H.E.S.S. Highlights

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Abstract: The High Energy Stereoscopic System (H.E.S.S.) of Imaging Atmospheric Cherenkov Telescopes (IACTs), located in Namibia, is being operative since December 2003. The array of four 13-meters telescopes detects very-high energy (VHE) γ-rays from 0.1 TeV up to a few tens of TeV. Since the beginning of the operation, the H.E.S.S. collaboration has reported the discovery of more than seventy new sources, including extragalactic and galactic objects. Here we report on the latest discoveries and observations with the H.E.S.S. telescope array.

Key words: H.E.S.S. telescopes, very high energy gamma rays, Galactic sources, extragalactic sources

1 Introduction

The H.E.S.S. telescope array is located in Namibia at 23°16′17″ S 16°29′58″ E, at 1800 m above the sea level. H.E.S.S. is a system of four large (13 m diameter) IACTs, designed to detect γ-rays in the very-high-energy (VHE; E > 100 GeV) domain. Each telescope has a mirror area of 107 m² and a total field of view of 5°, well suited to the study of extended sources. The system works in a coincidence mode requiring at least two of the four telescopes to have triggered in each event. Its angular resolution reaches ~ 5″ per event and its sensitivity for a point-like source, is 2.0 × 10^{-13} ph cm^{-2} s^{-1} (1% of the Crab Nebula flux above 1 TeV) for a 5σ detection, within 25 hours observation time. In the last two year, the H.E.S.S. nominal sensitivity has been recovered and boosted thanks, in one hand, to the re-coating of the telescopes mirrors and on the other hand to the new analysis techniques applied to the data based in multi-variate analysis and likelihood reconstruction [1–4].

While the location of H.E.S.S. in the southern hemisphere emphasizes Galactic sources, new results have also been obtained for extragalactic objects.

This report can only give a brief overview; for details and further references, the reader is referred to the publications cited. The official H.E.S.S. Source Catalog can be found online* and includes all the VHE γ-ray sources which were detected by H.E.S.S. and subsequently published in refereed journals.

2 Galactic Sources

2.1 The H.E.S.S. Galactic Plane Survey

The H.E.S.S. telescope array has conducted in the last years a systematic scan of the Galactic plane, the so-called Galactic Plane Survey (GPS) [5, 6], which has supposed a major breakthrough in the Galactic sources field. The survey, covering the yet unexplored range between [-85°, 60°] in longitude and [-2.5°, 2.5°] in latitude, has revealed more than fifty new VHE γ-ray sources, including shell-type supernova remnants (SNRs), SNRs interacting with molecular clouds, pulsar wind nebulae (PWNe), X-ray binary systems, yet unidentified objects (the so-called dark sources in which not obvious counterparts at other energy wavelengths are found, see e.g. [7]), and the diffuse emission in the central 100 pc of the Milky Way, locating the Galactic Center γ-ray point-like source with a...
Fig. 1. Significance (pre-trial) map of the H.E.S.S. GPS.

precision of 6′′, consistent with the black hole Sgr A* but excluding the nearby remnant Sgr A East. The sources line up along the Galactic plane, with a rms spread in latitude of about 0.3°, consistent with the scale height of the distribution of molecular gas and with the width of the distribution of SNRs and pulsars. Nearly all sources are extended, with rms sizes up to 1.2° (see i.e. Vela X).

Figure 1 shows the most recent [8] pre-trial significance map of the entire H.E.S.S. GPS for an integration radius of 0.22°, suitable for detection of extended sources [9]. The color transition from blue to red is set to 7.4σ pre-trials, corresponding to 5σ post-trials. A multivariate analysis technique [2] based on shower and image shape parameters is used to discriminate γ-ray events from cosmic-ray-induced showers.

The next subsections summarize the most recent results classified under different VHE γ-ray population types.

2.2 Supernova Remnants

Shell-type SNRs are considered as prime acceleration sites for the galactic cosmic-rays, at most up to 10^{15} eV. Two type of VHE γ-ray emission associated with SNRs has been discovered with H.E.S.S., VHE γ-ray emission from shell-like SNRs such as RXJ1713.7–3947 [10] or most recently SN 1006 [11], in which in general the VHE morphology is in good agreement with the synchrotron X-ray emission; and VHE γ-ray radiation which seems to be originated via proton-proton interaction of cosmic-rays which are believe to be accelerated in the SNR, interacting with local molecular clouds in its vicinity, such as i.e. W28 [12].

