EPJ Web of Conferences **136**, 03001 (2017) DOI: 10.1051/epjconf/201713603001
RICAP16

H.E.S.S.-II - Gamma ray astronomy from 20 GeV to hundreds of TeV's

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Abstract. Since the commissioning of the fifth big telescope in December 2012, H.E.S.S. II is the only hybrid array of Imaging Atmospheric Cherenkov Telescopes operating in the energy range $\sim$ 20 GeV to several hundreds of TeV. The last years have seen a tremendous effort in the design, implementation and optimization of analysis techniques suitable for monoscopic & stereoscopic events. At the same time, a complete redesign of the acquisition scheme resulted in a very significant speed-up of repointing, allowing the big telescope to be on target just $\sim$ 20 s after receiving a Gamma-Ray Burst (GRB) alert notification. With its deep sensitivity, broad energy range, and fast reaction time, H.E.S.S. II provides an unprecedented high-quality view of the Universe at the highest energies, in a multi-wavelength and multi-messenger approach which is currently based on agreements many collaborations including in particular Fermi, IceCube, ANTARES and VIRGO/LIGO.

In the last, we conducted deep observations of several galactic regions of primordial importance, among them are the Galactic Center region and its halo (particularly relevant for dark matter searches), the Crab Nebula, the supernova remnant RXJ 1713.7-3946, the Vela pulsar and several binary systems such as LS 5039 and PSR B1259-63. Outside the Milky Way, the blazars PKS 2155-304 and PG 1553+113 have been extensively monitored, and H.E.S.S.-II forms part of a multi-wavelength campaign of the flaring activity of Mrk 501 in 2014.

Highlights of these observations with H.E.S.S.-II have been presented and discussed at the conference. Moreover, after ten years of H.E.S.S. phase I observations, we are currently preparing a Legacy Release of the H.E.S.S. Galactic Plane Survey. A special edition of Astronomy & Astrophysics is currently under preparation, and will contain many important legacy results from H.E.S.S.-I. Major results from this very deep scan of the Milky Way performed with H.E.S.S.-I, including among others spectacular findings from the Large Magellanic Cloud, have been presented.

1 Introduction

In the recent years the field of very high energy (VHE) γ-ray astronomy has evolved from single source discoveries to large systematic surveys, consisting of several hundred - or even thousands - hours of observation, which allows from the first time population studies to be performed. At the same time, deep exposure have been taken on sources of particular importance ("*Key science projects*"),

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establishing new classes of sources as γ-ray emitters. The largest Imaging Atmospheric Cerenkov Telescope, namely the fifth telescope of H.E.S.S.-II (CT5), was inaugurated in September 2012 and is now operating regularly, allowing observation of γ-rays down to 10 GeV.

2 The H.E.S.S. Legacy Survey

The H.E.S.S. Galactic plane survey (HGPS) [1] is a major long-term project, corresponding to $\sim$ 2700 hours of high-quality observations acquired with the H.E.S.S.-I telescope array from 2004 to 2013. Results have already been published on a small ($\sim$ 10%) fraction of the current data set [2, 3]. The region of the Milky Way covered by the HGPS (Galactic longitude between and 65 degrees and Galactic latitude $|b| < 3.5$ degrees) is depicted as a white rectangle in Fig. 1 and compared to the HEGRA (in blue) and VERITAS Cygnus (in green) surveys.

The HGPS data set combines dedicated survey operations (using a fixed-grid pointing strategy) with deep observations of sources of particular interest, leading to non uniform exposure and thus sensitivity across the survey region (Fig. 1, lower panel), the point-source sensitivity being always better than $\sim$ 2% in $0.2 \lesssim E \lesssim 100$ TeV.

A catalogue of 77 cosmic accelerators was derived from the HGPS using a semi-automatic pipeline, out of which 6 are new sources that were previously unknown or unpublished. Less than

