H.E.S.S. Status

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H.E.S.S. has been in full operation since December 2003 and has provided a wealth of exciting new results from the survey of the Galactic plane at VHE energies, and on VHE gamma-ray emission from supernova remnants, binary systems and pulsar wind nebulae. New results are also reported for Galactic Center sources and for extragalactic sources.

1 The H.E.S.S. telescope system

H.E.S.S. is a system of four large (13 m diameter) imaging atmospheric Cherenkov telescopes, operated by an international collaboration of about 100 physicists from 8 countries. The telescopes [1] are located in the Khomas highland of Namibia, near the tropic of Capricorn. With their cameras [2] containing 960 photomultiplier pixels and covering a 5° field of view, they provide multiple images of gamma-ray (and cosmic-ray) induced air showers in the Cherenkov light emitted by the shower particles, and enable the stereoscopic reconstruction of the shower geometry. The full four-telescope system is in operation since December 2003. The telescopes operate about 1000 h per year during moonless night time, recording shower events at a rate of about 300 Hz. Near zenith, the energy threshold - defined as the energy of peak detection rate for typical source spectra - is about 100 GeV, increasing with zenith angle to 250 GeV at $45°$ and 700 GeV at $60°$. The system provides an angular resolution of 0.1° for individual gamma-rays; gamma-ray sources can typically be located with a precision of 1' or better, limited for intense sources by systematic errors at the 20" level. The sensitivity of the H.E.S.S. telescope system is about one order of magnitude better than previous instruments, and allows to detect sources with a flux of 1% of the Crab Nebula in 25 h.

Highlights from H.E.S.S. include the Galactic Plane Survey, which unveiled a number of new VHE gamma-ray sources, the detailed studies of supernova remnants and pulsar wind nebulae, the discovery of gamma rays from a binary system and the study of emission from the Galactic Center region. 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, and to the other H.E.S.S. contributions to this conference. Unpublished results should be considered preliminary.

2 H.E.S.S. and the old southern-hemisphere sources

Already during the initial operation of H.E.S.S., significant disagreements concerning previous results on southern VHE sources emerged: the Vela pulsar, the pulsar PSR B1706-44, the famous supernova SN 1006 and the starburst galaxy NGC 253 could not be detected as VHE gamma-ray sources, with limits [3–5] well below previously claimed fluxes. For the source near Sgr A, the measured spectrum [6] differs significantly from the one reported by CANGAROO [7]. Only for the remnant RX J1713.7-3946 [8] and the AGN PKS 2155-304 [9] reasonable agreement with earlier results [10, 11] is found. Given that H.E.S.S. reproduces the flux and spectrum of the Crab nebula as measured by northern Cherenkov instruments, and that results are stable during two years of increasingly sophisticated analysis and calibration of the telescope system, it is clear that the disagreements are real and that either the sources have varied over time – which would be somewhat surprising for extended sources such as SN 1006 or NGC 253 – or that the earlier single-telescope data suffered from undetected problems, related, e.g., to variations in night-sky brightness.

3 H.E.S.S. results on extragalactic sources

In the first years of operation, H.E.S.S. has surveyed a significant number of AGNs, mostly resulting in flux limits, which are – despite rather short observation times – significantly better than previous limits; a set of 19 flux limits was reported in [12]. Positive detections were achieved for the new source PKS 2005-489 [13], for PKS 2155-304 [9,14], for the radio galaxy M87 and – in observations at large zenith angles – for Mrk 421 [15]. The Mkr 421 data have the interesting feature that at the large zenith angles, H.E.S.S. provides a detection area in excess of a square kilometer at high energy, which allowed determination of the spectrum to beyond 10 TeV, as well as the demonstration of a flux-dependent shape of the spectrum [15]. PKS 2155-304 is remarkable in that despite its relatively large redshift of 0.117, the source is detected with high significance – over 50 σ – and the spectrum is well determined, with a photon index $\Gamma \approx 3.3$. New multiwavelength data have been obtained characterizing the spectrum from radio wavelengths to VHE gamma rays (Fig. 1); comparison with archival X-ray data shows that the source was in a rather low state. M87 was the first non-blazar AGN to be detected (by HEGRA [16]); H.E.S.S. data confirm this discovery with a 4.6 σ signal based on 2003 and 2004 data. The flux is lower than measured by HEGRA, indicating variability and hence a compact source region.

Figure 1: Spectral energy distribution for PKS 2155-304 [14]. Colored data points (H.E.S.S., RXTE, ROTSE, NRT) refer to simultaneous observations. Curves refer to leptonic (dotted and dashed lines) and hadronic models (full line), see [14] for details.

