Very High Energy $\gamma$-ray Observations with H.E.S.S.

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The H.E.S.S. Imaging Atmospheric Cherenkov Telescope Array is currently the most sensitive instrument for Very High Energy (VHE) $\gamma$-ray observations in the energy range of about 0.1-10 TeV. During more than two years of operation with the complete 4-telescope array, many galactic and extragalactic VHE $\gamma$-ray sources have been discovered. With its superior sensitivity and its large field-of-view camera, H.E.S.S. is particularly suited for surveys and detailed studies of extended sources. A selection of recent H.E.S.S. results is presented in this proceeding.

1 The H.E.S.S. Experiment

H.E.S.S. is an array of four Imaging Atmospheric-Cherenkov Telescopes (IACTs) located in the Khomas Highlands of Namibia ($S 23^\circ16'18'' E 16^\circ30'1''$) at an altitude of 1800 m above sea level. Each telescope consists of a segmented 107 m$^2$ mirror of 13 m diameter which reflects Cherenkov photons onto a 960 pixel photomultiplier camera with a large field-of-view of about 5$^\circ$. The focal length of the instrument is 15 m.

H.E.S.S. makes use of the stereoscopic technique, i.e. air showers are imaged by several telescopes simultaneously. In order to suppress background (mostly due to muons) at the hardware level and to enable stereoscopic reconstruction, a stereo trigger accepts only those events which were seen by at least two telescopes. The reconstruction of the air shower from different points of view leads to a superior angular resolution of better than 0.1$^\circ$ per event. Positions of strong point-like sources are determined with a precision of 20-30$''$, limited by the pointing accuracy of the array. Studies to further reduce the pointing systematics are ongoing.

The energy of the primary $\gamma$-ray is estimated with a typical energy resolution of less than 15%. The energy threshold of the array before analysis cuts is about 100 GeV for observation at zenith and increases to about 700 GeV at 30$^\circ$ of altitude.

H.E.S.S. is currently the most sensitive instrument in its field: a significant (5 $\sigma$) detection of point-like sources with a Crab-like flux takes 30 seconds. Fainter sources with fluxes of only 1%
of the Crab Nebula are detected in 25 hours of observation time. H.E.S.S. reaches a good off-axis performance in its large field-of-view cameras. This makes the instrument ideal for surveys and studies of extended sources.

A first-look data analysis is performed during data taking. This enables one to monitor the data quality and quickly react to any malfunctions of the system. Furthermore, re-observations can be scheduled immediately in case a particular target shows interesting physics. Final calibration and analysis of the data is later performed in Europe, where two independent calibration and several analysis chains are used to cross-check results. For more information on analysis techniques see

2 Selected results from H.E.S.S.

H.E.S.S. recorded useful data during commissioning of the array (with a reduced number of telescopes and a number of different trigger configurations). The instrument was completed in December 2003 and is operating since then with full performance. H.E.S.S. observations have resulted in far too numerous results than could be presented here. Therefore, for the purpose of this paper, only a selection of recent H.E.S.S. highlights will be presented.

2.1 Galactic Plane survey

The location of H.E.S.S. in the southern hemisphere makes the instrument ideal for observations of the Galactic Plane, in particular in the direction of the Galactic centre. The inner part of the Galactic Disk is expected to host a rich population of all types of potential multi-TeV particle accelerators like pulsars, supernova remnants (SNRs), and massive stars. In the central 60° in galactic longitude and 6° in galactic latitude, 91 SNRs and 381 pulsars have so far been detected in different energy bands.

Prior to the start of H.E.S.S. observations, only two strong Galactic sources were known in VHE γ-rays: TeV γ-ray emission from the Galactic Centre had been reported by the Whipple and Cangaroo collaborations. The latter also claimed TeV emission from the SNR RX J1713.7-3946 later confirmed by H.E.S.S. measurements in 2003.

The potentially large number of γ-ray sources combined with the enhanced sensitivity of H.E.S.S. motivated a deep scan of the inner part of the Galactic Plane, which was carried out in 2004. The survey covered a range of −30° < l < 30° and −3° < b < 3° in Galactic longitude and latitude, respectively. In 230 hours of live time, an average flux sensitivity of about 2% of the Crab above 200 GeV was reached. The scan revealed fourteen previously unknown VHE γ-ray sources with a significance > 4 σ (Fig. 1), all of which are extended in shape when accounting for the angular resolution of the instrument. Due to good pointing accuracy most of the sources could be identified with already known counterparts in other wavelength bands. There is, however, a substantial fraction of sources for which there exists no known counterpart yet. Whether or not these are driven by yet undiscovered physics processes (e.g. Dark Matter annihilation) remains one of the exciting tasks for future investigations.

