

VHE gamma-ray astronomy: observations

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Abstract. The recent operation of a new generation of Cherenkov telescopes is providing unprecedented results which are opening in the last months a truly new age in VHE cosmic gamma-ray observations. We're in the dawn of the setting of a new window in our observation of the cosmos: VHE gamma-ray astronomy. The techniques and concepts used by these new telescopes is reviewed and the main scientific highlights from the observations performed so far are presented.

1. Introduction.

We are in a very special moment in VHE Cosmic gamma-ray observation: at present a **real revolution** in the consolidation of Cherenkov Telescopes as astronomical instruments is taking place. After many years of slow development, Cherenkov Telescopes are now in the phase transition from being “HE experiments” to being “telescopic installations” in the astronomical sense. This fact is motivating an exploding interest in the astronomical community.

The reason for this phase transition is the big observational step occurred within the last few months [1] at the quantitative level (tripling the number of detected sources) but also at the qualitative level (producing extremely high quality detections allowing unprecedented detailed studies).

We are at the dawn of a **golden age** for Cherenkov Telescopes and for that reason, this article will concentrate in the discussion of the status of the observations with these instruments.

The outline of this write-up is as follows: in section 2 we'll remind about the instruments and techniques which are on the basis of this revolution and will emphasize the decisions in their historical evolution leading to the present situation. Section 3 will review the scientific highlights which are the basis for the claim of such a revolution. Finally, section 4 will give a summary of the present situation and an outlook on the exciting near future.

2. Instruments and techniques.

Cosmic gamma-ray observation has been performed **directly** from satellites in the High Energy (HE) range for gamma energies below, say 10 GeV and **indirectly** from ground-based installations in the Very High Energy (VHE) regime, for gamma ray energies above few hundred GeV.

EGRET, the last cosmic gamma ray detector on a satellite into operation until few years ago, was able to detect as many as about 350 sources (out of which almost 250 remain still unidentified) with a tiny effective area (about 0.1 m²) and established already HE gamma-ray astronomy as a consolidated field.

On the contrary, a whole generation of instrument on the ground, pioneered already back in 1969 by the Whipple Telescope in Arizona, has been able to detect just a handful of new sources and some

of them without confirmation. Whipple took about 20 years to detect its first source, the Crab Nebula, an intense and steady gamma-ray source established by Whipple in 1989 and that nowadays is used as the “standard candle” for VHE gamma ray astronomy. After that discovery, a whole set of new instruments flourished around the globe trying to open that new observation window. The most productive have been the CANGAROO telescopes in the Australian outback, which started already in 1992, the HEGRA telescopes in the Canary Islands, which started in 1993 and ended in 2002 and the CAT Telescope in the French Pyrenees, which started in 1996 and ended in 2003.

In spite that these instruments provide effective areas which reach almost 50000 m², the total number of confirmed sources detected is less than a dozen and for some of them the detection significance is not enough as to allow for detailed studies.

This fact motivated the community to go for a new generation of instruments which is now carrying the aforementioned revolution.

To understand the technical characteristics that have made possible this revolution, we shall remind the basic concepts behind the Cherenkov Telescope technique: VHE cosmic gamma rays interact in the atmosphere producing electromagnetic showers which reach their maximum development at about 10 kilometers height. The ultra-relativistic electrons and positrons in these showers emit Cherenkov light within a cone of typically about 1 degree aperture and therefore, making a light spot on the ground of about 150 meters radius. For this reason, the area illuminated on the ground is of about 50000 m² (see figure 1). This light flash lasts typically few nanoseconds and therefore, although it might be very dim, it might be distinguishable from the night sky light background if a telescope with the proper design is placed within the light spot.

The main characteristics needed for a Cherenkov Telescope are a large light collector and a fast and sensitive camera able to detect few photons in few nanoseconds. Nevertheless, another crucial characteristic is the capability of discriminating the Cherenkov flashes produced by gamma rays from those produced by hadrons, few orders of magnitude more frequent. That is achieved with a fine pixelization of the camera allowing imaging the shower development through its Cherenkov light emission. Typical gamma-ray images have an elliptical shape and can be adjusted with a second moment analysis to the so-called “Hillas parameters” while hadronic images, due to the rich shower structure in hadronic interactions have a more complex image shape comprising islands from secondary interactions and pieces of muon rings.

