EPJ Web of Conferences **319**, 05002 (2025) https://doi.org/10.1051/epjconf/202531905002
RICAP-24

The population of Galactic supernova remnants in the TeV range

Rowan Batzofin[1,*], *Pierre* Cristofari[2], *Kathrin* Egberts[1], *Constantin* Steppa[1], and *Dominique* Meyer[3]

[1]Universität Potsdam, Institut für Physik und Astronomie, Campus Golm, Haus 28, Karl-Liebknecht-Str. 24/25, 14476 Potsdam-Golm, Germany
[2]Observatoire de Paris, PSL Research University, 61 avenue de l'Observatoire, Paris, France
[3]Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans s/n, 08193 Barcelona, Spain

Abstract. Galactic Supernova remnants (SNRs) are likely to be significant sources of cosmic rays (CRs) up to the knee of the CR spectrum. They produce gamma rays in the very-high-energy (VHE) range. About a dozen SNRs emitting VHE gamma rays have been detected by current instruments and it is expected that many more will be detected by future instruments. However, the details of particle acceleration at SNRs, and the mechanisms producing VHE gamma rays remain poorly understood. We studied the population of SNRs in the TeV range and its properties by confronting simulated samples to the catalogue of VHE gamma-ray sources from the H.E.S.S. Galactic Plane Survey (HGPS) under consideration of the multi-dimensional detection threshold of the HGPS. This allows us to address fundamental questions concerning particle acceleration at SNR shocks. Particularly, what is the efficiency of particle acceleration? What is the spectrum of accelerated particles? Is the VHE gamma-ray emission dominated by hadronic or leptonic interactions? We present here the first systematic exploration of the SNR-population parameter space relevant to our model. We identify preferred parameter combinations for which $\gtrsim 90\%$ of the Monte Carlo realisations are in agreement with VHE gamma-ray data and exclude parts of the parameter space in contradiction with the HGPS data. One finding is a preference for large hadron domination (lower electron-to-proton fractions of Kep $\lesssim 10^{-4.5}$) in the simulated SNRs, but despite this a significant fraction ($\sim 50\%$) of the detectable simulated SNRs are dominated by leptonic emission.

1 Introduction

SNRs are thought to be able to accelerate cosmic rays via the first-order Fermi mechanism called diffusive shock acceleration (DSA) [1]. The accelerated protons and electrons from the SNR can interact with the interstellar medium (ISM) to produce very-high-energy (VHE) gamma rays. These gamma rays are produced primarily through two mechanisms: the decay of neutral pions, created from proton-proton collisions (hadronic mechanism), and the inverse Compton scattering of accelerated electrons on soft photons (leptonic mechanism). Many

---

[*] e-mail: rowan.batzofin@uni-potsdam.de

Galactic SNR shocks have been detected in the gamma-ray energies, from detections by Fermi the *Fermi* Large Area Telescope (*Fermi*-LAT) [2] at GeV energies to the High Energy Stereoscopic System (H.E.S.S.) [3], the Very Energetic Radiation Imaging Telescope Array System (VERITAS) [4] and the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) [5] at TeV energies. The Large High Altitude Air Shower Observatory (LHAASO) can detect sources at >100 TeV, some of the sources in The First LHAASO Catalogue of Gamma-Ray Sources [6] are associated with SNRs.

In this work we simulated the population of TeV-emitting SNRs and confront it to the population detected in the H.E.S.S. Galactic Plane Survey (HGPS) [7]. We constrained the simulations using the measurements made in the HGPS, we included the information on the position and angular-extent-dependent HGPS sensitivity when comparing the simulated SNRs to the SNRs in the HGPS. In this work we show some interesting results from our paper published earlier this year [8]. The SNR population model is described very briefly in Sect. 2, in Sect. 3 the method by which we compare our simulations to data is described. We show our results in Sect. 4 and give our conclusions in Sect. 5.

2 SNR population model

To simulate the population of Galactic SNRs emitting in the TeV range, we need 3 ingredients: a model for the particle acceleration at SNR shocks and the gamma-ray emission that follows, a description of the spatial distribution of SNRs in the Galaxy, and a description of the gas density distribution in which the SNR shocks are expanding. We created our SNR population model following the work from [9] but with the following refinements: An inclusion between the ejecta masses and explosion energies for the SNRs, a refined description of the magnetic field amplification and corresponding maximum energy of accelerated protons and electrons, the inclusion of diffusive shock reacceleration at SNR shocks, and multiple prescriptions for the spatial distribution of SNRs. For the full details of the SNR population model see [8].