Among the first type, a new shell-type radio SNR, G353.6–0.7 [13], has been recently discovered entirely on the basis of VHE observations associated with the extended source HESS.J1731–347 [14]. Follow-up observations with H.E.S.S. increasing the data set from 14 to 60 h revealed a shell-like morphology (in Figure 2) well in agreement with the radio observations with a luminosity of $L = 1.1 \times 10^{34}$ erg s$^{-1}$, slightly larger than the one measured in RX.J1713.7–3947, $L = 0.8 \times 10^{34}$ erg s$^{-1}$, making HESS.J1731–347 the most luminous VHE γ-ray shell detected to date.

These deep H.E.S.S. observations have also allowed a detailed morphological and spectral studies along the shell of other SNRs previously detected such as Vela Jr. (RX.J0852-4622) [15]. With a similar luminosity than the above mentioned RX.J1713.7–3947, $L = 0.65 \times 10^{34}$ erg s$^{-1}$, the new observations shows a uniform spectral indices along the shell and confirm the correlation with the X-ray image.

The deep and wide exposure of the GPS also permits us to perform population studies using different catalogs. A systematic search for VHE γ-ray on the direction of 203 radio SNRs from the Green catalog [16] has been done [17]. The upper limits derived were used to constrain the standard hadron acceleration scenario in SNRs [18]. Among these SNRs, two of them are of special interest. Upper limits on the
last two remaining non-thermal X-ray SNRs were derived, namely SNR G1.9+0.3, the most young SNR known, and SNR G330.2+1.0 [19]. Those upper limits are compared with current predictions for hadronic and leptonic scenarios, limiting different parameters such as magnetic field, distance, etc.

Despite the increasing number of SNRs detected at TeV energies, the acceleration of cosmic-rays has not been univocally proven yet. 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. Two new candidates for this second scenario have been detected by H.E.S.S., HESS J1852–000 [20] and HESS J1457–593 [21], in which a good correlation with CO data [22] hints an scenario in which those molecular clouds are illuminated by protons accelerated in a close-by source.

### 2.3 Pulsar Wind Nebulae

PWNe represents the major Galactic source population revealed by the H.E.S.S. GPS. These VHE γ-ray sources are associated with very young (τ <10^{15} years) and energetic pulsars (\dot{E}>10^{35} erg/s). In this leptonic scenario, particles are accelerated to VHE as they propagate away from the pulsar or at the shocks produced in collisions of the particle winds with the surrounding medium. As a result of the interactions of relativistic leptons with the local magnetic field and low energy radiation, non-thermal radiation is produced up to \sim 100 TeV. For a few μG magnetic fields, young electrons create a small synchrotron nebula around the pulsar which should be visible in X-rays, whereas the TeV nebula, generated by inverse Compton (IC) process is much larger. PWNe are currently the most efficient sources in producing VHE γ-rays, with more than half of the sources detected in the GPS associated with them. New and deeper multi-wavelength observations to search for pulsars and counterpart PWNe have unveiled the origin of many of the formerly classify as unidentified sources.

For instance, observations with the Fermi-LAT satellite has allowed not only the association of high-energy pulsars with new H.E.S.S. sources (see i.e. HESS J1458–608 [23] or HESS J1831–098 [24]), but also the identification of new components in detected H.E.S.S. sources, such as HESS J1834–087 (W41) [25]. Figure 3 shows the new H.E.S.S. observations, in which a compact region is clearly distinguished from an extended one when deriving the radial profile around the X-ray nebula and pulsar candidate in the center of the VHE source.

![Fig. 3. Radial profile of normalised excesses of HESS J1834–087 centred on the pulsar candidate position. The fitting functions are composed by two gaussians (red line) or by a single gaussian (black line). Preliminary.](image)

Apart from the large and extended VHE sources associated to relic PWNe, such as HESS J1825–137 and recently HESS J1303–631 [26], in which a clear energy-dependent morphology was recently reported by H.E.S.S., an increasing number of composite SNRs, in which the PWNe is still expanding in the...
shell, has been detected. A text-book example is the composite SNR G327.1–1.1 and the new source HESS J1554–550 [27], in which the detected TeV emission is spatially coincident with the X-ray and radio PWN, well inside the remnant. A similar case is the new discovered source HESS.J1818–154 [28], embedded in the SNR G15.4+0.1 (see Figure 3). HESS.J1818–154 was discovered after a long exposure of 145 h at 1.5% of the Crab Nebula flux and no X-ray or radio PWN has been detected yet, allowing SNR G15.4+0.1 to be identify as a composite SNR by means of VHE observations only.