One of the most powerful image parameters in discriminating gammas from hadrons is the so-called “alpha”, given by the angle between the ellipse major axis and the direction linking the camera center and the ellipse center. For Cherenkov flashes coming from the telescope’s pointing direction, “alpha” should peak at zero degrees. Given the fact that the arrival direction of hadronic cosmic rays is quite randomized by the action of galactic magnetic fields, their “alpha” distribution is, instead, flat.

Another concept which helps in the reduction of the hadronic background and hence, improves the sensitivity is the use of a system of telescopes within the Cherenkov light pool to provide simultaneous viewpoints of the shower development. This helps in addition in improving the energy and angular resolution [2].

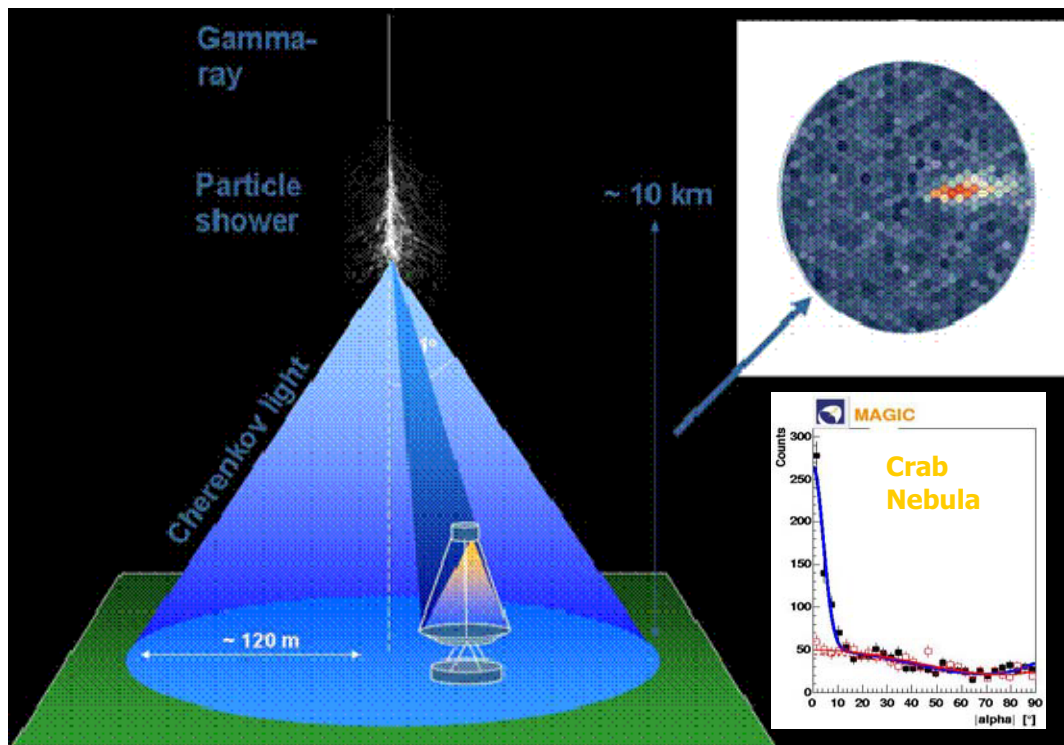


Figure 1. Detection concept for a Cherenkov telescope. See text for an explanation.

With the experience acquired with the first generation of Cherenkov telescopes, the main goals motivating the design of the new generation were:

- **Reduce the energy threshold.** Since all the sources show power law spectra, reducing the energy threshold should allow to observe larger fluxes. That requires the use of larger Cherenkov light collectors and therefore, the construction of **large telescopes**.
- **Improve sensitivity.** By improving the background rejection one can improve the analysis sensitivity and therefore increase the source discovery potential. As already mentioned, the use of **telescope arrays** with the proper spacing provides an improved gamma-hadron separation.

