Statistical Search for Counterparts of Galactic VHE Gamma-Ray Sources

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***Abstract*. Recent advances in the instrumentation to observe Very-High Energy (VHE) gamma rays have made the discovery of many new sources possible, most of them being discovered in the Galactic plane survey of H.E.S.S., an array of imaging atmosperic Cherenkov telescopes in Namibia. Of these sources, a significant number can be identified as pulsar wind nebulae. Based on a statistical comparison of H.E.S.S. data with existing pulsar catalogues it is shown that for a sample of pulsars in the central Milky Way, those with large spin-down energy flux are with a high probability associated with VHE gamma-ray sources detected by H.E.S.S.. In addition similar studies for other classes of objects which have already shown associations with or are candidates for VHE gamma-ray emission are presented.**

***Keywords*: gamma-ray astronomy, population study, pulsar wind nebulae**

I. Introduction

The H.E.S.S. experiment is an array of four imaging atmospheric Cherenkov telescopes located in Namibia. It was the first instrument to perform deep surveys of the Galactic plane in Very-High Energy (VHE) γ-rays and has discovered a large number of VHE γ-ray sources. These sources can be associated with different classes of astrophysical objects, a significant fraction being pulsar wind nebulae (PWNe). In this study, the Parkes Multibeam Pulsar Survey (PMPS) [1] catalogue is used to investigate a possible correlation between pulsars and VHE γ-ray sources. Similar studies have been performed for catalogues of different astrophysical objects like Galactic bubbles [2], [3], Wolf-Rayet stars [4] and high-mass X-ray binaries [5].

II. Method

A significance map of the Galaxy is used to determine the significance of a VHE γ-ray excess at the position of a catalogue object. Figure 1 shows this map as obtained in the H.E.S.S. Galactic plane survey for the range $-105^\circ < l < 65^\circ$ in Galactic longitude and $|b| < 5^\circ$ in Galactic latitude. A significance of at least 5 standard deviations above background is required as a signature of a VHE γ-ray signal. For extended objects maps with correlation radii appropriate for the source size as given in the catalogue are used.

To estimate the fraction of chance coincidences between the catalogue objects and VHE γ-ray sources in the survey map, Monte-Carlo simulations have been performed. Artificial catalogues have been created resembling the properties of the original catalogue. All major quantities like the longitude, the latitude, and the mean radius (in case of extended objects) for the simulated objects are picked randomly from fits to the original catalogue distributions. The simulated catalogues have been treated like the real catalogues and compared to the VHE gamma-ray significance map.

In case of the pulsars the investigation is performed as a function of the spin-down energy flux $\dot{E}/4\pi d^2$. The wandering of the pulsars off the Galactic plane while getting older results in a dependence of $\dot{E}/4\pi d^2$ on the Galactic latitude. Fig. 2 shows this two-dimensional distribution. A narrowing of the latitude distribution at high spin-down fluxes can be observed. To model this behaviour, the data is divided in bands in $\dot{E}/4\pi d^2$ (dashed lines) and for each band the latitude distribution is fit with a Gaussian. The widths of these Gaussians are plotted as a function of $\dot{E}/4\pi d^2$ in Fig. 3. The dashed line is a linear fit used for interpolation. For each simulated pulsar a random value for $\dot{E}/4\pi d^2$ is picked according to the catalogue distribution and the corresponding Galactic latitude is then determined from a Gaussian with a width taken from Fig. 3. Other catalogues with correlated quantities are simulated in a similar way.

III. Results

A. Pulsar Wind Nebulae

The results for the PWN correlation study are shown in Fig. 4 and 5. Figure 4 shows the $\dot{E}/4\pi d^2$ distribution of all and detected pulsars for the data (all: grey shaded area, detected: solid line) as well as the simulations (all: hatched area, detected: dashed line). For high spin-down fluxes more real than simulated pulsars are detected in VHE γ-rays. This can as well be seen in Fig. 5 which shows the ratio of detected to all PWNe for data (points) and simulation (shaded boxes). The height of the shaded boxes represents the uncertainty of the modelling for the Monte-Carlo with different numbers of $\dot{E}/4\pi d^2$ bins in the method described above. The probability that the detection of VHE γ-rays from high-power pulsars ($\dot{E}/4\pi d^2 > 10^{35}$ erg s^{-1} kpc^{-2}) is

