Very-high-energy (VHE, E > 100 GeV) γ-rays provide a unique view of the non-thermal universe, tracing the most violent and energetic phenomena at work inside our Galaxy and beyond. The latest results of the H.E.S.S. Galactic Plane Survey (HGPS) undertaken by the High Energy Stereoscopic System (H.E.S.S.), an array of four imaging atmospheric Cherenkov telescopes located in Namibia, are described here. The HGPS aims at the detection of cosmic accelerators with environments suitable for the production of photons at the highest energies and has led to the discovery of an unexpectedly large and diverse population of over 60 sources of TeV gamma rays within its current range of l = 250 to 65 degrees in longitude and |b| < 3.5 degrees in latitude. The data set of the HGPS comprises 2800 hours of high-quality data, taken in the years 2004 to 2013. The sensitivity for the detection of point-like sources, assuming a power-law spectrum with a spectral index of 2.3 at a statistical significance of 5 σ, is now at the level of 2% Crab or better in the core HGPS region. The latest maps of the inner Galaxy at TeV energies are shown alongside an introduction to the first H.E.S.S. Galactic Plane Survey catalog. Finally, in addition to an overview of the H.E.S.S. Galactic source population a few remarkable, recently discovered sources will be highlighted.

1 Introduction

The superior sensitivity of the latest generation of imaging atmospheric Cherenkov telescopes such as H.E.S.S.\(^1\), MAGIC\(^2\), and VERITAS\(^3\), has resulted in the discovery of numerous VHE γ-ray sources, and currently more than 140 sources are listed in the online TeV γ-ray catalogue TeVCat\(^a\). The High Energy Stereoscopic System (H.E.S.S.) in particular is ideally suited for undertaking a deep survey of our Galaxy, due to its high sensitivity, comparatively large field-of-view of 5°, and its angular resolution of ~0.1°. Its location in the Khomas highlands of Namibia allows it a prime view of the inner Galaxy. Here we report on the status and latest results of the H.E.S.S. Galactic Plane Survey (HGPS), the deepest and most comprehensive survey of the inner Galaxy undertaken in VHE γ-rays so far. The latest maps are shown, alongside advanced methods for the suppression of cosmic-ray induced background. The construction of a software framework to detect and model sources of VHE γ-rays in the survey data set is introduced. The VHE γ-ray source population in our Galaxy is dominated by objects that are linked to the final stages in stellar evolution, namely pulsar wind nebulae (PWNe) and supernova remnants (SNRs). For nearly a third of the sources, however, no plausible counterpart at other energies has been found yet, or the physical origin of the detected emission remains unclear. A snapshot of our current understanding of the H.E.S.S. source population on the Galactic plane is shown,

\(^{a}\text{http://tevcat.uchicago.edu/}\)
Figure 1: Illustration of the different background estimation methods for image and spectral analysis, as well as the challenges the high density of extended sources in the inner Galaxy poses. Exclusion regions (see Section 2 for details) are shown as grey areas. The field-of-view of $2^\circ$ radius is illustrated as green solid circles. 

Left panel: The adaptive ring background technique. Right panel: The reflected region background technique.

as well as a few interesting examples of recent sources.

2 Maps

In the HGPS, the inner Galaxy has been systematically raster scanned using observation positions with overlapping fields-of-view, with the main goal of discovering new VHE $\gamma$-ray sources and enabling population studies of Galactic source classes as a consequence. Advanced analysis techniques for background suppression \(^4,^5,^6,^7\) play a very important role in the data analysis. After calibration and quality selection, a multi-variate analysis technique \(^4\) based on extensive air shower and image shape parameters is used to discriminate $\gamma$-ray-like events from cosmic-ray-induced showers. A minimum image amplitude of 160 photoelectrons is required.