Integral fluxes and energy spectra have been obtained for all sources. Energy spectra can be described by power-law parametrisations

$$\frac{dN}{dE} = F_0 E^{-\Gamma},$$

and similar values of the photon index Γ were found for all sources. The average value of Γ = 2.32 matches expectations for the source spectrum of Galactic cosmic rays. Recently, the MAGIC collaboration has confirmed two of the newly discovered H.E.S.S. sources, HESS J1813-178 and HESS J1834-087. Their integral fluxes and photon indices agree well with those from H.E.S.S. observations.
Figure 1: Significance map of the H.E.S.S. Galactic Plane survey in 2004, including data from re-observations of source candidates from the original scan and observations of the known γ-ray sources RX J1713.7-3946 and the Galactic Centre region.
2.2 Supernova remnants

Supernova remnants, left behind by gigantic explosions of massive stars, have since long been thought to be one of the prime sources of VHE cosmic rays. Shock acceleration is believed to be the mechanism accelerating charged particles to energies of 100 TeV and beyond, naturally resulting in a power-law shaped energy spectrum. VHE $\gamma$-rays can trace those particles by means of two common scenarios: If the accelerated particles were electrons, they could produce $\gamma$-rays by means of Inverse Compton scattering off ambient photons. Protons and nucleons could undergo nucleonic reactions with ambient material and produce, among other particles, neutral pions, followed by the decay $\pi^0 \rightarrow \gamma\gamma$.

At least 5 sources seen in the H.E.S.S. Galactic Plane scan could be identified as SNRs. One of the best studied examples is RXJ 1713.7-3946, a shell-type supernova remnant, which was observed by H.E.S.S. in 2003. With an angular resolution more than an order of magnitude better than the spatial extension of the SNR, H.E.S.S. was the first to resolve the morphology of a TeV $\gamma$-ray source. In 2004, RXJ 1713.7-3946 was re-observed for 33 hours live time. A strong signal is observed with a significance of about 39$\sigma$ (Fig. 2), which enables detailed spectral and morphological studies. Good spatial correlation of the $\gamma$-ray flux with X-rays proves that SNRs are indeed accelerators of VHE particles. Although the interpretation of the H.E.S.S. results in the context of data in other energy bands seems to favour a hadronic acceleration scenario, no strong conclusion can yet be drawn about the parent population dominantly responsible for the observed $\gamma$-ray flux.

Figure 2: Image of RXJ 1713.7-3946 in VHE $\gamma$-rays. The linear colour scale is in units of excess counts. The white contours denote the significance of the features. The levels are linearly spaced and correspond to 5, 10, and 15$\sigma$, respectively. In the lower left corner a simulated point source is shown as it would appear in this particular data set.
2.3 Galactic Centre region

The inner 100 parsec of our Galaxy are known as the most violent and active region in our solar neighbourhood. Not only does it host a central supermassive black hole, but also numerous other objects like supernovae remnants, massive stars and giant molecular clouds.

In 2003 H.E.S.S. observed a strong source of TeV $\gamma$-rays (HESS J1745-209) from the direction of the Galactic Centre. The Galactic Centre region was re-observed in 2004, and the initial discovery was confirmed with a high significance of about 38 $\sigma$ (Fig. 3 (a)). The centre of gravity of the (almost) pointlike excess is spatially coincident (3″ ± 12″(stat.)) with the central black hole Sagittarius A*.

However, even with the good pointing accuracy of the instrument (20″), the SNR Sagittarius A-East cannot be ruled out as the source of the observed TeV $\gamma$-ray flux. The energy spectrum of the excess is shown in Fig. 4 (left side) separately for the 2003 and 2004 data sets. The 2004 data match the previous results both in observed flux and photon index.

Figure 3: VHE $\gamma$-ray images of the GC region. (a) $\gamma$-ray count map, showing the strong source G0.9+0.1 and the emission coincident with the gravitational centre of our galaxy. The position of Sagittarius A* is marked with a black star. (b) Same map after subtraction of the two bright sources. White contour lines indicate the density of dense molecular clouds, traced by CS emission. The green ellipses show 95% confidence regions for the position of two unidentified EGRET sources.
The energy dependence is best described by a straight power-law of index $\Gamma = 2.25$, with no hint for a break or curvature in the spectrum up to energies of 20 TeV. A detailed analysis shows no variability of the VHE flux or the photon index on time scales of years, months, days, hours, or minutes. While a variable source would disfavour an SNR or, more exotically, annihilation of Dark Matter particles, as the source of the observed TeV $\gamma$-ray excess, no firm conclusion can yet be drawn from the non-observation of such variability.

Annihilation of light Dark Matter (DM) particles (neutralinos in most common DM scenarios) in the vicinity of the central black hole Sagittarius A* can be searched for by comparing the predicted energy spectra of the $\gamma$-rays produced in the annihilation process with the energy spectrum measured by H.E.S.S. Fig. 4 (right side) shows the spectral energy density ($E^2 \times$ differential flux) of the observed excess together with best-fit curves of predictions of different annihilation models. As can be seen, all predicted spectra are curved at high energies (for reasons of energy conservation), clearly in contradiction to the observed power-law behaviour of the 2004 H.E.S.S. measurements. Secondly, the neutralino masses determined by the fits are rather large compared to common expectations. As a consequence, the bulk of the observed $\gamma$-ray excess is probably of astrophysical rather than of particle physics origin. However, a small admixture of $\gamma$-rays from DM annihilations cannot be ruled out.

