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The γ-ray sky seen with H.E.S.S.

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Summary. — H.E.S.S. is an array of four imaging Cherenkov telescopes located in the Khomas Highlands of Namibia. It has been in operation since December 2003 and detects very-high-energy (VHE) γ-rays with energies ranging from 100 GeV to $\sim$ 50 TeV. Since 2004, regular observation of the Galactic Plane has yielded the discovery of more than 50 sources, belonging to the classes of pulsar wind nebulae (PWN), supernova remnants (SNRs), γ-ray binaries and, more recently, a stellar cluster and molecular clouds in the vicinity of shell-type SNRs. H.E.S.S. has observed also a variety of AGN, studied their spectral and temporal behaviour and detected fast and intense TeV variability. Highlights of the most recent H.E.S.S. observations are presented and their implications are discussed.

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Introduction

The current generation of imaging atmospheric-Cherenkov telescopes (IACTs) has opened a new astronomical window on the Universe in the very-high-energy (VHE; $E > 100$ GeV) domain. Over two-thirds of the about 100 VHE γ-ray sources are located in our Galaxy, of which most were discovered by the IACT array H.E.S.S. (High Energy Stereoscopic System) during its Galactic Plane Survey (GPS). Although a significant fraction of the Galactic VHE γ-ray sources do not appear to have obvious counterparts at other wavelengths [1], the majority of them are associated with the violent, late phases of stellar evolution, *e.g.*, supernova remnants (SNR), pulsar wind nebulae (PWN) of high spin-down luminosity pulsars, and massive Wolf-Rayet (WR) stars in stellar clusters. H.E.S.S. has also devoted about 300 hours per year to extra-galactic observations resulting in the discovery of a dozen of new sources and in deeper studies

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of few AGN with monitoring and multi-wavelength campaigns. An overview of the most recent (galactic and extra-galactic) H.E.S.S. observations is reported.

1. – The H.E.S.S. Telescope array

H.E.S.S. is an array of four 13 m diameter imaging Cherenkov telescopes located in the Khomas Highlands in Namibia, 1800 m above sea level [2]. Each telescope has a tesselated mirror with an area of $107\,\mathrm{m}^2$ [3] and is equipped with a camera comprising 960 photomultipliers [4] covering a field of view of 5° diameter, the largest of all the IACTs currently in operation. H.E.S.S. uses a stereoscopic trigger, which drastically reduces background from single muons and night-sky background, keeping dead-time low and allowing for a low energy threshold of the array [5]. Employing the stereoscopic detection technique, the H.E.S.S. array has an angular resolution of 0.1° and an energy resolution of 15%. Due to the powerful rejection of hadronic showers provided by stereoscopy, the complete system (operational since December 2003) can detect point sources at flux levels of about 1% of the Crab nebula flux near zenith with a significance of 5 σ in 25 hours of observation [2]. With very recent analysis methods [6, 7] H.E.S.S. has relevantly enhanced its significance.

This high sensitivity, the angular resolution of a few arc minutes and the large field of view make H.E.S.S. suited for effectively survey large areas of the Galaxy within a reasonable amount of time, detect γ-ray emission from very distant extra-galactic sources, and to study the properties of variable sources.

2. – The Galactic sources

The original H.E.S.S. Galactic Plane Survey (GPS) covered the inner galaxy within $\pm 30°$ in longitude and $\pm 3°$ in latitude [8]. Between 2005 and 2009 the GPS has been extendend [9] (more than doubled in Galactic longitude), covering the region between $\sim 275°$ and $\sim -60°$. In addition, the overall exposure along the Galactic plane has also been increased significantly (by a factor 6) from the initial ~ 230 h of observations to over 1400 h. Approximately 450 h of data were taken in survey mode, and an additional ~ 950 h of data are a result of pointed observations. The latest image of the pre-trials statistical significance of this extended H.E.S.S. GPS is shown in fig. 1 in [9].

The extension of the GPS has led to the discovery of a variety of VHE sources: shell-type supernova remnants (SNR), pulsar wind nebulae (PWN), γ-ray binaries and massive stellar cluster. Highlights of the most recent discoveries of this variety of sources are presented.