To generate maps, the remaining background is estimated locally by the ring background technique \(^8\), where for each trial source position (red filled circles) in the field-of-view (of $2^\circ$ radius, green circle) the background is estimated from a ring centered on this position (blue shaded circles), as shown in the left panel of Figure 1. Regions on the sky containing known VHE $\gamma$-ray sources (grey areas) are excluded from background estimation. These exclusion regions are automatically generated from significance maps which are smoothed with a top-hat function with radii of 0.1°, 0.2° and 0.4°, by thresholding them at the level of 5$\sigma$ and dilating each excluded pixel by a further 0.1° (small exclusion regions, dark grey) or 0.3° (large exclusion regions, light grey). For the small exclusion regions, the resulting maps for 0.1° and 0.2° radius are added, excluding all significant emission from the background but cutting quite close to the edges of sources. For the large exclusion regions, the resulting maps for 0.1°, 0.2° and 0.4° radius are added, cutting away more of any emission that is possibly extending into the area for background estimation. The resulting large exclusion regions, used for the production of maps, turn out to cover areas of the sky that are comparatively large on the scale of the size of the field-of-view. Therefore, as illustrated in the left panel of Figure 1, the ring radius is adaptively enlarged when a large fraction of the ring area overlaps with an excluded region, until an appropriate ring of the same thickness is reached. The statistically significant value for each position is then calculated \(^9\), by summing the candidate events within a fixed and predefined...
correlation radius, e.g. 0.1° (suitable for point-like sources), and comparing to the estimated background level at that position. Figure 5 shows the latest significance map obtained for the survey region.

Figure 6 depicts the current sensitivity to VHE $\gamma$-ray sources, as an example for point-like sources emitting a power-law spectrum with index 2.3 and located at a Galactic latitude of $b = -0.3°$, the approximate average among known Galactic sources. The sensitivity is below 2% Crab for practically all of the longitude range $l = 283°$ to $59°$ at this latitude. This can also be seen in a slice of this map, shown in Figure 4.

3 Source catalog

Using the H.E.S.S. survey maps as input, we have implemented a pipeline to generate a source catalog, which will be published alongside with the maps. The aim is to have detection criteria as well as morphological and spectral analysis as uniform as possible, to make this source catalog useful for the astronomical community to compare to data from other wavelengths, e.g. Fermi\textsuperscript{b} or HAWK\textsuperscript{c}, for radio or X-ray data, as well as Galactic source population studies and diffuse emission measurements.

To construct the catalog, we use a likelihood fit of the H.E.S.S. counts map taking the exposure and point spread function as well as the estimated background into account. To acknowledge the fact that most sources in the H.E.S.S. Galactic plane survey region have been found to be extended, we are producing an extended source catalog by modelling the excess as the superposition of symmetric Gauss-shaped sources. The Gauss shape is not physically motivated, it was chosen as one commonly used empirical shape in the absence of an expected source morphology model. Figure 2 displays the fitting process. In the left panel a significance map of the Kookaburra region and HESS J1427$-608$ is shown, while the middle and right panel show a 2 sources model and 3 sources fit model, respectively, alongside with their resulting residual maps. The 3 sources solution, i.e. the Kookaburra region splitting up into the two sources HESS J1420$-607$ and HESS J1418$-609$, is significantly better. Indeed it is believed that the emission from HESS J1420$-607$ and HESS J1418$-609$ is produced by two different, large-offset PWNe, K3 powered by the high-spin down pulsar PSR J1420$-6048$ in case of HESS J1420$-607$, and the Rabbit or R2, in case of HESS J1418$-609$\textsuperscript{14}. The third source, HESS J1427$-607$, is slightly extended and so far could not be identified with a counterpart such as an SNR or PWN\textsuperscript{15}.

For H.E.S.S. the background is dominated by the small fraction of hadronic air showers that cannot be distinguished from gamma-ray-induced air showers. After source detection and subsequent estimation of source position and extension, for each catalog source a circular source region containing most of the emission according to the best-fit source model excess map is chosen, and the spectral analysis is run independently of the maps. The measurement of spectra is done by using the reflected background method\textsuperscript{8} (see right panel of Figure 1). In this method, multiple background regions (OFF regions, blue filled circles) arranged in a circle are used for each trial source position (ON region, red filled circle), where each OFF region has the same size and shape as the ON region and an equal offset to the observation, or pointing, position. Due to the equal offset of ON and OFF regions from the pointing direction of the system, no radial acceptance correction is required with this method, making it ideal for spectral analysis. Figure 1 also illustrates the motivation behind using two different sets of exclusion regions, as the large exclusion regions can be too large to allow for spectral extraction in many cases, and the small exclusion regions are used instead.

The difficult part about the catalog construction is the high source density in the inner Galaxy. There are several regions of multi-degree-scale excess along the Galactic plane where

\textsuperscript{8}http://fermi.gsfc.nasa.gov
\textsuperscript{9}http://www.hawc-observatory.org
it is not obvious how to best represent them in an extended source catalog. Therefore we are investigating e.g. adding a criterion to the catalog construction method that prevents large and bright sources from decomposing into multiple, strongly overlapping components.