While for previous VHE instruments the sources shown in Fig. 3(a) were close to the detection limit, the sensitivity of H.E.S.S. enables the search for much fainter emission. Subtracting the best-fit model for point-like emission of the two strong sources HESS J1745-209 and G 0.9+0.1 yields the map shown in Fig. 3(b). The subtraction reveals the presence of diffuse emission along the Galactic Plane, as well a a TeV $\gamma$-ray source coincident with the unidentified EGRET source 3EGJ1744-3011.

The diffuse emission spans in a region of roughly $2^\circ$ in galactic longitude with an rms width of about $0.2^\circ$ in galactic latitude. The reconstructed $\gamma$-ray spectrum integrated within $|l| \leq 0.8$ and $|b| \leq 0.3$ is well described by a power law with photon index $\Gamma = 2.29$, close to what is found for the bright central source.
Assuming the diffuse emission being produced near the centre of the Galaxy (at a distance of 8.5 kpc from the observer), the latitude extension translates into a scale of about 30 kpc. This is very similar in extension to giant molecular clouds in this region. Indeed, at least for $|l| \leq 1^\circ$, there is a striking correlation between the morphology of the observed $\gamma$-rays and the density of molecular clouds as traced by CS emission. This is a strong indication for the presence of a nucleonic cosmic ray accelerator in the centre of our Galaxy, since accelerated nucleons would interact with the ambient gas of the clouds, giving rise to the observed $\gamma$-ray flux via $\pi^0 \rightarrow \gamma \gamma$ decays. The fact that no emission is seen further than $|l| \approx 1^\circ$ suggests that the cosmic rays stem from a rather young source near the Galactic Centre. A simple diffusion model assuming a source age of about $10^4$ years can well reproduce the observed $\gamma$-ray flux distribution.

2.4 Extragalactic sources

Apart from Galactic objects, H.E.S.S. observed a long list of possible extragalactic sources of VHE $\gamma$-rays. Active Galactic Nuclei (AGN) are of particular interest, since they are known to emit radiation in all wavebands, including VHE $\gamma$-rays. Furthermore, these objects are known to be highly variable. To constrain any model of AGN, data are needed for a wide energy range, in particular at the highest energies where only a very limited number of measurements exists. H.E.S.S. observed a number of known AGN and star burst galaxies. Objects like PKS 2005-489, Mkn421, or PKS 2155-304 were detected with high significance. The latter was also observed in a simultaneous multi-wavelength campaign covering radio, optical, X-ray, and VHE $\gamma$-ray emission, and short-time variability of the flux has been discovered. For other objects, no VHE $\gamma$-ray emission was found, and strong upper limits were obtained for 19 AGN and the star forming galaxy NGC 253.

For very distant AGN, a significant softening of energy spectra is expected because of the partial absorption of VHE $\gamma$-rays due to photon-photon interactions with the Extragalactic Background Light (EBL). For such AGN with hard observed spectra, one can therefore constrain the amount of EBL present in the universe, which is of great importance for cosmological studies. Following this logic, H.E.S.S. observations of the blazars H 2356-309 (redshift $z = 0.165$) and 1ES 1101-232 ($z = 0.186$) revealed that the universe is more transparent to VHE $\gamma$-rays than previously thought.

3 The Future of H.E.S.S. : H.E.S.S. II

While H.E.S.S. continues to take interesting data, the H.E.S.S. collaboration is designing and constructing an upgrade to the existing telescope array. H.E.S.S. phase II consists of a very large single telescope that will be placed in the centre of the H.E.S.S. I array. The mirror collection area of H.E.S.S. II is about 600 $m^2$, exceeding that of a single H.E.S.S. telescope by about a factor 6. The camera has a $3^\circ$ wide field-of-view, made up of about 2000 PMTs. The pixel size is $0.07^\circ$, which will result in a more resolved shower image compared to H.E.S.S. I. For the operation of H.E.S.S. II two different modes are foreseen: In coincidence mode, the new telescope is triggered by the H.E.S.S. I array. In the energy range between 0.1 TeV and a couple of 10 TeV, this will increase the sensitivity of the array by at least a factor of 2 compared to H.E.S.S. I. When operating in stand-alone mode, the energy threshold of the new telescope will be about 30 GeV.
4 Conclusions

The H.E.S.S. experiment has been fully operated since December 2003. For the past two years it has run with full performance and produced numerous exciting new results in VHE $\gamma$-ray observations. H.E.S.S. shows for the first time that the latest generation of ground-based Cherenkov telescope arrays has reached a sensitivity where real $\gamma$-ray astronomy is feasible. The sensitivity of H.E.S.S., combined with its good angular resolution, provides an excellent handle to study and understand the physics processes that take place in galactic and extragalactic sources of VHE $\gamma$-rays.

Starting in 2008, H.E.S.S. II will explore the $\gamma$-ray sky with even higher sensitivity and at least two-times lower energy threshold. This will provide a comfortable overlap in energy with the upcoming GLAST satellite experiment.

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