These two concepts are complementary but, within a limited budget, might be exclusive. The very large telescope design has been the main driving concept for the MAGIC telescope proposal while the telescope array was the option taken by the rest of proposals for the new-generation instruments (CANGAROO-III, HESS, VERITAS).

In addition, other important design concepts which characterize the new generation of instruments are:

- The use of wide-field cameras. This provides survey capability, the opportunity of having serendipitous discoveries and also the possibility of performing source morphology studies. For instance HESS has a camera with 5 degree FoV.
- The use of an isochronous reflector together with a fast digitization. This provided the possibility of using the Cherenkov photon arrival time for improving further the gamma-hadron separation. For instance, MAGIC has reached sub-nanosecond timing
- The use of a light telescope structure. This enables a fast transient phenomena follow-up, as is needed in the case of Gamma Ray Bursts. MAGIC has, for instance, less than 20 second repositioning time.

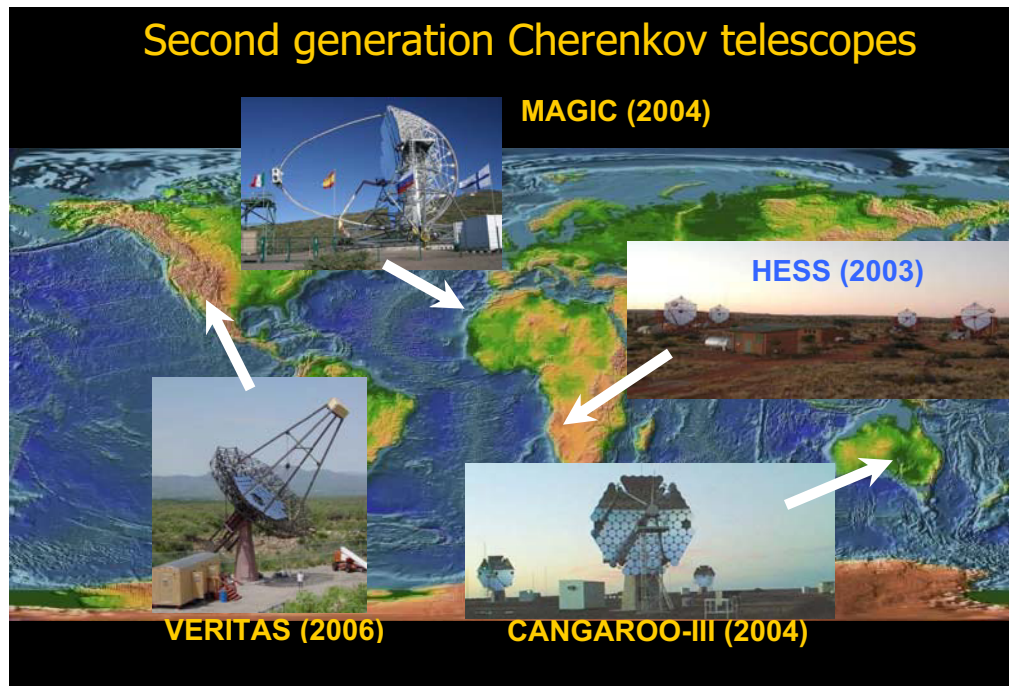


Figure 2. The installations of the second generation of Cherenkov telescopes which are making a real revolution in the field.

These concepts have been the key design elements implemented in the new generation instruments which are the following (see figure 2):

- HESS is presently a telescope array composed by four 12 meter diameter telescopes placed at Namibia, which started operation in 2003 [2].
- MAGIC is presently a single, 17 meter diameter telescope installation placed at the Canary Islands, which started operation in 2004 [3].
- CANGAROO-III is a telescope array composed by four 10 meter diameter telescope placed at Australia, which started operation in 2004 [4].
- VERITAS will be a telescope array composed by four 12 meter diameter telescopes placed at Arizona, which shall start operation in 2006 [5].