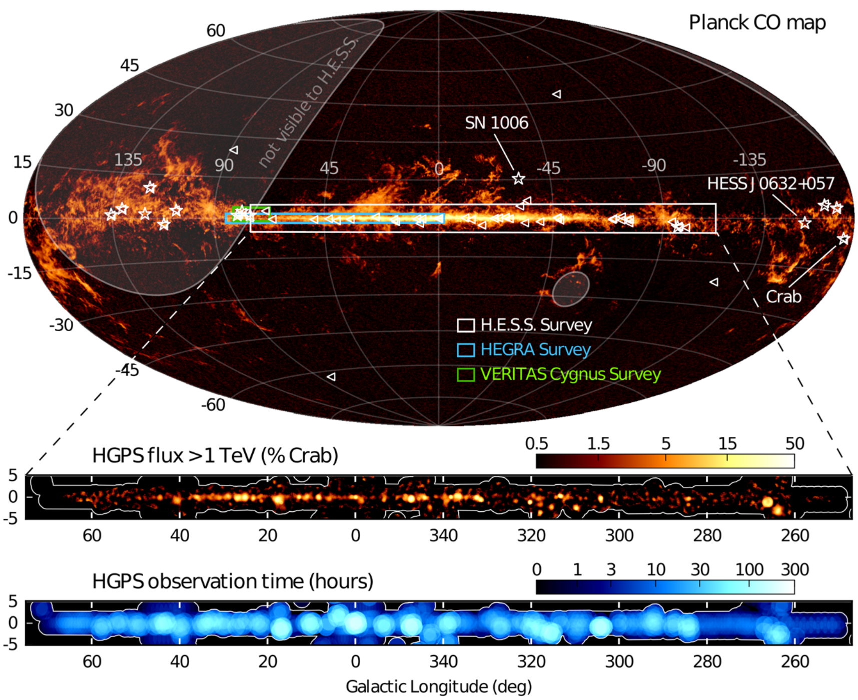

Figure 1. H.E.S.S. Galactic Plane Survey region, flux map and exposure map (from top to bottom). The all-sky image on the top panel shows a Planck CO Map with *Fermi*-LAT identified Galactic 1FHL sources (triangles) and the 15 known Galactic TeV sources (white stars) outside the HGPS region. The HEGRA Galactic Plane Survey [4] and the VERITAS Cygnus survey [5, 6] regions are illustrated in blue and green, respectively. From [1].

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half of the source (31) are firmly identified, the largest population consisting of pulsar wind nebulæ (PWN) followed by supernova remnants (SNRs) and binary systems. Most of the remaining sources are confused (several possible counterparts) while a significant fraction (12 sources) have no known counterparts at other wavelengths.

The HGPS is a unique tool for population studies (e.g. PWN [7] or SNR [8]). In particular, it appears that most young and powerful pulsars have a PWN detected in VHE. This allows for the first time to construct a PWN evolution model.

The paper and legacy data will be released in 2017, including FITS maps and a source catalog (morphology & spectra).

3 Very high emission from pulsars

The detection of very high energy pulsations from the Crab pulsar by the MAGIC collaboration came as a surprise to the community [9]. Later detection of pulsed emission above 100 GeV [10, 11], and up to at least 1 TeV [12] implies that the emission takes place in the vicinity of the light cylinder, and triggered an intense theoretical and experimental activity.

Despite its longer period, $P = 89.3$ ms, its larger characteristic age $\tau_c = 11$ kyr and its much smaller spin-down power $\dot{E} = 6.9 \times 10^{36}$ erg s^{-1} [13], the Vela pulsar is, due to its proximity ($d = 287^{+19}_{-17}$ pc [14]) exceptionally bright in radio and in HE γ rays, and is, after the Crab pulsar, one of the best natural candidates for VHE emission. The Vela pulsar is surrounded by a strong wind nebulae, detected in particular by *Fermi*-LAT [15].

The HE γ-ray phasogram is characterized by two main sharp peaks (P1 and P2) and a third peak (P3) in the bridge (Fig. 2, bottom left). The ratio of the peak intensity between P1 and P2, and the location and intensity of P3 vary with energy [16, 17].

The Vela pulsar was observed by H.E.S.S. during 40 hr between 2013 and 2015. A specific reconstruction was developed for monoscopic mode observations, and the resulting VHE phasogram is shown in Fig. 2, top left: the peak P2 is detected with a statistical significance of $> 15\sigma$, and a total

