Status of the VHE astronomy with Cherenkov telescopes

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Abstract

The field of Very High Energy (VHE, E>100 GeV) gamma-ray astronomy has undergone a major revolution over the last four years, thanks to the results obtained by the new imaging Air Cherenkov Telescopes (IACTs). The latest generation of Cherenkov telescopes, such as H.E.S.S., VERITAS, and MAGIC, has increased the observation energy range from 100 GeV to multi-TeV, which allowed the field to enjoy a period of rapid growth, today boasting a source catalogue containing about 50 emitters of VHE gamma-rays from a variety of classes, including supernova remnants, blazars, pulsars, and microquasars. Other kinds of objects, such as pulsars, galaxy clusters or GRBs, are expected to produce also VHE gamma-rays. Furthermore, a large number of new unidentified sources without obvious counterparts at lower wavelength have been discovered. We will review the latest results published and discuss the most interesting cases.

Key words: gamma-ray sources

1. Introduction

The window of ground-based gamma astronomy was opened in 1989 by the observation of a strong signal from the first TeV gamma source, the Crab Nebula, by the Whipple collaboration. Since then, increasing progress has been made in this new field of astronomy and discoveries of new sources have been made by newer ground-based VHE γ-ray instruments. Those instruments can be classify in two groups: Instruments with high sensitivity, the so-called imaging Cherenkov telescopes (IACTs) such as VERITAS [19], MAGIC [16], H.E.S.S. [17] and CANGAROO [18], which operates in the energy range from 0.05 to 50 TeV, have large collection areas ($>10^4$m^2), good angular resolution (typically $\sim$0.05^o) and high capacity of background rejection using the *imaging* technique, but are limited by a small aperture (0.003 sr) and the request of observations under dark night conditions (10% duty cycle). IACTs allow to study in detailed the energy spectra and sources morphology, and are able to perform surveys of limited regions of the sky. The second group (Milagro [1], Tibet [15] and ARGO) is characterized on the contrary by large aperture (> 2 sr) and high duty cycle (>90%) instruments, operating in a slightly higher energy range (1 - 100 TeV) but with limited angular resolution (0.3-0.7^o) and lower sensitivity than the one of the telescopes. These later instruments are optimum to carry on unbiased sky survey and study very extended sources not accessible by the imaging telescopes.

Over the last years, the number of known VHE gamma-ray sources increased rapidly: the last count gives more than 70 sources, among them 7 or more supernova remnants, about 20 pulsar wind nebulae and 20 unidentified sources, four binary systems, diffuse emission from clouds and 23 extragalactic sources. Fig. 1 shows the updated VHE γ-ray sky map [22].

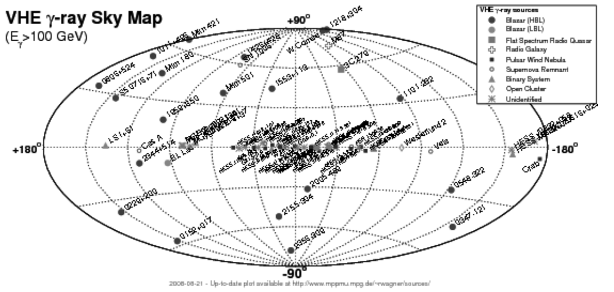

Fig. 1. The VHE γ-ray sky map

2. Galactic sources

The H.E.S.S. telescope has conducted recently an extension of the scan of the inner Galactic Plane Survey (GPS) [2], which has supposed a major breakthrough in the Galactic field. The survey, covering the yet unexplored range in longitude between [-85^o,60^o] and [-2.5^o,2.5^o] in latitude, has revealed more than two dozens of new VHE sources, consisting of shell-type SNRs, pulsar wind nebulae, X-ray binary systems, a putative young star cluster, yet unidentified objects, the so-called dark sources, in which not obvious counterparts at other energy wavelengths are found (see e.g. [3], [4]), and the diffuse emission in the central 100 pc of the Milky Way, being able