These four installations, out of which two are in the northern hemisphere and two in the southern, given their different latitude do provide good time coverage around the globe for source follow-up.

3. Scientific highlights and observations.

Since the start of their operation, the new installations which are already active have made observations leading to a series of scientific results which are the basis of the claim for a real revolution in the field. The main scientific highlights coming from these observations are the following:

I. Discovery of many new Galactic sources by HESS:

HESS performed a Galactic Plane survey extending from -30 to 30 degrees in galactic longitude and ± 3 degrees in latitude expending 112 hours of observation. This scan allowed the discovery of 16 new galactic sources with significances larger than 4 sigma out of which 9 had significances larger than 6 sigma (see figure 3). Some of the sources have been observed afterwards to confirm the signal and perform detailed studies. Most of these new sources are shell-type Supernovae and pulsar-wind Nebulae although still many remain unidentified and some of them belong to a new class of objects observed for the first time emitting in gamma rays [2,6].

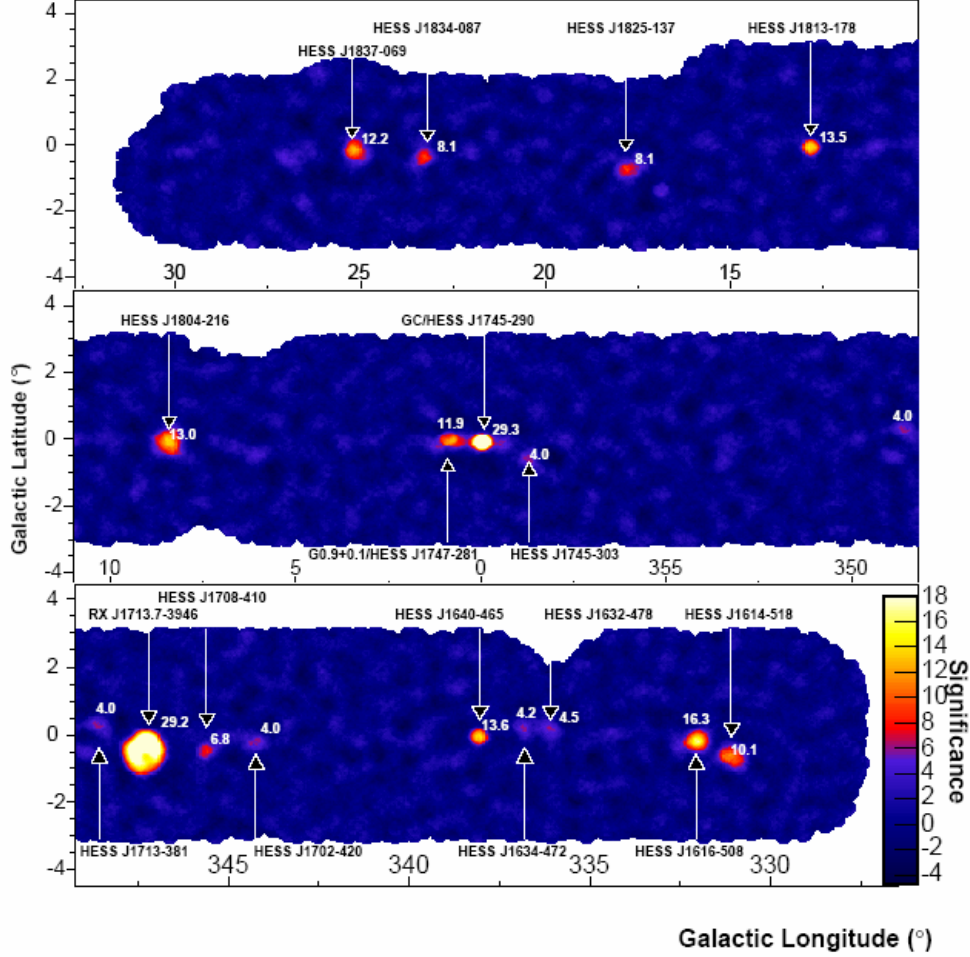


Figure 3. The sources detected by the HESS array during the scan of the Galactic plane. For each source, the significance of the detection is quoted.

