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Establishing a connection between high-power pulsars and very-high-energy gamma-ray sources

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Abstract: In the very-high-energy (VHE) gamma-ray wave band, pulsar wind nebulae (PWNe) represent to date the most populous class of Galactic sources. Nevertheless, the details of the energy conversion mechanisms in the vicinity of pulsars are not well understood, nor is it known which pulsars are able to drive PWNe and emit high-energy radiation. In this paper we present a systematic study of a connection between pulsars and VHE γ-ray sources based on a deep survey of the inner Galactic plane conducted with the High Energy Stereoscopic System (H.E.S.S.). We find clear evidence that pulsars with large spin-down energy flux are associated with VHE γ-ray sources. This implies that these pulsars emit on the order of 1% of their spin-down energy as TeV γ-rays.

In 1989, the Crab Nebula was discovered as the first celestial source of VHE γ-radiation [1]. The pulsar inside the nebula drives a powerful wind of highly relativistic particles that ends in a termination shock from which high-energy particles with a wide spectrum of energies emerge [2]. High-energy electrons[1] among these particles can give rise to two components of electromagnetic radiation: a low-energy component from synchrotron radiation and a high-energy component from inverse Compton (IC) up-scattering of ambient photons.

Recently, advances in VHE instrumentation have made the discovery of many new, predominantly Galactic, sources possible. Of these, a significant number can be identified as PWNe. Prominent examples are the PWN of the energetic pulsar PSR B1509−58 in the supernova remnant MSH 15−52 [3], and HESS J0835−455 [4], associated with Vela X, the nebula of the Vela pulsar.

These γ-ray PWNe are extended objects with an angular size of a fraction of a degree, translating into a size of some 10 pc for typical distances of a few kpc. In addition to the open puzzle of pulsar spin-down power conversion, a surprising observation is that the centroids of these γ-ray PWNe are often displaced from their pulsars by distances similar to the nebular size. Such displacements, although usually at smaller scales, are also seen in some X-ray PWNe. The origin of the displacement remains unknown. It might be attributed to pulsar motion (e.g. [5]), causing the pulsar to leave its nebula behind, or to a density gradient in the ambient medium [6].

The aforementioned examples of coincidences between VHE γ-ray sources and radio pulsars motivated a systematic search for VHE counterparts of energetic pulsars using the H.E.S.S. system of imaging Cherenkov telescopes located in Namibia [7]. To be detectable by H.E.S.S., a source at distance d has to provide a γ-ray luminosity in the 1 TeV to 10 TeV range of $L_\gamma \sim 10^{32}\, d^2\, \mathrm{erg\,s^{-1}kpc^{-2}}$. Assuming a conversion efficiency of 1% of pulsar spin-down energy loss $\dot{E}$ into TeV γ-rays (where $\dot{E}$ is determined from the measurement of the rotation period Ω and the rate

1. here and in the following, 'electrons' refers to both electrons and positrons

at which the rotation slows down $\dot{\Omega}$), PWNe of pulsars with $\dot{E}$ around $10^{34}\ d^2$ erg s^{-1}kpc^{-2} might be detectable. We note that for typical electron spectra, only a small fraction of the total energy in electrons is carried by the multi-TeV electrons, that are responsible for TeV γ-rays by IC scattering off ambient photons (including those from the cosmic microwave background) and for keV γ-rays by synchrotron radiation. Even a 1% energy output in TeV γ-rays already implies a large fraction of spin-down energy loss going into relativistic electrons.

Here we investigate how the probability to detect in VHE γ-rays PWNe surrounding known pulsars varies with the spin-down energy loss of the pulsar, testing the plausible assumption that the γ-ray output of a PWN correlates in some fashion with the power of the pulsar feeding it.

The VHE γ-ray data set used to search for γ-ray emission near the location of known radio pulsars comprises all data used in the H.E.S.S. Galactic plane survey [8, 9], including an extension of the survey to Galactic longitudes $-60^\circ < l < -30^\circ$, dedicated observations of Galactic targets and re-observations of H.E.S.S. survey sources. The search covers a range in Galactic longitude from -60° to 30° while the range in Galactic latitude is restricted to ± 2 deg, a region well covered in the survey. A total of 435 pulsar locations are tested, taken from the Parkes Multibeam Pulsar Survey (PMPS, [10] and references therein), as recorded in the ATNF pulsar catalogue. Pulsars without measured period derivatives are ignored. Over the range of the H.E.S.S. survey, the PMPS provides reasonably uniform sensitivity [11], enabling a reliable estimate of the frequency of chance coincidences between a γ-ray source and a pulsar. The analysis of the γ-ray data follows the standard H.E.S.S. analysis [12]. Initially, a sky map is generated providing the significance of a γ-ray excess for a given position. Taking into account the properties of known γ-ray PWNe, the search is optimised for slightly extended sources – on the scale of the angular resolution (≈ 0.1 deg) of the H.E.S.S. telescopes – and allows for small offsets from the pulsar positions. Each excess is determined by counting γ-ray candidate events within $\theta \leq 0.22$ deg ($\theta^2 \leq 0.05$ deg^2) of a given position and subtracting a background estimated from areas in the same field of view. The sky map is used to look up the significance of a γ-ray excess at the position of the radio pulsars, as well as for randomly generated test positions used to evaluate the statistical significance of the association (details are given below). We require an excess significance of at least 5 standard deviations above the background as a signature of a VHE γ-ray signal. Given the modest number of trials - the 435 pulsar locations - the number of false detections is negligible with this requirement and in any case small compared to the probability for chance coincidences between radio pulsars and VHE γ-ray sources.