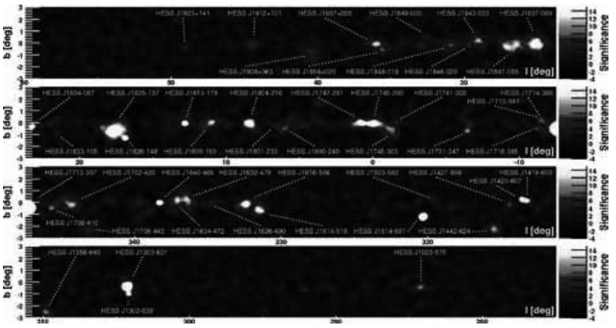

Fig. 2. Significance (pre-trial) map of the H.E.S.S. Galactic Plane Survey in four panels.

to locate the Galactic Center γ-ray source with a precision of 6", consistent with the black hole Srg A* but excluding the nearby remnant Sgr A East. MAGIC and VERITAS had contribute to the galactic field with the discovery of the γ-ray binary LSI +61 303 [12], the stellar mass black hole binary Cygnus X-1 [13], the supernova remnant IC443[10] and they have confirmed several sources such as the first unidentified source, HEGRA TeV J2032+4130 [5]. Figure 3 shows the pre-trial significance map of the entire H.E.S.S. GPS. The official H.E.S.S. Source Catalog can be found online[1] and includes all of the VHE γ-ray sources which were detected by H.E.S.S. and subsequently published in refereed journals.

2.1. Supernova remnants

Shell-type supernova remnants (SNRs) are considered as prime acceleration sites for the galactic cosmic-rays, at most up 10^{15} eV. Up to 7 firm detections are seen in TeV γ-rays: IC 443 [14], RX J0852-4622 [21], RCW 86 [20], RX J1713.7-3946 [2], W28 [6], Cas A and SN 1006 [21]. Three of them have been resolved (RX J0852-4622, RCW 86 and RX J1713.7-3946) with unpreceding angular resolution, proving thus the acceleration of particle responsible of the VHE emission in the shell (see Fig. 3). Two mechanisms have been proposed to explain the VHE emission, through synchrotron radiation and Inverse Compton scattering produced by a population of electrons, or through collisions of accelerated protons with gas. The close correlation between γ-ray emission and X-ray emission, like in the case of RX J1713.7-3946, may favor a leptonic scenario, although it requires 10 μG magnetic field, while the filaments seen in X-ray images of SNR are often interpreted as evidence for rapid cooling of electrons as they move away from the shock fronts, which requires much higher fields in the 100 μG range. On the contrary, older SNRs such as W28, show a good agreement with dense molecular cloud, being so a strong argument for the presence of protons accelerated by the remnant.

SN 1006 was detected by H.E.S.S. after 103 h of data accumulated over the years 2003 to 2008 (Fig. 2), with a flux level well below any previous upper limit. Using the pre-defined search region from the published paper reporting the first observation, which resulted in an upper-limit [21], the signal from the north-east rim was detected with a significance of over 5 sigma. A second gamma-ray excess appears in the south-west corner of the remnant. The morphology of the VHE gamma ray source is again quite similar to the X-ray source. The morphology of SN 1006 and X-rays and gamma rays can be explained as due to the interstellar magnetic field threading the remnant from north-east to south-west, inhibiting efficient particle acceleration in regions where the field is parallel to the supernova shock front.

2.2. Pulsar wind nebulae

Pulsar wind nebulae (PWN) represents the major Galactic source population revealed by the H.E.S.S. scan, being the Crab Nebula the first VHE γ-ray source. These VHE sources are associated with very young ($<10^{15}$ years) and energetic pulsars ($\dot{E} > 10^{35}$ erg/s. Two classes of PWN seems to be emerging:

- Point-like sources, centered in the pulsar candidate, such as kes 75 and Crab.
- Evolved pulsar wind nebulae, typically very extended sources (few tens of pc), associated with very young, energetic pulsars, and the TeV emission is mostly displaced with respect to the pulsar position. HESS J1825-137 can be considered as the prototype of such objects. Other recent examples are HESS J1809-193 and HESS J1356-645. The VHE emission and morphology can be explained by cooling of particles suffering radiative energy losses as they flowing away from the pulsar, resulting in the shrinking of the source towards the pulsar with increasing energy.