Two new binary system candidates have been reported by H.E.S.S. recently. The first one, HESS J0632+057 [32] has been finally identified in a joint campaign with the Veritas collaboration through long-term X-ray observations with SWIFT, that succeeded in confirming the nature of HESS J0632+057. Bongiorno et al, 2011 [33] presented strong evidence for periodic X-ray variability with a very long period of 321±5 days, implying the discovery of a binary for the first time on the basis of TeV observations. The second newly discovered candidate HESS J1018-589 [34] has been associated through observations with the Fermi-LAT satellite. A 16.4 days variable source (1FGL.J1018.6–5856) was reported by [35] positionally coincident with the H.E.S.S. source (see Figure 5). H.E.S.S. observation of the region shows a point-like source surrounded by a diffuse emission, likely originated in two different emission regions. No variability has been discovered yet at VHE making the association unclear yet, although deep observations and uniform exposure in time with H.E.S.S. should help to clarify the origin of the VHE emission.

2.4 Binary Systems

In a binary scenario composed by a massive star and a pulsar or microquasar, modulated VHE γ-rays can be produced by different mechanisms, namely inverse Compton emission or pion production of high energy protons with the stellar wind. Two firmly identified binary systems have already been detected with H.E.S.S., LS 5039 [29] and PSR B1259–63 [30]. The former is composed by a massive Be star, SS 2883 and the pulsar PSR B1259-63 in a highly eccentric orbit of 3.4 yrs. The pulsar passed through periastron again in December 2010 and January/February 2011 and was re-detected by H.E.S.S., filling up a non-observed region of the light curve [31] and contributing to a wide multi-wavelength campaign. The results of these observations, which are also contemporaneous with the flaring event observed at high-energy with Fermi-LAT, will be presented in an upcoming paper.

Fig. 4. HESS.J1818–154 γ-ray sky map, with VLE 90 cm radio contours superimposed in green. Preliminary.

2.5 New VHE γ-ray emitters

Beside the already known VHE γ-ray source types, H.E.S.S. is still observing new type of sources
which are susceptible of accelerating cosmic-rays (leptons or hadrons) and producing VHE radiation. One of the most intriguing sources reported recently by H.E.S.S., HESS J1747-248 [36] shows a striking positional coincidence with the brightest globular cluster at high-energies, Terzan 5. However, the VHE \(\gamma\)-ray source is elongated, and appears (marginally) offset by \(\sim 4'\) from the center of the cluster (see Figure 6). Different models [37, 38] can account for the total VHE luminosity, but none of them explain the extension and offset, leaving the association unclear.

Fig. 6. VHE \(\gamma\)-ray image of the Terzan 5 region. The 4 to 6\(\sigma\) significance contours are shown in green. The circles show the half-mass radius of about 30'' (in black) and the larger tidal radius of 4.6' (in cyan) of the GC. The cross indicates the best-fit source position, and its error.

Regions like the one around W49, including the bright radio SNR W49B and the luminous HII region W49A, hosting a large number of active, high-mass star formation, have been also observed with H.E.S.S. [39]. The analysis of the observations shows promising results although a clear evidence of new type of accelerator is still on hold.

3 Extragalactic Sources

3.1 The Large Magellanic Cloud

The Large Magellanic Cloud (LMC), located at a distance of 48 kpc, has been observed with H.E.S.S. since 2003. It hosts a number of interesting sources, including the bright pulsar PSR J0537–6910 (\(E = 4.9 \times 10^{36} \text{ erg s}^{-1}\)) and its nebula N157B, the very recent SN explosion (SN 1987A) and the massive star forming region 30 Doradus. The analysis of 90.4 h of observations [40] reveals a VHE bright point-like source at the position of the pulsar PSR J0537–6910 with a luminosity (on the 1 to 10 TeV energy range) of \(4.1 \times 10^{36} (48 \text{ kpc}/d)^2 \text{ erg s}^{-1}\), implying an efficiency of 0.08\(\dot{E}\), similar to other PWNe detected in our Galaxy. The discovery of the first extragalactic PWNe at a distance of 48 kpc evidences again the high efficiency of PWNe in accelerating electrons and producing VHE \(\gamma\)-rays, allowing their detection at large distances.