4 The H.E.S.S. Galactic plane survey

The H.E.S.S. Galactic plane survey (Fig. 2) was conducted in the summer of 2004 and covered the region of $\pm 30^\circ$ in Galactic longitude and $\pm 3^\circ$ in latitude, at a typical sensitivity of a few % of the Crab flux. Eight new VHE gamma ray sources with a post-trial significance exceeding 6σ were discovered during the survey [17], in addition to three previously known sources in the survey region - the Galactic center, G0.9+0.1, and RX J1713.7-3946. The sources line up along the Galactic equator, 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 supernova remnants and pulsars. Their Galactic origin is confirmed by the fact that nearly all sources are extended, with rms sizes up to 0.2°. H.E.S.S. can typically resolve a source as extended when its rms size exceeds 2'-3'.

Figure 2: Significance map for the H.E.S.S. survey of the central section of the Galactic plane.

Counterparts for the new sources were searched, primarily in radio- and X-ray catalogs. Plausible associations with supernova remnants (SNR) exist for three of the new sources – HESS J1640-465 (Fig. 3(a)), HESS J1834-087 (Fig. 3(b)) and HESS J1804-216. Three sources – HESS J1804-216, HESS J1825-137 and HESS J1616-508 could be associated with nebulae powered by sufficiently energetic pulsars; of these, HESS J1825-137 will be discussed in detail later. The source HESS J1813-178 remained unidentified in the original survey paper [17] but has meanwhile been identified; it coincides with a supernova ring discovered in radio data [18, 19], and also with previously unpublished ASCA [20] and INTEGRAL [20] sources. HESS J1614-518 (Fig. 3(c)) has no plausible counterpart at other wavelengths.

Figure 3: Smoothed excess maps of some of the new sources, together with potential counterparts in other wavelength ranges. (a) HESS J1640-465, coincident with SNR G338.3-0.0. (b) HESS J1834-087, coincident with SNR G23.3-0.3 (W41). (c) HESS J1616-508 and HESS J1614-518; for the second source no counterpart is known.

5 Supernova remnants studied with H.E.S.S.

Another H.E.S.S. highlight is the detection of resolved supernova remnant (SNR) shells (Fig. 4), for RX J1713.7-3946 [8] and for RX J0852.0-4622 ("Vela Junior") [21], both objects discovered in VHE gamma-rays by CANGAROO [10, 22]. In both cases, TeV gamma ray emission can be clearly traced to the supernova shell, demonstrating that the shock wave accelerates particles to multi-TeV energies, generating photons via interactions with gas – in case of protons - or by Inverse Compton scattering – in case of accelerated electrons. While the intensity of the gamma-ray emission

Figure 4: Supernova remnants RX J1713.7-3946 (left) and RX J0852.0-4622 ("Vela Junior", right). Color scale indicates gamma-ray count rates, contour lines the X-ray emission measured by ASCA (RX J1713-3946) [23] and ROSAT (RX J0852.0-4622) [24]

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varies along the circumference, the strong correlation with the location of the shell - as seen e.g. in X-rays - is evident. The energy spectrum of RX 1713.7-3964 has been measured over two decades in energy (Fig. 5(a)), up to 30 TeV, and approximately follows a power law with index 2.1 to 2.3, with indications for a cutoff or break at the highest energies. The spectral index coincides with predictions of shock-wave acceleration models; the high photon energies detected demonstrate that energies of primary particles reach up to 10^{14} eV and beyond. The spectral index is - within errors - constant across the entire remnant (Fig. 5(b)).

Assuming that X-rays represent synchrotron radiation ($\sim B^2$) and that the gamma rays are generated in Inverse Compton scattering – thereby naturally accounting for the good correlation between X-rays and VHE gamma rays (Fig. 4(a)) – a local magnetic field $B \approx 10$ μG can be determined from the relative levels of X-ray and gamma-ray intensities. A standard E^{-2} electron injection spectrum describes the radio and X-ray spectra, but fails to account for the almost constant index of the gamma-ray spectrum; the Inverse Compton peak should be visible in the energy range covered by H.E.S.S. With a steeper spectrum, $E^{-2.5}$, the gamma-ray spectrum can be accommodated, but then model predictions overshoot the radio flux [25] by almost two orders of magnitude. In contrast, models which use a higher magnetic

Figure 5: (a) Energy spectrum of gamma rays from RX 1713.7-3964, based on the 2003 data (open points) and the 2004 data (full points). (b) Spectral index determined from a power-law fit for 14 regions of the remnant. No significant variation of the index is found across the remnant. The contour lines indicate the gamma-ray flux.

field (which suppresses the Inverse Compton component for a given X-ray intensity) and which add gamma-rays generated in proton interactions, achieve a good description of wide-band spectra; of course at the expense of introducing additional free parameters (proton flux and spectrum). In summary, remarkable progress has been made in pinning down SNRs as cosmic accelerators, and there is a preference for a hadronic origin of the high-energy gamma rays; however, fully conclusive evidence is still lacking.