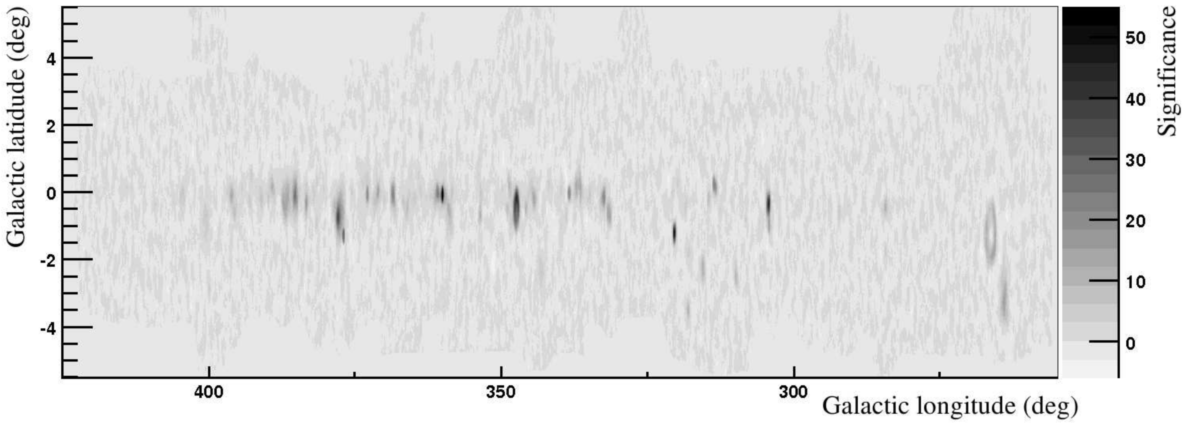

Fig. 1. H.E.S.S. significance map of the region $-105° < l < 65°$, $|b| < 5°$, with a correlation radius of $\theta = 0.22°$ as obtained by the H.E.S.S. Galactic Plane Survey.

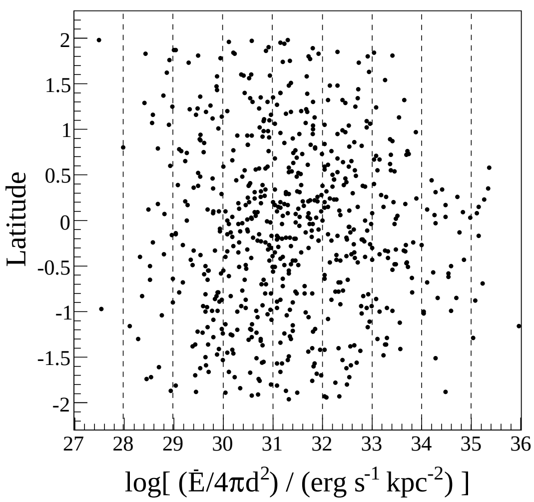

Fig. 2. The spin-down energy flux distribution of the PMPS pulsars [1] within the H.E.S.S. Galactic plane survey region as a function of the Galactic latitude. The pulsars with higher spin-down energy flux seem to be located closer to the Galactic plane. In each of the bands delimited by the dotted lines, a Gaussian is fitted to the latitude distribution.

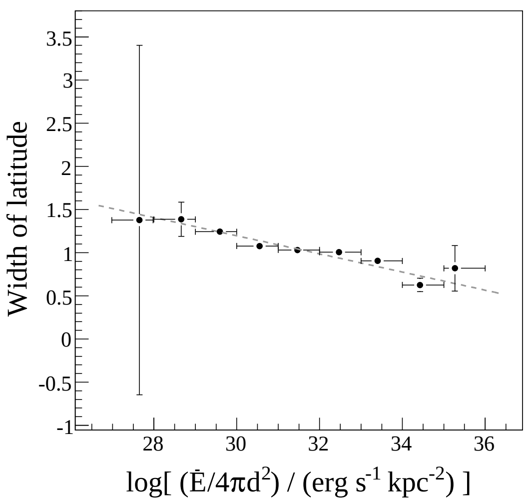

Fig. 3. The widths of the Gaussians (fitted to the latitude distribution) as a function of $\log[\dot{E}/4\pi d^2]$. The vertical error bars are the errors on the widths from the respective Gaussian fits, while the horizontal bars show the width of each $\log[\dot{E}/4\pi d^2]$-band. The dashed line is a linear fit to the distribution of the widths.

caused by a chance coincidence is $\sim 0.22\%$. For pulsars with $\dot{E}/4\pi d^2 > 10^{34}$ erg s^{-1} kpc^{-2}, the probability of chance coincidence is $\sim 0.094\%$.

B. Galactic Bubbles

The same type of study has been performed for Galactic bubbles [2], [3] as e.g. observed by GLIMPSE survey [6]. These bubbles are formed by the interaction of strong stellar winds from young hot stars with the interstellar medium. About 25% of the bubbles coincide with known HII regions, the other 75% appear to be formed by late-B stars, whose ultraviolet radiation is not strong enough to ionise the surrounding ISM. Since these are two candidates for VHE γ-ray emission, it is interesting to search for correlations between the bubbles and H.E.S.S. data. However, there is no obvious possible acceleration mechanism proposed for Galactic bubbles.