Of the 435 pulsars, 30 are found with significant γ-ray emission at the pulsar location (Fig. 1, top left panel). The lower left panel of Fig. 1 displays the fraction of pulsars with such γ-ray emission for different intervals in spin-down flux $\dot{E}/d^2$. The fraction is about 5% for pulsars with spin-down flux below 10^{33} erg s^{-1}kpc^{-2} and increases to about 70% for pulsars with $\dot{E}/d^2$ above 10^{35} erg s^{-1}kpc^{-2}. Not all of these associations are necessarily genuine. The rate of chance coincidences is estimated by generating 10^6 realisations of random pulsar samples (each consisting on average of 435 "pulsars") following the distribution in longitude and latitude of the PMPS pulsars and taking into account the narrowing of the distribution in latitude with increasing spin-down flux. The expected fraction of chance coincidences is shown as dark shaded areas in Fig. 1 and varies between 4% to 12%. All associations with pulsars with $\dot{E}/d^2 < 10^{33}$ erg s^{-1}kpc^{-2} are within statistical errors consistent with chance coincidences. Indeed for plausible values of the ratio between the γ-ray luminosity and the pulsar spin-down energy loss, $L_\gamma/\dot{E}$, no detectable emission would be expected from such pulsars. On the other hand, the detection of emission from high-power pulsars is statistically significant. The probability that the detection of VHE sources coincident with 9 or more of the total of 23 pulsars above $\dot{E}/d^2 > 10^{34}$ erg s^{-1}kpc^{-2} results from a statistical fluctuation is $\sim 3.4 \times 10^{-4}$. For detection of 5 or more of the total of 7 pulsars above 10^{35} erg s^{-1}kpc^{-2}, the chance probability is $\sim 4.2 \times 10^{-4}$.

Given the high density of pulsars, a single γ-ray source may even coincide with more than a single pulsar, and thus appear more than once amongst the "detections" in the upper left panel of Fig. 1.

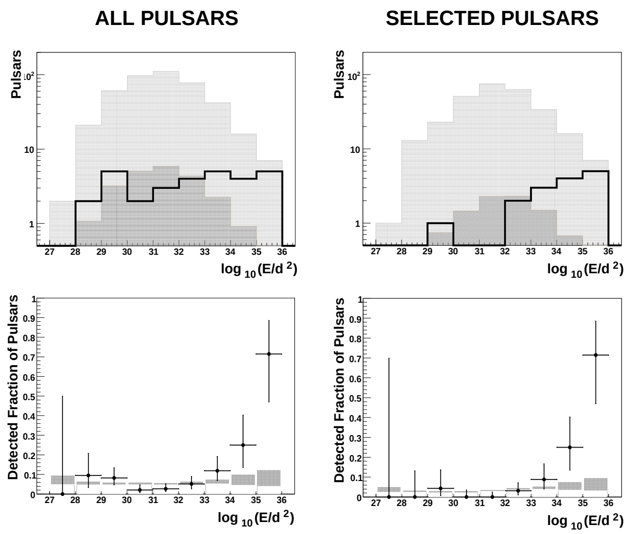

Figure 1: **Top row:** Distribution in $\log_{10}(\dot{E}/d^2)$ of all PMPS pulsars in the H.E.S.S. scan range (shaded in light grey), of chance coincidences (shaded in dark grey) and of detected pulsars (black line). Here, $\dot{E}/d^2$ is measured in $\mathrm{erg\,s^{-1}kpc^{-2}}$. **Bottom row:** The points show the fraction of pulsars with significant γ-ray excess at the pulsar position, as a function of $\log_{10}(\dot{E}/d^2)$. The shaded band represents the probability for a chance coincidence. The width of the band accounts for the uncertainty in the width of the latitude distribution of pulsars. **Left:** all pulsars; **right:** double occurrences of gamma-ray sources removed by omitting pulsars which overlap with stronger pulsars or known non-pulsar sources.

