Discovery of new TeV supernova remnant shells in the Galactic plane with H.E.S.S.

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Abstract. Supernova remnants (SNRs) are prime candidates for efficient particle acceleration up to the knee in the cosmic ray particle spectrum. In this work we present a new method for a systematic search for new TeV-emitting SNR shells in 2864 hours of H.E.S.S. phase I data used for the H.E.S.S. Galactic Plane Survey. This new method, which correctly identifies the known shell morphologies of the TeV SNRs covered by the survey, HESS J1731-347, RX 1713.7-3946, RCW 86, and Vela Junior, reveals also the existence of three new SNR candidates. All three candidates were extensively studied regarding their morphological, spectral, and multi-wavelength (MWL) properties. HESS J1534-571 was associated with the radio SNR candidate G323.7-1.0, and thus is classified as an SNR. HESS J1912+101 and HESS J1614-518, on the other hand, do not have radio or X-ray counterparts that would permit to identify them firmly as SNRs, and therefore they remain SNR candidates, discovered first at TeV energies as such. Further MWL follow up observations are needed to confirm that these newly discovered SNR candidates are indeed SNRs.

Introduction

In the past ten years of operation a significant part of observation time of H.E.S.S. has been used to observe the Galactic plane, either survey observations or dedicated pointing observations of selected targets. H.E.S.S. with its large field-of-view of \(\sim 3^\circ\) diameter and a point spread function of \(\sim 0.07^\circ\) is well suited to study extended sources in our galaxy [1]. From the currently known Galactic TeV \(\gamma\)-ray sources, the largest fraction consists of still unidentified objects, many of them pulsar wind nebula (PWN) candidates. The work presented here deals with the question whether unidentified or new TeV \(\gamma\)-ray in the H.E.S.S. phase I data can be identified as SNRs. Rather than focusing on their spectral properties or possible associations with nearby molecular clouds, our approach is based on a systematic search for shell-like morphologies in extended sources present in the HGPS.

Search method

The HGPS is a survey of the inner part of the Milky Way. In total, 2864 h of good quality data are used [2]. A sensitivity of at least 2\% of the Crab nebula flux is reached in the covered area and the angular resolution is \(\sim 0.07^\circ\). On the data products of this survey a systematic search for new TeV-emitting SNR shells is done. To search for sources with a shell morphology, a projected 3D shell model emitting homogeneously between \(R_{\text{in}}\) and \(R_{\text{out}}\) (the shell morphology hypothesis) is tested against a symmetric Gaussian model (the null hypothesis). This is done on a grid of
sky coordinates with a spacing of 0.02°×0.02°. Due to the large number of test positions, a limited set of parameters, both for the shell and the Gaussian, are tested instead of leaving the parameters free (see Table 1). Therefore, the search is not complete, but we are presenting a systematic approach with a minimal bias coming from the limited set of parameters. The search reproduces all known shell-like sources within the survey region. In addition, three sources showing a shell like morphology are identified. In order to overcome some of the statistical shortcomings of the gridded search presented above, a source-by-source study on the resulting candidates is performed. For this analysis, additional data that became available beyond the HGPS data set for HESS J1534-571 are included. Again, a symmetric Gaussian model and a 3D shell are tested, now letting all parameters to vary freely. Since the models are not nested, the Akaike information criterion [3] was used to assess the significance of the shell over the Gaussian null-hypothesis model.

**TABLE 1.** List of tested parameters; shell width $w$ is defined as $w = R_{\text{out}} - R_{\text{in}}$.  

| Shell ($H_1$) parameters |  
|--------------------------|  
| $R_{\text{in}}$ | 0.1°, 0.2°, 0.3°, 0.4°, 0.5°, 0.6°, 0.7°, 0.8°  
| width $w$ | $10^{-5} \times R_{\text{in}}, 0.1 \times R_{\text{in}}, 0.2 \times R_{\text{in}}$  
| Gaussian ($H_0$) parameters |  
| $\sigma$ | 0°, 0.05°, 0.1°, 0.2°, 0.4°  

**Dedicated analysis**

**Sky maps**

From the measured excess and the expected $\gamma$-rays, calculated as

$$N_{\text{ref}} = T \int_{E_{\text{min}}}^{\infty} \Phi_{\text{ref}}(E) A_{\text{eff}}(E, q) \, dE$$

assuming a power law differential spectrum ($\Phi(E)$), the surface brightness is derived. In this formula $T$ is the run livetime and $A(E, q)$ the instrument’s effective area for a given energy $E$ and observation condition $q$ (e.g. zenith angle).