2·1. *Supernova remnants.* – Galactic cosmic rays are believed to be accelerated via first-order Fermi mechanism at the expanding shock waves of supernova remnants (SNRs) [10]. Two points strongly support this scenario: i) the fact that SNRs alone are capable of maintaining the galactic CR flux at the observed level, provided that a fraction of about 10% of their explosion energy is somehow converted into cosmic rays [11, 12], and ii) the fact that some shell-type SNRs have been detected at TeV energies. The direct experimental investigation of "young" SNRs as sources of cosmic rays is indeed possible with VHE γ-rays, as particle acceleration is assumed to occur primarily in the outer expanding shock-waves, which are capable of confining the accelerated particles in their interior (until the shock velocity decreases substantially).

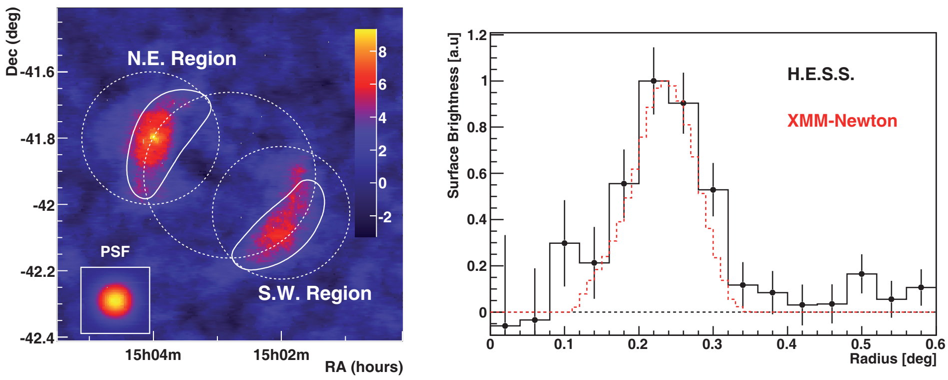

Fig. 1. – Left: H.E.S.S. γ-ray significance map of SN 1006. The solid contours correspond to the regions which contain 80% of the non-thermal X-ray emission from the XMM-Newton flux map in the 2–4.5 keV energy range after smearing with the H.E.S.S. PSF, shown in the inset. Right: radial profile around the centre of the SNR obtained from H.E.S.S. data and XMM-Newton data (2–4.5 keV).

The H.E.S.S. array has up to now discovered 3 TeV shell([1]): RX J1713.7-3946 [14], RX J0852.04622 (better known as *Vela Junior*) [15], and recently SN1006 [16]. SN 1006 is type Ia supernova exploding into an approximately uniform medium and magnetic field, and relatively low gas density. Therefore, this supernova is an ideal case to study particle acceleration mechanisms. With ~ 130 h of data taken between 2003 and 2008, H.E.S.S. has detected a gamma-ray excess from the NE and SW parts of this remnant (see left panel in fig. 1) [16]. The source clearly exhibits a bi-polar morphology, is strongly correlated with non-thermal X-ray emission measured by XMM-Newton [17] (see right panel of fig. 1). The SED can be accounted for by either inverse Compton (IC) emission or a mixed scenario including leptonic (IC) and hadronic ($\pi^0 \rightarrow \gamma\gamma$) components. Both hypotheses lead to a satisfactory description of the whole multi-wavelength data set.

The most recent addition to the list of shell-type TeV SNR is the source HESS J1731-347, which appeared in the first GPS with no clear counterpart at other wavelengths and therefore initially not identified. Recently however, the new shell-type supernova remnant (SNR) G353.6-0.7 was discovered in radio data, positionally coinciding with the H.E.S.S. source. X-ray observations covering a fraction of the TeV source revealed a shell structure emitting non-thermal X-rays. With a deeper observation of this source (totally ~ 60 h) H.E.S.S. have finally identified a clear shell morphology for HESS J1731-347 [18].