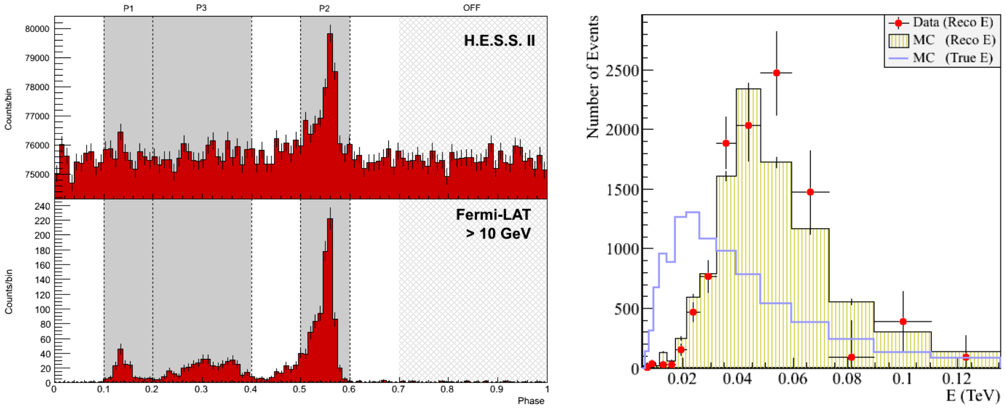

Figure 2. Left: Phase folded distribution of events of the Vela Pulsar with H.E.S.S.-II (top) and *Fermi*-LAT (bottom). **Right:** Energy distribution of events in the P2 Peak compared to Monte Carlo simulations.

excess > 15000 over a huge background, demonstrating that H.E.S.S. operates in a different statistical regime than *Fermi*-LAT.

Detailed comparison with Monte Carlo simulations (Fig. 2, right) validate the analysis pipeline and indicate that γ-rays of energy as low as 10 GeV can be detected by CT5, although with an important reconstruction energy bias. The VHE energy spectrum in the P2 peak is consistent with a steep power law ($\Gamma = 4.1 \pm 0.2_{\mathrm{stat}}$), in very good agreement with that of *Fermi*-LAT.

4 Supernova remnants as sources of cosmic rays

Expanding shock waves in SNRs are believed to be able to accelerate cosmic rays up to multi-TeV energies through the mechanism of diffusive shock acceleration (DSA), see e.g. [18].

In the last years, SNRs have been firmly established as sources of VHE γ-ray emission. At least five SNRs with clear shell-type morphology resolved in VHE γ rays were detected by H.E.S.S., allowing direct investigation of the SNRs as sources of cosmic rays: RX J1713.7-3946 [19, 20], RX J0852.04622 (also known as Vela Junior) [21], SN 1006 [22], HESS J1731-347 [23] and RCW 86 [24]. All of them show a very clear correlation between non-thermal X-ray and VHE γ-ray emissions. Recently, three additional candidates of shell-type SNRs were identified in the HGPS [25], HESS J1534-571, HESS J1614-518 and HESS J1912+101, the latter being the first TeV-only shell candidate, identified through its morphology and without known counterpart.

The SNR RX J1713.7-3946 is one of the brightest Galactic X-ray SNRs, possibly associated with the guest star AD393 which, according to Chinese astronomers, appeared in the constellation Scorpius [26]. It was the first young, shell-type SNR to be resolved in VHE γ rays [19], with a typical shell morphology consistent with X-ray observations. Both leptonic and hadronic scenarios are considered to explain the origin of the emission.

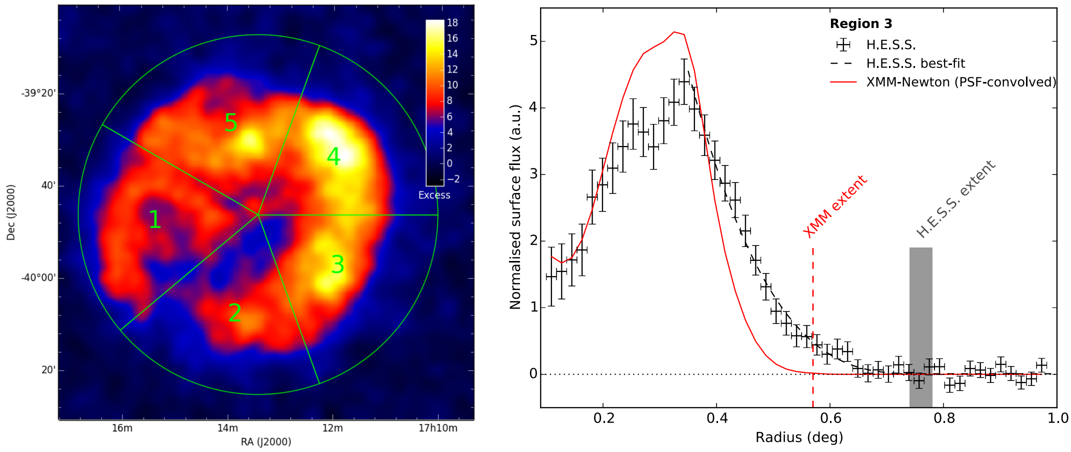

Figure 3. Left: Quadrants used in the H.E.S.S.VHE γ-ray image of RX J1713.7-3946 to investigate possible particle escape. **Right**: Radial profile of γ-ray (black) and X-ray (red) emission in quadrant number 3 [28].