6 H.E.S.S. observations of pulsar wind nebulae

Another interesting class of new TeV gamma-ray sources are pulsar wind nebulae (PWN), which are potentially responsible for a significant fraction of the new sources, and for some of the strongest. A supernova explosion frequently leaves a pulsar behind, which, it its high magnetic and electric fields, generates a steady stream of high-energy electrons and positrons. This pulsar wind blows a hole into the remnant, compressing ejecta in a pulsar wind termination shock, in which the electrons can be re-accelerated. The energy content of the pulsar wind is typically a few orders of magnitude lower than the kinetic energy available for particle acceleration in the supernova ejecta, which makes it surprising that pulsar wind nebulae - with the Crab

Nebula as the best-studied example - are such prominent sources. The reason is that energy in pulsar wind electrons is far more efficiently converted to gamma rays than the energy of protons and nuclei accelerated in the main supernova shock. Typical radiative life times for electrons are O(10^3) y, compared to O(10^7) y for protons, which compensates for the deficit in energy. PWN detected in X-rays sometimes appear shifted relative to the pulsar [26, 27]; explanations include a (single-sided) jet-like emission or the "crushing" of one side of the PWN by the reverse shock [28], which is released when the supernova shock wave has swept up a significant amount of material, generating a back-reaction. If a supernova explodes into an inhomogeneous environment - as most supernovae do - the reverse shock from the side of the denser medium will reach and crush the corresponding side of the PWN while - if observed at the right time - the other half of the PWN is still unaffected.

A particularly nice candidate for a displaced PWN is HESS J1825-137. Located south of the pulsar PSR B1823-13, the VHE gamma-ray emission peaks at the pulsar and then falls off towards the south (Fig. 6). Exactly the same feature is seen in X-rays [27], except that the characteristic extension of the nebula is a few arcminutes rather than a fraction of a degree. A natural explanation is [29] that in the estimated 10 μG field in the nebula, the X-ray generating electrons have higher energies than those responsible via Inverse Compton scattering for the VHE gamma rays. The higher-energy X-ray electrons cool faster and have a shorted range.

Another interesting PWN is MSH 15-52, associated with the pulsar PSR B1509-58 inside the G 320.4-1.0 / RCW 89 shell. The elongated and single-sided nebula was seen in ROSAT images [30]; high-resolution Chandra images [31] revealed a jet-like feature. MSH 15-52 was first detected as a gamma-ray source by CANGAROO [32]. H.E.S.S. observations resolve an extended source [33] (Fig. 7(a)), aligned in the same direction as the Chandra jet feature, and with a power-law energy spectrum extending to well beyond 10 TeV (Fig. 7(b)).

Particularly interesting objects are pulsars in binary systems. Their often eccentric orbits allow the study of how gamma-ray emission is influenced by the companion star. PSR B1259-63 is a distant binary, consisting of a pulsar in a highly eccentric 3.4 y orbit around a massive star with a disk-like equatorial wind. The closest approach - last in March 2004 - is about 20 stellar radii. Near periastron, particles potentially accelerated by the pulsar find enhanced targets for generating gamma-rays, both in the form of the intense photon field of the star, and in the form of the wind. In February 2004, H.E.S.S. detected this system as a TeV source [34] (Fig. 8). Surprisingly, however, the light curve - interrupted by full-moon periods - indicates a double-humped shape with a minimum near periastron. This time variation suggests that interactions of the pulsar wind with the disk material dominate the shape of the light curve. Another surprise was the discovery of a second, steady and extended (0.16°) gamma-ray source about 0.5° north of the pulsar, HESS J1303-

Figure 6: (a) Distribution of gamma-ray excess counts for HESS J1825-137, near the pulsar PSR B1823-13 (= PSR J1826-1334). (b) X-ray [27] and (c) gamma-ray counts in a slice in declination, centered on the pulsar.