These deep observations constrain too emission models for SN 1987A, for which an upper limit at \(\mathcal{F}(>1 \text{ TeV}) < 1.1 \times 10^{-9} \text{ m}^{-2}\text{s}^{-1}\) was derived. A more sophisticated analysis is needed to analyse the large region (5\(\times\)5\(''\)) covered by 30 Doradus. The analysis and observations on the LMC is still ongoing and a complete description will be published in the following months.

3.2 Starburst Galaxies

The detection with H.E.S.S. of the starburst Galaxy NGC 253 [41] has meant the discovery of a new type of VHE \(\gamma\)-ray emitter. These type of galaxies are characterize by a high formation rate of massive stars. The high intensity of cosmic-rays, coupled with the large amount of target gas, has resulted in predictions that these objects should be detectable in VHE \(\gamma\)-rays created in collisions of cosmic-rays with gas particles, despite the large distances of these objects. H.E.S.S. has dedicated a large observation time (~170 h) to investigate in detailed the VHE emission detected. This, together with the analysis of 30 months of publicly available Fermi-LAT data, has determined a hard photon index spectral behavior, smoothly aligning the high-energy and VHE emission, suggesting a common origin and favoring an hadronic scenario, in which the transport of particles are dominated by energy-independent processes. The new results were presented by [42] and in the upcoming paper.

3.3 Radio Galaxies

The giant radio galaxy M 87 provides a unique environment to study relativistic plasma outflows and the surrounding of super-massive black holes (SMBH). Its prominent jet is resolved from radio to X-rays displaying complex structures (knots, diffuse emission, strong variability, and super-luminal motion). The angular resolution of ground based VHE IACT does not allow for a direct determination of the origin of the VHE emission in the inner kpc structures. But the location of the VHE emission can be assess by means of variability and correlation studies.
with other wavelengths.

Up to now, three episodes of enhanced VHE activity have been detected from M87. The first one, detected in 2005 by H.E.S.S. [43], occurred during an extreme outburst of the jet feature HST-1 [44]. The coincidence of the two events led to a debate about HST-1 as possible emission site for the VHE emission. During the second flaring episode, detected in 2008, HST-1 was in a low flux state, but radio measurements showed a flux increase of the core region within a few hundred Schwarzschild radii of the SMBH, suggesting the direct vicinity of the SMBH as the origin of the VHE emission [45]. This conclusion was further supported by the detection of an enhanced X-ray flux from the core region by Chandra. The third episode of increased VHE activity detected occurred in 2010 during a joint VHE monitoring campaign by MAGIC and VERITAS. The detection of the high state triggered further MWL observations by the VLBA, Chandra, and other instruments, including H.E.S.S.

3.4 Active Galactic Nuclei

The number of active galactic nuclei (AGNs) detected at VHE has increased in the past few years, yielding to a catalogue of ~ 40 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. H.E.S.S. devotes over 400 hours of observation time per year to the observation of extragalactic sources resulting in the discovery of several new sources, up to 17 new AGNs [47]. The latest discoveries include AP Lib [48], SHBL J001355.9-185406 [49], PKS 0447-439 [50], 1ES 0414+009 [51], 1ES 1312-423 and 1RXS J101015.9-311909.

Multi-wavelength observations are of crucial importance for AGNs studies. A good example of this is the recent detection of the BL Lac type object AP Lib. The energy spectrum is well described by a power law of photon index $2.5 \pm 0.2$. Following the detection, additional X-ray observations where performed with RXTE and Swift. The spectral energy distribution (SED) obtained from the observational data (in Figure 9) shows an extremely broad IC peak if considering a one-zone synchrotron self-Compton model, which challenges this simple approximation.
Beside the above mentioned AGNs (a complete report can be found in [47]) a new extreme BL Lac candidate has been recently reported by H.E.S.S. The new discovered source HESS J1943+213 [52] was found in the GPS and it is one of the few point-like source lying at l=57.76 °, b=-1.29° on the Galactic Plane. The source has a soft spectrum with photon index of 3.1±0.3, unusual in Galactic sources which tend to have harder spectrum of the order of ~2.2. The best-fit position of HESS J1943+213 coincides with an unidentified hard X-ray source IGR J19443+2117, which was proposed to have radio and infrared counterparts. There is no Fermi LAT counterpart down to a flux limit of 6×10^{-9} cm^{-2}s^{-1} in the 0.1 to 100 GeV energy range. The SED has been derived for non-simultaneous observations (see Figure 10). The data from radio to VHE γ-rays do not show any significant variability and no massive star has been found that could lead to a binary system hypothesis. In addition, the distance estimates for its counterparts place them outside of the Milky Way. All available observations favor an interpretation of HESS J1943+213 as an extreme, high-frequency peaked BL Lac object with a redshift z>0.14, which would make it the first extragalactic source discovered serendipitously in the H.E.S.S. GPS.