A merger of two catalogues provided by Churchwell et al. [2], [3] is used for the correlation study. The first catalogue contains 322 bubbles with longitudes $10° < |l| < 65°$, while the second catalogue contains 269 bubbles within $10°$ of the Galactic centre. The properties of the respective catalogues have been taken into account separately in the Monte Carlo simulations.

Figure 6 shows the ratio of the number of detected bubbles divided by the number of all bubbles as a function of their eccentricity. The ratio is consistent with chance coincidences within statistical errors, no significant excess is found in the data with respect to the simulations.

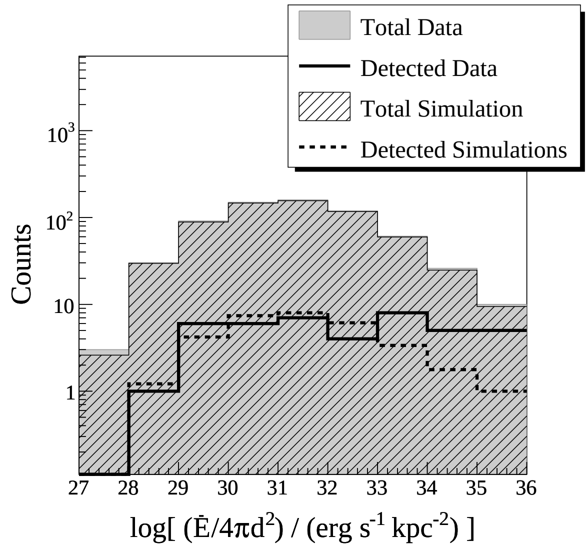

Fig. 4. The $\log[\dot{E}/4\pi d^2]$ distribution of all (areas) and detected (lines) PWNe, as well for the data as for the MC simulations.

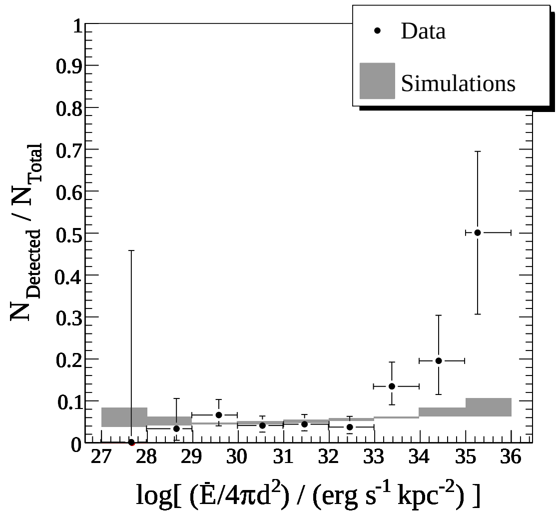

Fig. 6. Ratio of detected over all Galactic bubbles for the data (points) and the simulation (shaded boxes).

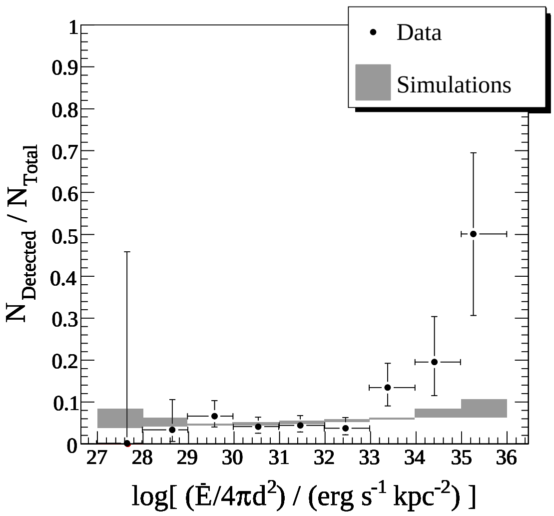

Fig. 5. The ratio of detected over all PWNe for the data (points) and the simulation (shaded boxes). The $\log[\dot{E}/4\pi d^2]$-error bars show the width of each band, while the point shows the center of gravity of the respective band.

C. Other Objects

Further objects for which catalogues have been compared to the H.E.S.S. results are Wolf-Rayet stars [4] and high-mass X-ray binaries [5].

When superimposing the positions of the Wolf-Rayet stars on a H.E.S.S. significance map ($\theta = 0.22°$) only five show a significance above 5 σ and all of these VHE γ-ray sources have well-established counterparts. A detailed correlation study for Wolf-Rayet stars is therefore not possible.

For the high-mass X-ray binaries only 3 show a significant excess in the H.E.S.S. survey map so a correlation study is as well not possible due to the limited statistics of detected sources.

An analysis of HII regions [7], star forming regions [8], [9], OB stars [10], and supernova remnants [11] is currently ongoing.

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