2·2. *Pulsar wind nebulae.* – A significant fraction of VHE γ-ray sources is associated with energetic pulsars. These sources can generate bubbles of relativistic particles and magnetic field when their ultra-relativistic wind interacts with the surrounding medium (SNR or interstellar medium). Their confinement leads to the formation of strong shocks, which can accelerate particles up to hundreds of TeV and beyond, thus generating luminous nebulae seen across the entire electromagnetic spectrum. H.E.S.S. has detected a wide range of PWN, the most prominent examples being the Crab Nebula and Vela X.

([1]) With the current statistics, the shell morphology of RCW 86 is not statistically significant [13].

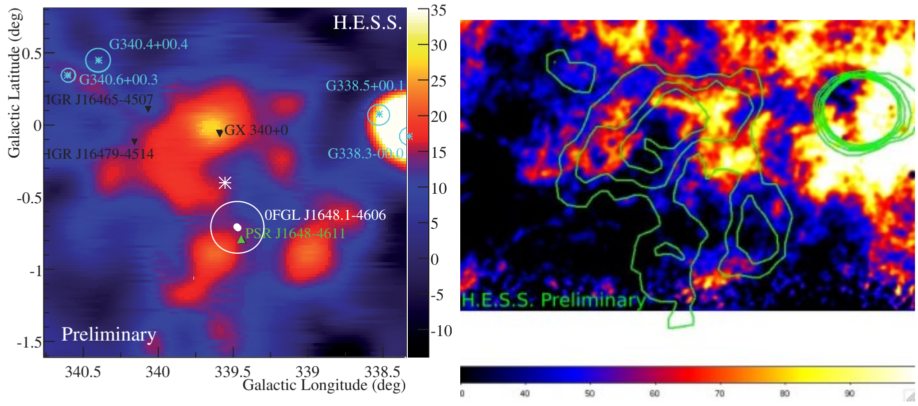

Fig. 2. – (Colour on-line) Left: preliminary excess counts map of the region around Westerlund 1 (cross). The pulsar PSR J1648-4611 (green triangle) and the Fermi-LAT source 0FGL 1648.1-4604 (circle) [22]. Right: preliminary H.E.S.S. significance contours from 4 to 8 σ overlaid on the HI channel map at a velocity of $-55\,\mathrm{km/s}$ [23].

The Vela X region, within 2 degrees of the pulsar PSR B0833-45, has been observed by H.E.S.S. in 2004 and 2005. A strong signal was seen from an extended region to the south of the pulsar [19], but within a smaller integration region of radius 0.8° around the position. Recently, additional observations from 2006 and 2009 allowed further investigation of the PWN in the TeV regime. Significant emission has been detected in a larger region than the cocoon to 1.2° from the center of gravity [20]. The spectrum in such a ring results to be compatible with the one of the cocoon (except for the integrated flux which is about a factor 3 less).

2˙3. *Massive stellar clusters.* – Most of the identified objects in the TeV domain are connected to the late phases of stellar evolution like, *e.g.*, SNRs or PWN. However, some of the VHE γ-ray emitters seem to be connected to the birthplaces of these objects, namely massive star-forming regions and massive stellar clusters.

Westerlund 1 is the most compact young stellar cluster in our Galaxy, with a total mass of around $60000\,\mathrm{M}$, at a distance of 4 to 5 kpc from Earth. The cluster harbors the presently known richest population (≥ 24) of stars in the Wolf-Rayet (WR) phase. Different possible acceleration mechanisms can be at play in massive stellar clusters: a fraction of the power (up to $3 \times 10^{39}\,\mathrm{erg\,s^{-1}}$) is available to accelerate particles to very high energies, *e.g.*, at the boundaries of windblown bubbles, in colliding wind zones in binary systems or in the framework of collective wind or wind/SN ejecta scenarios.