The maps are correlated with a circle of radius 0.1° and smoothed with a Gaussian filter ($\sigma = 0.01°$). The excess is derived using a gamma/hadron separation based on boosted decision trees, a reconstruction technique based on Hillas parameters, and a ring background method[4, 5]. To increase the angular resolution and to reduce the background level, a cut on individual image amplitudes of 160 p.e. is applied; the resulting energy threshold of the data sets is $\sim 600$ GeV.

**Morphology study**

**Spectra**

In order to obtain an energy spectrum with a broad energy range, the standard procedure is to lower the image amplitude cut. For HESS J1534-571 and HESS J1614-518, the image amplitude cut is lowered to 60 p.e., resulting in an energy threshold of $\sim 300$ GeV. In the case of HESS J1912+101, this standard procedure, could not be performed however, mostly due to mostly due to problems arising from background estimates which become relevant for large, low surface brightness sources in certain sky areas. Here, the more conservative image cut of 160 p.e. is kept to reduce systematic uncertainties. The on-source counts for the spectra are extracted from circles with radii $R = R_{\text{out}} + R_{68}$ ($R_{68}$ is the 68% containment radius of the point spread function, typically 0.07°) and centred at the respective best fit positions of the shells. Power laws are fitted to the spectrum of each source respectively; more complex models are statistically not favoured.
TABLE 2. Results from the morphological study of the three new TeV shells. $p_{\text{shell}}$ is the null hypothesis probability that the fit improvement of the shell ($H_1$) over the Gaussian ($H_0$) is due to fluctuations, according to the Akaike Information Criterion [3]. Shell fit results: $(l_0, b_0)$ are the center coordinates, $R_{\text{in}}$ and $R_{\text{out}}$ are the inner and outer radii of the homogeneously emitting spherical shell.

| Source      | $E_{\text{min}}$ (TeV) | $E_{\text{max}}$ (TeV) | $I_{0,1\text{TeV}}$ | $\Gamma$ |
|-------------|----------------------|----------------------|------------------|---------|
| HESS J1534−571 | 0.422    | 61.897   | $2.99 \pm 0.30 \pm 0.90 \times 10^{-12}$ | 2.51 ± 0.09 ± 0.20 |
| HESS J1614−518 | 0.316    | 38.312   | $8.33 \pm 0.49 \pm 2.50 \times 10^{-12}$ | 2.42 ± 0.06 ± 0.20 |
| HESS J1912+101 | 0.681    | 61.897   | $3.89 \pm 0.45 \pm 1.17 \times 10^{-12}$ | 2.56 ± 0.09 ± 0.20 |

FIGURE 1. Left: Surface brightness map with a correlation radius of 0.1° and a Gaussian smoothing ($\sigma = 0.01°$; significance contours 3, 4, 5, 6$\sigma$; green ellipse is showing SNR G323.7-1.0 [6]. Right: Spectral results with statistical errors fitted with a power law model with $1\sigma$ error butterfly.

Multiwavelength study

An SNR candidate of the MGPS2 radio survey is identified as a counterpart of HESS J1534−571, from the matching position and shell morphology. Therefore, HESS J1534−571 is classified as an SNR. The radio counterpart is represented in the surface brightness map by a green ellipse [6]. The Fermi catalogues 3FGL and 2FHL list an extended source at the position of HESS J1614−518 (green circle in the surface brightness map) [7, 8]. The spectral properties are consistent with the results presented here. Current observations of HESS J1534−571 with Suzaku-XIS have not revealed any X-ray emission from this source. Matsumoto et al. [9] report an extended X-ray emission coincident
with the North-Eastern component of HESS J1614-518. Because of the lack of SNR or SNR candidate counterparts, HESS J1614-518 and HESS J1912+101 are classified as SNR candidates.

Conclusions

The work presented here shows that the current generation of ground-based γ-ray instruments is well suited to detect new SNRs from a blind search in a survey observation. As a result of this study we classify HESS J1534-571 as an SNR and HESS J1614-518 and HESS J1912+101 as SNR candidates. The absence of a clear non-thermal X-ray emission from these sources might stem from the fact that the γ-ray radiation observed at very high energies is caused by hadronic interactions. Nevertheless, leptonic scenarios cannot be ruled out at present. Further MWL observations will help to constrain the radiation processes.

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