II. Detailed studies of Galactic sources by HESS:

The quality of the observations for some of these sources is such that studies with unprecedented detail and accuracy have been possible. For instance, for some of the Shell-type supernovae, morphological studies have been carried out allowing not just the detailed study of the correlation of the emission region shapes with the observation on other wavelengths (see figure 4) but also the study of the emission spectra in different regions of the Supernova shell.

This high quality of the observational data allows a precise check with the theoretical models and should allow an unprecedented understanding of the source physics [2,6]

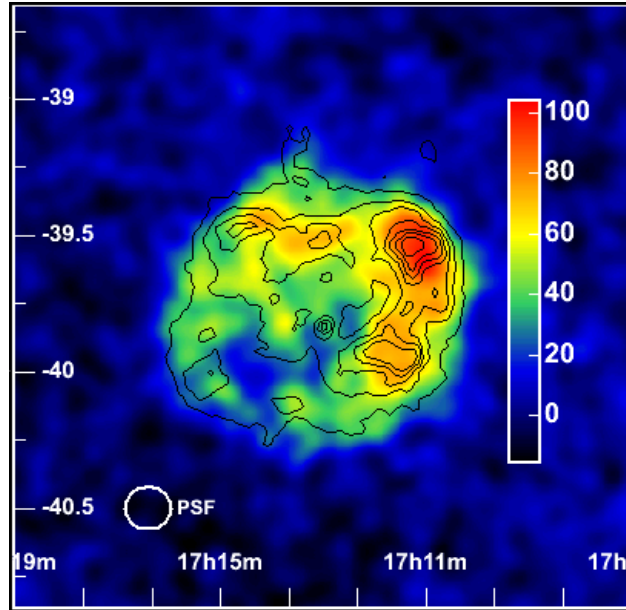


Figure 4. The Shell-Type Supernova remnant RX J1713-3946 with the number of gammas observed by HESS in a color scale superimposed to the x-ray observation contours.

III. Discovery of new classes of Galactic VHE gamma-ray emitters by HESS:

Two of the new Galactic sources discovered by HESS correspond to new classes of VHE gamma ray emitters [2]:

- *The first variable Galactic source*, which actually is binary system in which a pulsar (PSR B1259-63) describes a 3.4 year highly eccentric orbit around a $\sim 10 M_{\odot}$ Be star with a closest approach ~ 20 stellar radii crossing a strong solar wind and being periodically obscured by the companion star.
- *Microquasar (LS 5039)*, the first one observed emitting in VHE gamma rays and which constitutes a scaled version of a Quasar in which the accreting material onto the compact object originating the VHE gamma ray emission is provided by the mass transfer from a massive companion star.

IV. Detailed study of the Galactic Center by HESS and MAGIC:

The galactic center has been independently observed by HESS and MAGIC (in this case at large zenith angle) providing spectrum measurements in nice agreement which contradict the measurements previously published by the CANGAROO collaboration [2,3]. The observed signal is consistent with point-like emission from Sgr A* (with an slight hint for extension), is steady from year to minute scales and the spectrum is very well fitted by an unbroken power law with index ~ 2.3 from about 150 GeV up to almost 30 TeV, which rules out most of the possible interpretations in terms of Dark Matter annihilation.

V. Discovery of 4 new AGN by HESS and MAGIC:

HESS has discovered three new Blazars (PKS2005-489 $z=0.071$, H2356-2009 $z=0.165$, 1ES1101-232 $z=0.186$) and MAGIC a new one (1ES1218+304 $z=0.182$). The unprecedented large distance to some of these new Blazars has allowed the use of the measured gamma ray spectra to place already strong constraints on the Extragalactic Background light (EBL) density by unfolding the expected effect due to the gamma-gamma absorption [2,3]. The conclusions of the HESS and MAGIC collaborations agree in pointing to a more transparent universe to gamma rays that predicted by most of the theoretical models and with very small EBL densities with saturate the lower limits provided by the determinations obtained from galaxy counts.