631 [35] (Fig. 8). HESS J1303-631 – with a spectrum with photon index $\Gamma \approx 2.4$, reaching up to 10 TeV – is another "dark accelerator" without known counterpart at other wavelengths, despite of follow-up observations with Chandra [36].

7 H.E.S.S. observations of the Galactic center region

Another very interesting region is obviously the Galactic center. H.E.S.S. detected two sources near the Galactic center, HESS J1747-281 [37], coincident with the SNR G0.9+0.1 and HESS J1745-290 [6], coincident with the Sgr A complex. The source of gamma rays in SNR G0.9+0.1 is presumably again a PWN; the gamma ray source is definitely smaller than the SNR shell visible in radio [37]. The origin of the source at the Galactic center – prior to H.E.S.S. seen by CANGAROO [7] and VERITAS [38] with lower significance – is less clear; it could be associated with processes near the central black hole, with the SNR Sgr A East or with the annihilation of speculative dark-matter particles ("neutralinos") left over from the big bang and responsible for structure formation in the universe; the density of such particles should peak as $r^{-\alpha}$ at the Galactic center, with $\alpha \geq 1$ derived from many-body simulations. The location of the H.E.S.S. source is within the 20" systematic pointing errors fully consistent with

Figure 7: (a) Smoothed excess map from MSH 15-52 [33]. The white contour lines denote the X-ray count rate measured by ROSAT [30]. The black point and the star lie at the pulsar position and at the excess centroid, respectively. The inset shows the point spread function after smoothing. (b) Gamma-ray spectrum from MSH 15-52. The lines show the result of a fit to X-ray and gamma-ray spectra, where gamma rays result from Inverse Compton upscattering by electrons, with microwave background, IR from dust and starlight as targets [33].

Figure 8: Light curve of VHE gamma rays from the direction of the pulsar PSR B1259-63. The dotted line indicates the point of closest approach between the pulsar and the Be star, the shaded areas show the (approximate) crossing of the disk-like stellar wind. The small inset shows the field around PSR B1269-63 as seen in February 2004, with the second source HESS J1303-631 north of the pulsar.

Figure 9: (a) Angular distribution of the gamma-ray emission from the Sgr A source HESS J1745-290. Shown is the distribution in the angle θ^2 relative to the source. (b) Spectral energy density of HESS J1745-290. Lines: spectra resulting from the annihilation of typical MSSM neutralinos and from Kaluza-Klein dark-matter particles [40].

Sgr A*, but an origin in Sgr A East cannot safely be excluded. A possible clue could therefore come from the exact angular distribution of the gamma rays (Fig. 9(a)). Indeed, while the peak at small angular distance from Sgr A* is essentially consistent with the angular resolution of the instrument, the angular distribution has a pronounced tail, which is not accounted for by the point spread function. A fit based on dark-matter distributions yields good agreement for $\alpha \approx 1.0$. More constraints concerning the nature of the source can come from the spectrum and the time variability of the flux. The measured spectrum Fig. 9(b)) is a pure power law, extending, with the most recent H.E.S.S. data, over two decades in energy. The measured flux is consistent with constant emission, on scales of (2) years, months, days and hours. However, caveats to be listed are that the total integrated observation time in 2003/4 was about 40 h, so flares might have been missed. Also, short flares (on daily or hourly time scales) must have a significant amplitude (flux variations of factors of a few) to be detectable. Nevertheless, the steady emission disfavors processes in the immediate vicinity of the black hole Sgr A*. Concerning the dark-matter signature, the observed power law spectrum does not match the typical (quark or gluon-fragmentation type) gamma-ray spectra from neutralino annihilation [39] (Fig. 9(b)), even ignoring the fact that most models prefer neutralinos in the energy range up to 1 TeV, not capable of generating spectra which extend beyond 10 TeV. Classical SUSY neutralinos have strongly curved spectra, at variance with observations. Models based on Kaluza-Klein dark matter particles provide enhanced few-body decay modes and flatter spectra [40], capable of reproducing the early H.E.S.S. 2003 data set. The full 2004 spectrum, extending down to 150 GeV, is not reproduced by these models (Fig. 9(b)). Hence, it seems very improbable that the full gamma ray signal from the Galactic center is caused by dark matter annihilation. A partial contribution, in particular at low energies, can not be excluded.

In summary, the first results from H.E.S.S. have revealed a number of interesting new objects in the TeV sky, many of them extended sources, providing a new handle to analyze processes in the sources. The H.E.S.S. results also demonstrate that Cherenkov instruments of the latest generation have passed a critical sensitivity threshold, where real TeV gamma-ray astronomy becomes feasible.

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