4 Galactic source population and recent discoveries

To date, 67 sources are listed in the catalog of published H.E.S.S. sources\(^d\). Figure 3 shows a pie chart of the H.E.S.S. Galactic source population, status February 2013, where the source classification is taken from TeVCat\(^e\). While the largest source class are pulsar wind nebulae (PWN, orange), followed by supernova remnants, either interacting with a molecular cloud (SNR MC, yellow) or exhibiting emission from their shell (SNR Shell, light green), there are to date only a few massive stellar clusters (dark red) and binary systems (light blue) identified as H.E.S.S. sources. A large part of the H.E.S.S. source population remains ambiguous, therefore Unidentified (dark blue). It should be noted that with further multi-wavelength data the distribution of this chart will likely change, not only will sources migrate from being unidentified to another source class, but in some cases possibly even between the defined source classes. Therefore this chart represents our knowledge at this point in time.

An example of a previously unidentified source that has now been identified as a PWN is HESS J1303−631, which was the first source classed as unidentified for H.E.S.S. Significant energy-dependent morphology of this source, as well as the identification of an associated X-ray PWN from XMM-Newton observations enable identification of the VHE source as an evolved PWN associated with the pulsar PSR J1301−6305\(^{10}\).

W49B is an SNR interacting with a molecular cloud, located in the W49 region. W49B has one of the highest surface brightnesses in radio of all the SNRs of this class in our Galaxy and is one of the brightest ejecta-dominated SNRs in X-rays. Infrared observations evidenced that W49B is interacting with molecular clouds and Fermi reported the detection of a coincident bright, high-energy $\gamma$-ray source\(^{11}\). H.E.S.S. detected significant emission from the W49 region, compatible with VHE emission from the SNR W49B\(^{12}\). The position of the emission is compatible with the brightest part of the radio emission from the SNR as well as with the GeV emission. Energy spectra in the GeV and TeV bands are in very good agreement. Given the

\(^d\)http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/
\(^e\)http://tevcat.uchicago.edu/
very high GeV luminosity, the GeV-TeV connection, and the fact that the SNR is interacting with a dense molecular cloud, a hadronic emission scenario is favored in the case of W49B.

Finally, HESS J1641−463 is an example for a source that remains unidentified, despite the existence of multi-wavelength data. It is found within the bounds of a radio SNR, however, the existing X-ray observations do not provide additional support to this scenario due to the lack of detection of an extended X-ray feature at the position of HESS J1641−463. In addition, the larger extension of the SNR G338.5+0.1 as compared to the H.E.S.S. source, and the relatively old age of the SNR inferred from its physical size suggests that the emission might not be necessarily connected with the SNR but rather with a PWN at its center, driven by an yet undetected pulsar. Due to its small size, compatible with a point-like source for H.E.S.S., the possibility that HESS J1641−463 is a binary system cannot be excluded.

5 Outlook

After nearly a decade of observing the Southern sky, H.E.S.S. is ending its surveying program of the Galactic Plane. With the additional, much larger fifth Cherenkov telescope in the centre of the H.E.S.S. array, H.E.S.S. is entering phase II and will concentrate on deeper observations with improved sensitivity and angular resolution. Here we have shown the latest results of the HGPS and an overview over the H.E.S.S. Galactic source population. We aim to present the entire data set of the HGPS, in the form of maps and a catalog, and to make it accessible to astronomers. With this large data set, population studies in the VHE range become possible for the first time.
Figure 4: Profile of the sensitivity map (refer to Figure 6) for $b = -0.3^\circ$.

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Figure 5: Significance map for the H.E.S.S. Galactic Plane Survey. The pre-trials significance for a correlation radius of 0.1 deg is shown. The colour transition from blue to red corresponds to $\sim 5\sigma$ post-trials significance. The significance has been calculated for regions on the sky where the sensitivity of H.E.S.S. for point sources (5\sigma pre-trials, and assuming the spectral shape of a power law with index 2.3) is better than 10\% Crab. Identifiers for sources that have been described in publications or announced at conferences are included.
Figure 6: Sensitivity of H.E.S.S. to point-like $\gamma$-ray sources with an assumed spectral index of 2.3, for a detection level of 5$\sigma$ pre-trial. The sensitivity is expressed as an integral flux above 1 TeV in units of $2.26 \times 10^{-9} \text{ m}^{-2} \text{ s}^{-1}$, which amounts to 1% of the Crab integral flux above 1 TeV.