3 Confronting our simulated populations with available H.E.S.S. data

The following parameters of our model were investigated:

1. K_{ep}: the electron-to-proton ratio in the fluid
2. α: the spectral index, in momentum, of the energy distribution of accelerated particles
3. η: the CR acceleration efficiency at the moment of cosmic ray production

We simulated 100 realisations per parameter set. For each source we determine whether it would have been detected in the HGPS depending on its location, luminosity and size. To account for the bias in the HGPS we followed the work in [10], in particular we accounted for the multi-dimensional exposure of the HGPS, the sensitivity of the HGPS varies greatly with position and source extent. Since many of the HGPS sources are unidentified, we created a lower limit and a stringent upper limit for the HGPS sources we compare to. For the lower limit we use the 8 firmly detected SNRs, for the upper limit we consider the sources in the lower limit as well as the 8 composite sources (pulsar wind nebula combined with a

SNR) and the 12 unidentified sources that are spatially coincident with a known SNR. This gives us a lower limit of 8 sources and a stringent upper limit of 28 sources. In addition to this constraint on the total number of detectable sources we also have a constraint based on the maximum energy the SNRs can accelerate CRs to. Since four of the HGPS SNRs can accelerate particles above 10 TeV, we require that our populations have at least 4 detectable SNRs that have a maximum energy above 10 TeV.

4 Results

The main result is illustrated in Figure. 1, where one can see what percentage of the populations for a given parameter set are in agreement with the HGPS based on our criteria: 1. at least 8 detectable SNRs (lower limit), 2. no more than 28 detectable SNRs (stringent upper limit), and 3. at least 4 detectable SNRs with a maximum energy above 10 TeV. The following regions of the parameter space can be ruled out: $\alpha \gtrsim 4.35$ and $K_{\mathrm{ep}} > 10^{-3}$. Increasing the spectral index decreases the flux of individual SNRs and thus results in less SNRs being detectable in the population. Increasing the electron-to-proton ratio increases the flux of individual SNRs and leads to more SNRs being detectable in the population. Increasing the acceleration efficiency also increases the flux of individual SNRs and results in more SNRs being detectable.

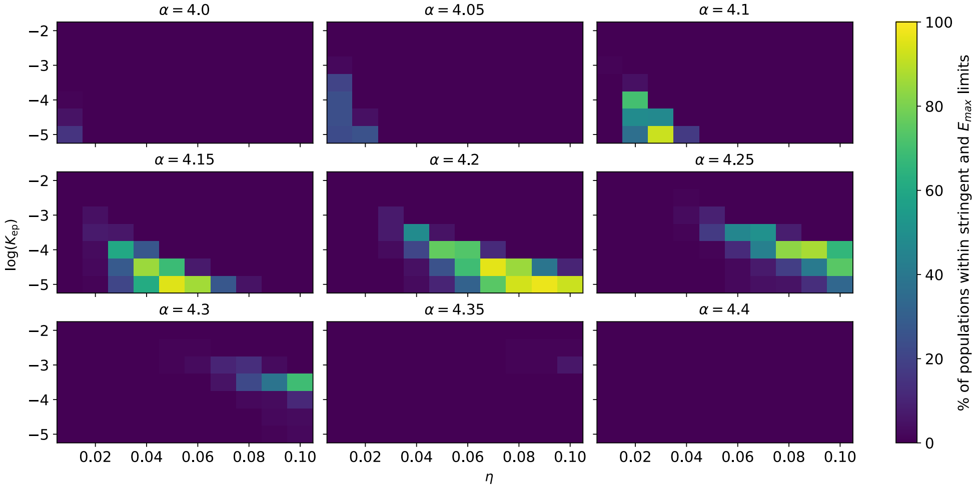

Figure 1: 2D histogram plots showing the percentage of populations that have at least as many detectable simulated SNRs as firmly detected H.E.S.S. SNRs and do not exceed the number of H.E.S.S. sources associated to SNRs, and have at least as many SNRs with $E_{\mathrm{max}} \geq 10$ TeV as HGPS SNRs.

In table 1 one can see all the populations with > 90% of realisations that are in agreement with the HGPS. It is noticeable that while the populations have very low electron-proton ratios they still have ∼ 50% of detectable SNRs dominated by leptonic emission. The sources in which the hadronic emission is dominant are typically younger and brighter than the sources in which the leptonic emission is dominant.

5 Conclusion

We performed a systematic search of the parameter space defined by the electron-proton ratio, the spectral index and the acceleration efficiency. We are able to reproduce populations

Table 1: Typical characteristics of the detectable SNRs in the simulated populations found to be the most compatible with the HGPS results, as described in Fig. 1. (Col. 3) The hadronic ratio is the ratio of the number of SNRs with gamma-ray luminosity dominated by the hadronic component to the total number of SNRs. (Col. 5-8) Had. and Lep. refer to simulated SNRs dominated by hadronic emission and simulated SNRs dominated by leptonic emission respectively.