### 4 Astroparticle Physics

On the astroparticle physics side, a large number of activities has been going on within the H.E.S.S. collaboration in the last years. Concerning quantum gravity energy scale, robust constrains on the linear and quadratic terms of the dispersion relations of the order of \( M^{1}_{\text{QG}} > 2.1 \times 10^{18} \text{ GeV} \) (\( \xi < 5.7 \)) and \( M^{4}_{\text{QG}} > 6.4 \times 10^{10} \text{ GeV} \) (\( \zeta < 3.6 \times 10^{16} \)) respectively have been derived from fast variability detected on AGNs (PKS 2155-304) [53].

An observation program to monitor the best candidates to originate VHE γ-ray from dark matter on objects free of astrophysical background sources has been carried on. This includes observations of dwarf Galaxies, such as Sagittarius [54], Carina and Sculptor [55], globular clusters such as NGC 6388 and M15 [56] and galaxy clusters such as Formax [57], from where upper limits have been derived.

But the most constraining upper limit comes from the Milky Way Halo [58, 59] from which limits on the velocity-weighted cross-section \( \langle \sigma v \rangle \) has been...
imposed (see Figure 11) at only one order of magnitude from predictions.

5 Future Plans

The next boost on the H.E.S.S. sensitivity, extending also the energy threshold down to a few tens of GeV will be thanks to the new very large telescope (28 m dish) in the center of the array. Figure 12 shows the H.E.S.S. site in August 2011. The end of the steel construction is foreseen for November 2011 while the first light is expected to be in June 2012.

The HESS experiment will have two operating modes. At high energies the system will operate in stereoscopic mode with the current array, as several telescopes will be hit by the Cherenkov pool of light. At lower energies, the 28 meter telescope only will be sensitive enough to detect a signal and will be operated in stand-alone mode.

6 Conclusions

The H.E.S.S. telescope array continues its successful exploration of the VHE γ-ray sky. During 2010 and 2011 the mirrors of the H.E.S.S. telescopes are being re-coated to lower the energy threshold back to the original value of ∼100 GeV and recover the initial sensitivity. At the same time, new analysis techniques have been applied, leading to the discovery of at least ten new source in the last months.

On the Galactic physics side, the H.E.S.S. GPS still plays 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: The number of VHE γ-ray shell-type SNR detected is increasing and deeper observations reveals new interesting features in the spectrum.
- SNRs interacting with molecular clouds: The H.E.S.S. good angular resolution allows a study of correlations with CO surveys in collaboration with the Nanten telescope and CfA 1.2 m telescope. Some of the new sources discovered show a promising coincident morphology between the γ-ray emission region and the gas.
- Middle-aged offset PWN and very young composite PWN: New sources showing energy-dependent morphology have been discovered and PWNe identified. Some of those were detected on the basis of VHE observations only.
- Binary systems: A new binary system has been discovered on the basis of VHE observations and a second candidate is established, increasing the sample and our understanding of such systems.
- New source type are under investigation, such as globular clusters and HII regions.

On the Extragalactic side, the H.E.S.S. extragalactic science program is still making crucial contributions in the field.

- The increasing number of blazars in the extragalactic domain allows population studies and the constrain of emission models.
- The high sensitivity reached also allows the detailed study of fast variable flares, comparing with simultaneous observations at other wavelengths.
- Deep observations of non-blazar objects such as M87 or NGC 253 (or Cen A [60]) have successfully reveal new and exiting results. NGC 253
results in combination with Fermi LAT data favors hadronic scenarios in which the underlying cosmic-ray sea could be derived from the high-energy and VHE observations.

- Deep observation has been performed on the LMC, resulting in the discovery of the first extragalactic PWNe.

Finally, the upcoming of the H.E.S.S. II upgrade in June 2012 will open a new window of observation at low energies and increase the H.E.S.S. sensitivity at least a factor 2 at TeV energies.

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References

[27] F. Acero, 2011, ICRC, 7, 184