2.3. Unidentified Sources

A large number of TeV γ-ray sources remain unidentified, that is, do not have a plausible counterpart at lower energies, where both, leptonic and hadronic models, predict in general synchrotron emission from charge particles, although highly suppressed in the latter case. They show rather hard spectral index and are mostly extended (see i.e. Fig. 4). In some cases, this could be due to lack of deep observations at other wavelength, but on some other cases, the VHE emission could be identify with pure protons accelerators, or explained with a leptonic population with a cutoff in the TeV range, in which

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[1] See http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources

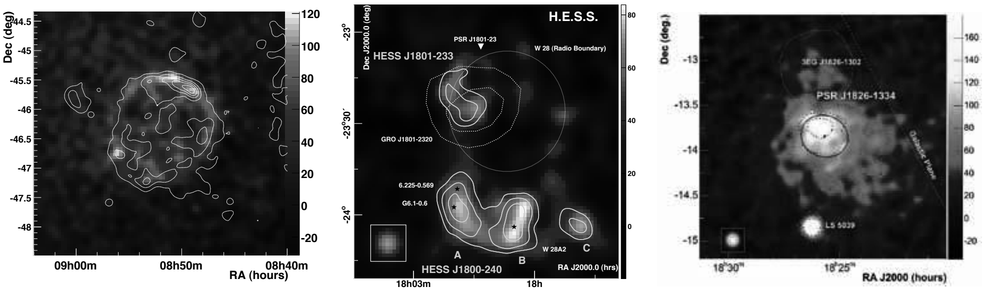

Fig. 3. On the left, RX J1713.7-3946. On the middle, the VHE emission from the old supernova remnant W28, coincident with an enhancement of ^{12}CO (J=1-2) data. On the right, the H.E.S.S. source coincident with SN 1006

case, in the KN regime high energy γ-rays can still be produced, but the synchrotron radiation peaks below the X-ray range and escapes detection. Some of them, such as HESS J1857+02 in which the energetic pulsar PSR J1856-0245 has been recently discovered , start to be identified by multiwavelength observations. HESS J1908+063 has been identified with MGRO J1908+06, and a new pulsar has also been found coincident with the VHE source.

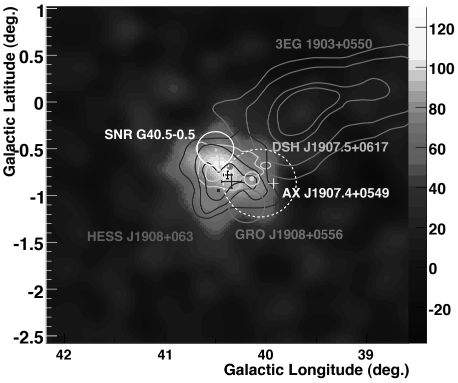

Fig. 4. Excess maps of HESS J1908+063.

3. Extragalactic Sources

The number of active galactic nuclei (AGNs) detected at VHE has increased in the past few years, yielding to a catalogue of $\sim$ 25 sources, most of them belong to the blazars class. Blazars are AGNs with the jet closely aligned with the line of sight, amplifying so by relativistic effects the observed intensity of emission. The spectral energy distribution shows usually two bumps, one in the UV-X range due to synchrotron emission, and a second peak in the X-γ range due to inverse Compton effects in leptonic models. All the sources detected by H.E.S.S. up to now are Blazars except for M87. Three new sources have been detected recently by H.E.S.S., RGB J0152+017 [7], 1ES 0229+200 [8], 1ES 0347-121 [9].