Population Parameters			% of realisations compatible with HGPS	Hadronic Ratio	Mean No. detectable SNRs	Mean Had. Age (kyr)	Mean Lep. Age (kyr)	Mean Had. Dist. (kpc)	Mean Lep. Dist. (kpc)
$\alpha = 4.2$	$K_{ep} = 10^{-5.0}$	$\eta = 0.09$	97.0	0.62	16.84	2.15	4.86	5.65	4.88
$\alpha = 4.2$	$K_{ep} = 10^{-4.5}$	$\eta = 0.07$	96.0	0.43	16.14	1.94	4.36	5.64	4.9
$\alpha = 4.15$	$K_{ep} = 10^{-5.0}$	$\eta = 0.05$	95.0	0.51	16.41	2.06	5.21	5.62	4.79
$\alpha = 4.2$	$K_{ep} = 10^{-5.0}$	$\eta = 0.08$	93.0	0.66	13.6	2.0	4.88	5.63	5.06
$\alpha = 4.1$	$K_{ep} = 10^{-5.0}$	$\eta = 0.03$	92.0	0.37	19.56	2.05	5.7	5.61	4.63
$\alpha = 4.2$	$K_{ep} = 10^{-5.0}$	$\eta = 0.1$	92.0	0.6	20.64	2.32	4.92	5.66	4.76

of SNRs that are in agreement with the HGPS. The Galactic population of SNRs can be explained by multiple regions of the parameter space. The sets of parameters that have $>$ 90% of populations with the HGPS require: $4.1 \lesssim \alpha \lesssim 4.2$, $10^{-5.0} \lesssim K_{ep} \lesssim 10^{-4.5}$ and $0.03 \lesssim \eta \lesssim 0.1$. Despite the low ratio of electrons to protons we still have $\sim$ 40% to 60% of sources in which the dominant emission is leptonic. Any additional constraints on any of the parameters would help narrow down the other parameters. The detectable SNRs are clearly a biased sample of all SNRs. Our parameter set that had the most populations in agreement with the HGPS is: $\alpha = 4.2$, $K_{ep} = 10^{-5.0}$ and $\eta = 0.9$. For this parameter set 97% of the populations are in agreement with the HGPS. 62% of the detectable SNRs in these populations are dominated by hadronic emission. For more details and results see our paper [8].

References

[1] V. Ptuskin, et al., Spectrum of Galactic Cosmic Rays Accelerated in Supernova Remnants, ApJ**718**, 31 (2010), `1006.0034`. 10.1088/0004-637X/718/1/31

[2] Fermi Collaboration, F. Acero, et al., The First Fermi LAT Supernova Remnant Catalog, ApJS**224**, 8 (2016), `1511.06778`. 10.3847/0067-0049/224/1/8

[3] H. E. S. S. Collaboration, H. Abdalla, et al., Population study of Galactic supernova remnants at very high γ-ray energies with H.E.S.S., A&A**612**, A3 (2018), `1802.05172`. 10.1051/0004-6361/201732125

[4] VERITAS Collaboration, V.A. Acciari, et al., Discovery of TeV Gamma-ray Emission from Tycho's Supernova Remnant, ApJ**730**, L20 (2011), `1102.3871`. 10.1088/2041-8205/730/2/L20

[5] MAGIC Collaboration, J. Albert, et al., Discovery of Very High Energy Gamma Radiation from IC 443 with the MAGIC Telescope, ApJ**664**, L87 (2007), `0705.3119`. 10.1086/520957

[6] LHAASO Collaboration, Zhen Cao, et al., The first lhaaso catalog of gamma-ray sources, The Astrophysical Journal Supplement Series **271**, 25 (2024). 10.3847/1538-4365/acfd29

[7] H.E.S.S. Collaboration, Abdalla, H., et al., The h.e.s.s. galactic plane survey, A&A **612**, A1 (2018). 10.1051/0004-6361/201732098

[8] R. Batzofin, et al., The population of galactic supernova remnants in the tev range, A&A **687**, A279 (2024). 10.1051/0004-6361/202449779

[9] P. Cristofari, et al., Acceleration of cosmic rays and gamma-ray emission from supernova remnants in the galaxy, Monthly Notices of the Royal Astronomical Society **434**, 2748 (2013). 10.1093/mnras/stt1096

[10] C. Steppa, K. Egberts, Modelling the galactic very-high-energy source population, A&A **643**, A137 (2020). 10.1051/0004-6361/202038172