Since the last H.E.S.S. publication [20], the amount of data has been doubled and high-resolution / high-throughput analysis techniques have been developed, e.g. [27], allowing to spatially resolve spectra with unprecedented resolution ($\lesssim 0.05°$). The resulting γ-ray image is shown in Fig. 3, left,

DOI: 10.1051/epjconf/201713603001

and has an energy threshold of $\sim$ 250 GeV. For the first time, maps of physical quantities, such as magnetic field in the case of a leptonic scenario, can be produced. The high statistics collected and the high resolution analysis permits a detailed analysis of the morphology. The γ-ray image from Fig. 3 has been divided in five quadrants for which the radial profiles have been determined. In several regions, such as region 3 (Fig. 3, right) the γ-ray emission appears significantly more extended than the X-ray one (smeared to the H.E.S.S. PSF), indicating for the first time diffusion of particles outside the shell and even escape of high energy particles, most likely of hadronic origin.

5 Galactic Centre

Since the original discovery of TeV emission from the Galactic Centre by H.E.S.S. [29] and diffuse emission from the ridge [30], deep observation of the region have been conducted (> 200 hr), allowing to investigate in more depth the nature and behaviour of the ridge emission [31].

Figure 4 shows the excess map of the galactic centre region, from which a profile of the cosmic ray density along the galactic plane was extracted. This profile shows a $1/r$ dependence, indicating diffusing propagation of cosmic rays injected continuously by a central source. The γ-ray spectrum extracted from the region immediately surrounding the central source shows a power-law spectrum of index 2.3 extending up to 50 TeV without any evidence of a spectral cut-off, giving evidence for a proton injection spectrum extending beyond PeV energies.

The Galactic Centre therefore appears to be the first galactic Pevatron to be confidently detected, and could account for a large fraction of the Galactic cosmic rays around the knee.

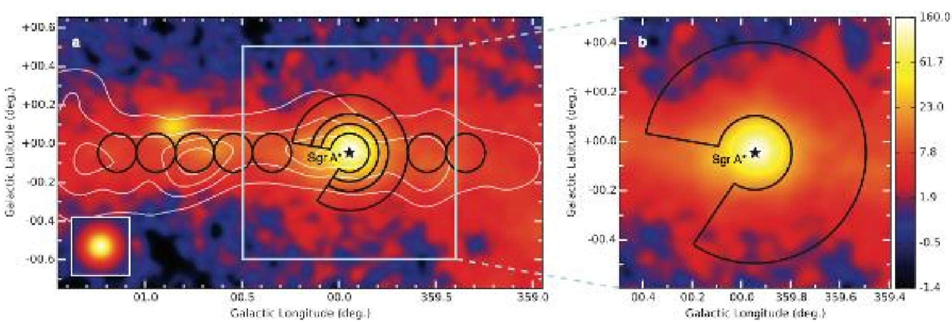

Figure 4. Excess map of the galactic centre region, showing the regions used for the derivation of a radial emission profile (left) and the region used for spectral extraction (right).

6 Active Galactic Nuclei

Several results on active galactic nuclei were presented at the conference, including the first H.E.S.S.-II results, in monoscopic mode, on the well know high synchrotron peaked blazars PKS 2155-304 and PG 1553+113 [32]. The data acquired with CT5 revealed a significant spectral curvature for both sources with respect to a simple power-law spectrum and contributed to close the gap with *Fermi*-LAT.

The discovery of TeV emission from the radio galaxy PKS 0625-354, the sixth source in the class of "γ-ray loud" radio galaxies, is important for modeling and understanding the contribution of non-blazar AGN to extragalactic γ-ray background.

7 Conclusions

The results presented here represents only a small fraction of the recent highlights from H.E.S.S.. Other results were presented at the conference, including the discovery of exceptional sources in the Large Magellanic Cloud (first superbubble in TeV γ-rays, most luminous PWN and a new SNR), results from searches for Dark Matter annihilation and updated measurement of Extragalactic Background Light. A special edition of Astronomy & Astrophysics on the H.E.S.S.-I legacy is currently in preparation, and will be released in 2017.

After more than 10 years of operation, the camera of H.E.S.S.-I are currently been upgraded with a new electronics, inspired from the design of CTA, to optimize the overlap with CT5 in the coming years and reduce the dead-time. Observation with a fully refurbished array will restart early 2017.

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