkov light illuminates an area of about 250 m diameter, where it can be captured with optical elements and be used to image the trajectory of the particle cascade, which vaguely resembles the trajectory of a shooting star. Reconstructing this trajectory in space and tracing it back on to the sky, the celestial origin of the gamma ray can be determined.

Accumulating many gamma rays, an image of the gamma-ray sky such as shown in Fig. 1.1 is created. Since Cherenkov light is very faint, large optical reflectors with areas in the 100 m² range and beyond are required to collect enough light, and the instruments can only be operated at night at dark sites. The Whipple Telescope in the United States pioneered this Imaging Atmospheric Cherenkov
Technique; after more than 20 years of development, the first source of very high-energy gamma rays, the Crab Nebula, was discovered in 1989 [6]. The Crab Nebula is among the strongest sources of very high-energy gamma rays, and is often used as a "standard candle". Modern instruments, using multiple telescopes to track the cascade from different perspectives and employing fine-grained photon detectors for improved imaging, can detect sources down to 1% of the flux of the Crab Nebula. Finely-pixelated imaging was first employed in the French CAT telescope, and the use of "stereoscopic" telescope systems to provide images of the cascade from different viewing points was pioneered by the European HEGRA instrument.

Currently, the world largest ground-based IACTs are HESS, MAGIC and VERITAS (Figure 2.3). HESS is an array of 4 clone telescopes, each of 12 m diameter, located in the Gamsberg Mountain in Namibia and is operating since 2003 with a very high scientific impact. A fifth telescope, dubbed HESS-II, of 28 m diameter, is under construction at the center of the array, and its completion is foreseen for 2010. MAGIC has operated since 2004 with a single dish of 17 m diameter and parabolic profile in the Canary island La Palma in Spain [5]. Despite the use of a single reflector does not guarantee the sensitivity of an array, its world-largest dish allowed to reach the lowest energy threshold of the IACT technique, performing for the first time observation below 100 GeV with this technique. Recently MAGIC has detected the first ever observed GR pulses at 25 GeV from the Crab pulsar. Recently this year, a second clone MAGIC telescope, dubbed MAGIC II, has been inaugurated. The use of the stereoscopic system will allow MAGIC phase-II to reach the sensitivity of larger arrays. A more recent experiment was started in the Arizona desert in USA, following the successful experience of the Whipple experiment. VERITAS has soon reached the expected performance, with sensitivity comparable (higher actually because of aging) to HESS and is starting to collect important scientific results.

3. The Future

The most advanced project for the EAS detectors is HAWC (High Altitude Water Cherenkov experiment). The aim of this project is to use high energy gamma rays probe the most extreme astrophysical environments including those that produce the highest energy cosmic-ray particles. The Milagro observatory has demonstrated that a detector with a wide field of view (2sr) and nearly 100% duty cycle can discover new sources of TeV gamma rays at energies between 10 and 100 TeV, and map the diffuse emission from the plane of our Galaxy. The HAWC (High Altitude Water Cherenkov) observatory builds on the experience and technology of Milagro to make a second-generation high-sensitivity detector. This unique detector will be capable of continuously surveying the TeV sky for steady and transient sources from 100 GeV to 100 TeV.

Concerning the Cherenkov telescopes, despite the promising achievements from the current generation of IACTs, there are a number of limitations that the future generation will overcome:

a) IACTs of current generation are sensitive in a limited energy range, from 100 GeV to 50 TeV. At the lower end, IACTs are limited by the background for low energy. At the high end, the limit is posed by insufficient statistics;

b) Due to the lack of a calibrated cosmic GR source, IACT spectral reconstruction is limited by systematic bias and statistical uncertainties on the energy reconstruction;

c) They have a limited aperture, with typical field of view (FOV) of the order of 3–5 deg diameter;

d) They have a limited angular resolution, which currently states around few arc-min;

e) They have limited collection area;

f) They are rather poorly automatized.

On the other hand, from a physical point of view, there are strong arguments to improve in the following aspects:

1. Decrease the energy threshold to few tens of GeV
2. Acquire sensitivity beyond 50 TeV
3. Increase sensitivity in the bulk range 100 GeV, 50 TeV
4. Improve energy and angular resolution

The accomplishment of the above goals is intimately related to the overcome of the technological questions discussed at the beginning of this section. For this reason, a new generation of IACT is under design now with expected performance well above the current generation. We believe that with CTA we are heading toward a new era of “precision GR astronomy”.

4. Conclusions

The field of VHE γ-ray astrophysics has gone through a dramatic evolution since 2004, thanks to the high sensitivity of the new generation of ground based gamma ray experiment IACTs. The HESS, MAGIC and VERITAS experiments represents a major step in that it has revealed, beyond the large number of sources, diverse classes of γ-ray emitting galactic objects and acceleration sites: young shell-type SNRs [11], SNRs interacting with molecular clouds, middle-aged offset PWNe, very young composite PWNe and γ-ray binaries. Given the large number of still unidentified sources, other potential classes of sources could emerge, including the promising case of massive star clusters. The increasing number of blazars sources in the extragalactic domain allows now for population studies, and one non-blazar source. Also, while the early attempts to constrain the intergalactic radiation field suffered from the very limited number of sources and a reduced range in red-shift, the growing number of objects, and especially the detection of 3C 279 [12] obtained at a low energy threshold by MAGIC, have definitely opened the path towards the cosmological application of γ-ray astrophysics. There is no doubt that VHE γ-ray astronomy is now a genuine branch of astronomy with multiple connections to cosmology and fundamental physics.

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