VI. Observation of AGN with orphan flares by MAGIC:

MAGIC has measured for the first time the spectrum of the Blazar 1ES1959+650 ($z=0.047$) in a low energy range (from ~ 200 GeV to ~ 2 TeV). This source is especially interesting because it has shown in the past flares without any counterpart on other wavelengths (orphan flares) and there are hints for detection of neutrinos and UHECR from its direction, and therefore might provide a connection between these three kinds of astronomies. The low flux measured by MAGIC points to detection in the low state [3].

VII. High time-resolution study of AGN flares by MAGIC:

MAGIC has observed an intense flare of the well-known Mkr501 Blazar which reached an intensity equivalent to 4 times the one of the Crab Nebula. Due to the high sensitivity of MAGIC, the rate of gamma rays recorded was so high that, for the first time, bins of 2 minutes in the light curve have been possible allowing an unprecedented accuracy in the study of the time variation of the emission [3]. This data is expected to provide strong constraints in the light speed dispersion relations predicted in Quantum Gravity theories.

VIII. Prompt GRB follow-up by MAGIC:

The extremely fast repositioning of the MAGIC telescope allowed the follow-up of a Gamma Ray Burst (GRB050713A) only 13 seconds after the reception of the alert provided by the SWIFT satellite and only ~ 40 seconds after the actual gamma ray burst happened [3]. MAGIC observed the GRB in coincidence with the BAT and XRT instruments and while the x-ray activity was still high. So far no significant gamma ray emission was detected in the recorded MAGIC data and this will provide already strong constraints in many GRB models.

4. Summary and outlook.

Ten years ago, in 1995 just three VHE gamma ray sources were known (Crab, Mkn421, Mkn501). Since then, sources were discovered by the instruments of the first generation at a rate of about one new source per year and up to 2003 about 12 sources were detected (although not all of them were confirmed). Since the start of the operation of the new generation of Cherenkov telescopes, the situation has made a quantitative and qualitative revolution. Now the sky is already populated by as many as 32 VHE sources and many others have already tentative detections which should be confirmed in the coming months [1]. As many new VHE sources have been discovered in the last year as in the previous 20 years... and likely many more are just around the corner !.

But not just the number of sources has increased drastically; also the quality of the data recorded has improved dramatically enabling studies with unprecedented precision in fluxes, spectra, morphology and light curves and unprecedented short follow-up times.

This big revolution is occurring in VHE gamma-ray astronomy due to the fact that the new generation of Cherenkov telescopes is yielding outstanding results, even beyond expectations, and are establishing VHE gamma-ray installations as astronomical observatories rather than as experiments: VHE gamma-ray is now emerging as a solid new astronomy.

But this is not the end of the story. In the coming years further developments are already on the way which will boost even further the field:

- The **GLAST** satellite will be launched in 2007. It should discover thousands of new HE sources and the LAT instrument, covering an energy range between 20 and 300 GeV should provide overlap with the observations of the Cherenkov telescopes.
- The **VERITAS** array should start operation in 2006 providing a similar coverage of the northern sky as the one already provided by the HESS array in the southern hemisphere.
- The **MAGIC** collaboration has already started the construction of a new 17 meter diameter telescope with improved camera, digitizers and mirrors with should see first light already in 2007 and transform MAGIC into the installation with the lowest energy threshold and the largest sensitivity worldwide [7].
- The **HESS** collaboration plans the construction of a giant 28 meter telescope to be placed at the middle of the HESS array by 2008 boosting the response at low energies [8].

In addition, two lines of further development are been discussed in the community:

- The construction of telescopes with much wider angle coverage to be able to do all-sky surveys and discover all the still hidden VHE sources which may require the development of large telescopes with very large cameras and, maybe, Fresnell lenses.
- The construction of telescopic installations with energy threshold below 10 GeV, which might require the deployment of arrays of giant telescopes at altitudes above 5000 meters.

We are at the down of a golden age in VHE gamma ray astronomy which has started with a brilliant present and has an exciting and extremely promising opportunity open for new ideas and developments in the near future.

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