The Westerlund 1 region was observed with H.E.S.S. between 2004 and 2008 during the GPS and lately with dedicated observations [21], resulting in a total of 34 h of good-quality data. This observation has revealed an extendend emission (over 2° in diameter) centered rougly on Westerlund 1 (fig. 2). This makes Westerlund 1 one of the largest structures observed in VHE γ-rays so far. However, it is not trivial from this result to identify the exact origin of the VHE γ-ray emission. Among the different types of counterparts only PSR J1648-4611 is coincident with the observed γ-ray emission, although it is unlikely to account for the full extendend emission. In addition, the Fermi-LAT

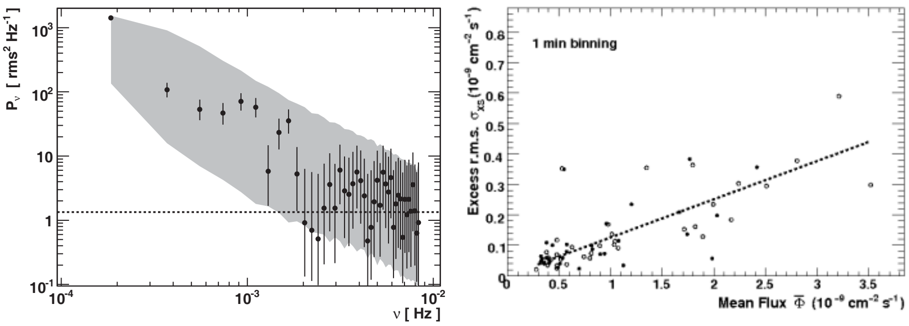

Fig. 3. – Left: Fourier power spectrum of the flare light curve of PKS 2155-304. The shaded area corresponds to the 90% confidence interval for a light curve with a power law of index −2. Right: the rms variability *vs.* mean flux for the flaring period of PKS 2155-304.

instrument has detected high energy emission coincident with the pulsar position [22]. Nevertheless, no significant periodicity could be detected yet. The comparison between the HI data and the VHE γ-ray emission suggests a correlation between them (see right panel fig. 2).

3. – The extragalactic sky

Except NGC 253 [24]—a sturburst galaxy—all the sources discovered by H.E.S.S. in the extragalactic sky (around 12, but continuously increasing) are AGN. Most of these sources belong to the high-frequency peaked class of the BL Lac objects (HBLs), which are well known to be variable objects.

A dramatic outburst of PKS 2155-304 occurred in July 2006 was detected by H.E.S.S.: during this flare, the VHE flux levels of this source varied between 1 and 15 Crab units and with timescales of the order of few minutes [25]. However, despite the considerable theoretical developments in the literature, existing one-zone models have some difficulties in explaining this fast variability without demanding large bulk Lorentz factors of (100 or even higher) to allow TeV γ-rays to escape from the compact area (unless to invoke multiple emission zones or very small emission region).

The PSD (power spectrum density) of the light curve of PKS 2155-304 flare showed a red (Brownian) noise-type power law distribution with an exponent close to 2 within the frequency range 10^{-4}–10^{-2} Hz (fig. 3). In addition, a linear relation between (absolute) rms variability amplitude and (mean) TeV flux has been found (fig. 3), indicating that the process driving the variability is a non-linear, log-normal stochastic process where the relevant normally distributed variable is the logarithm of the flux $\log(X)$ [26]. A log-normal distribution can be thought as the result of many multiplicative random effects, whereas additive effects would give rise to a normal (Gaussian) distribution with no linear rms-flux relation expected. Fluctuations in the disk accretion rate that can feed in the jet could account for a red-noise multiplicative process, although it is not trivial to link this with the minute timescale variability. A possible scenario where PKS 2155-304 is supposed to harbor a supermassive binary black-hole system has been proposed in [27].

4. – Towards H.E.S.S. II

The highlights here presented are only a very short overview of the most recent H.E.S.S. discoveries. In fall 2011 a fifth big telescope ($600\,\mathrm{m}^2$ mirror area and high-resolution camera [28]) will be operating on the H.E.S.S. site. With this addition to the current H.E.S.S. array, the energy threshold of the system will be reduced to $\sim 30\,\mathrm{GeV}$ (in single-telescope mode) and the sensitivity (in multi-telescope mode) will be enhanced, making it possible to study new types of physics and phenomena, such as pulsars and distant AGN, as well as making deeper observations of currently studied objects.

The overlapping in time of operation of H.E.S.S. II and the Fermi Large Area Telescope (LAT) will give an unprecedented opportunity to look at the sky simultaneously and to cover a common energy band with two different kinds of instruments, with the possibility to make cross-correlation studies.

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