3.1. The multi-wavelength campaigns

One of the most relevant results concerning multi-wavelength campaigns is the one obtained in observations of PKS 2155-304, carried on during October and November 2003, which involved H.E.S.S., Rossi X-ray Timing Explorer (RXTE), the Robotic Optical Transient Search Experiment (ROTSE) and the Nancay Radio Telescope (NRT). The spectral energy distribution (SED) of the source with the data obtained during the campaign is shown in Fig. 5. The experimental data set give constraints to the emission models. Considering leptonic and hadronic emission models, the discrimination is still missing but will be achieved with more sensitive and with lower energy threshold telescopes such as H.E.S.S II.

3.2. Variability

On the brightest sources, the study of VHE AGNs variability is now possible on short time-scales thanks to the high sensitivity reached by H.E.S.S. One of the strongest flaring episode registered are the ones observed in PKS 2155-304 in 2006. This variability of the VHE flux has been observed on several AGNs, on month scale and even day scale for the brightest sources. For M87, time variability on day scale has been observed, constraining so the size of the emission region to be of the order of the Schwartchild radius. For PKS 2155-304, time variability of the order of the minutes was measured. Such variability also puts constrains on the size of the emission region, i.e., hadronic models hardly explain this fast variability. This highly sampled data set allows other type of variability studies: description of random process, constraints on quantum gravity [10], etc.

3.3. Constraining the extragalactic background light

The study of AGNs at VHE has also allowed to constrain the extragalactic background light (EBL) in the Universe. The EBL is the accumulated light from all galaxies and first stars. A VHE photon colliding with an infrared EBL photon will produce an electron positron

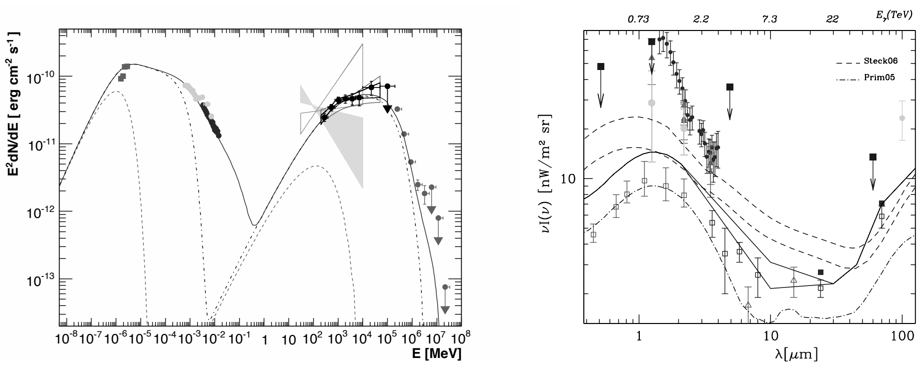

Fig. 5. On the left, spectral energy distribution of the AGN PKS 2155-304. On the right, constrains to the extragalactic background light derived from the observations of H 2356-309 and 1ES 1101-232.

pair. Therefore, the farther the VHE photon is coming from the higher is the probability for this photon to be absorbed by the EBL. The VHE spectrum of a fairly distant AGN can constraint on the density of the EBL, with simple assumptions on the emission spectrum. By observing the unexpectedly hard spectra of H 2356-309 (z=0.165) and 1ES 1101-232 (z=0.186) H.E.S.S. has inferred a very constraining value for the upper limit of EBL density, close to the lower limit given by the galaxy counting [11].

4. Summary

The H.E.S.S. GPS has played a major role in the fast development of the VHE field, unveiling a large number of sources, diverse classes of γ-ray emitting galactic objects and acceleration sites: young shell-type SNRs, SNRs interacting with molecular clouds, middle-aged offset PWN and very young composite PWN. Given the large number of still unidentified sources, other potential classes of sources could emerge. On the other hand, the increasing number of blazars in the extragalactic domain allows now to perform only population studies. The high sensitivity reached also allows to study in detail fast variable flares, comparing with simultaneous observations at other wavelengths. New types of Galaxies such the radio galaxies Cen A and M82 have been recently reported.

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