Removal of such double occurrences (Right panels of Fig. 1) does not change the conclusion, and none of the high-luminosity pulsars is affected. Details will be given elsewhere.

The results shown in Fig. 1 demonstrate that a large fraction of high-luminosity pulsars correlate with sources of VHE γ-rays, emitting with a γ-ray luminosity of order 1% of the pulsar spin-down power. The positive correlation does not necessarily imply that the pulsar or PWN itself is responsible for the γ-ray flux. It could also result from some other mechanism correlated with the pulsar or its creation, such as a supernova shock wave. The correlation found between γ-ray detectability and spin-down flux $\dot{E}/d^2$ argues in favour of a pulsar-related origin of the γ-ray signal. On the other hand, for the PMPS pulsar sample, $\dot{E}/d^2$ also correlates closely with the spin-down age T of the pulsar, $\dot{E}/d^2 \sim T^{-3/2}$, and obviously with distance d, both parameters relevant for determining the γ-ray flux from shock-wave driven supernova remnants.

The exact relation between pulsar parameters and γ-ray luminosity is an interesting issue. Variations in exposure and hence in detection threshold over the survey range, as well as the uncertainty in pulsar distance will smear out the turn-on curve of detectability versus $\dot{E}/d^2$ shown in Fig. 1, but cannot fully account for the rather slow turn-on over a range of more than one order of magnitude in $\dot{E}/d^2$, combined with a detection probability below unity for even the highest-power pulsars. This indicates that $\dot{E}/d^2$ cannot be the only parameter relevant for the γ-ray flux. The same conclusion is obtained from the observed variation of $L_\gamma/\dot{E}$ of about an order of magnitude among the detected pulsars. However, this present pulsar sample is too small to investigate the dependence of L_γ on multiple pulsar parameters, e.g. including pulsar age.

A constant $L_\gamma/\dot{E}$ is also not necessarily expected. For a given age, the integral energy fed by the pulsar into the PWN increases with $\dot{E}$. Apart from expansion losses, pulsar spin-down power is shared between particle energy and magnetic field energy. If equipartition between the two energy densities is assumed [13, 14], the magnetic field in the PWN will increase with $\dot{E}$ and hence the energy loss by synchrotron radiation will increase relative to and at the expense of inverse Compton γ-ray production. Indeed, un-pulsed X-ray luminosity of pulsars is observed to increase faster then $\dot{E}$, $L_X \propto \dot{E}^{1.4\pm0.1}$ [15]. In such scenarios, magnetic field values and therefore the balance between X-ray and γ-ray emission will also depend on volume, i.e. on the expansion speed of the nebula and hence on the ambient medium. In addition, the current spin-down luminosity $\dot{E}$ may not be the only relevant scale; if the pulsar age is shorter than or comparable to the electron cooling time, relic electrons injected in early epochs with higher spin-down power will still contribute and may enhance L_γ significantly compared to the quasi-steady state achieved for old pulsars.

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References

[1] T. C. Weekes, M. F. Cawley, D. J. Fegan, K. G. Gibbs, A. M. Hillas, P. W. Kowk, R. C. Lamb, D. A. Lewis, D. Macomb, N. A. Porter, P. T. Reynolds, G. Vacanti, Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique, ApJ342 (1989) 379–395.

[2] B. M. Gaensler, P. O. Slane, The evolution and structure of pulsar wind nebulae, Annual Review of Astronomy and Astrophysics 44 (2006) 17.

[3] F. Aharonian et al., Discovery of extended VHE gamma-ray emission from the asymmetric pulsar wind nebula in MSH 15-52 with HESS, A&A435 (2005) L17–L20.

[4] F. Aharonian et al., First detection of a VHE gamma-ray spectral maximum from a cosmic source: HESS discovery of the Vela X nebula, A&A448 (2006) L43–L47.

[5] E. van der Swaluw, T. P. Downes, R. Keegan, An evolutionary model for pulsar-driven supernova remnants. A hydrodynamical model, A&A420 (2004) 937–944.

[6] J. M. Blondin, R. A. Chevalier, D. M. Frierson, Pulsar Wind Nebulae in Evolved Supernova Remnants, ApJ563 (2001) 806–815.

[7] J. A. Hinton, The status of the HESS project, New Astronomy Review 48 (2004) 331–337.

[8] F. Aharonian et al., A New Population of Very High Energy Gamma-Ray Sources in the Milky Way, Science 307 (2005) 1938–1942.

[9] F. Aharonian et al., The H.E.S.S. Survey of the Inner Galaxy in Very High Energy Gamma Rays, ApJ636 (2006) 777–797.

[10] G. Hobbs et al., The Parkes multibeam pulsar survey - IV. Discovery of 180 pulsars and parameters for 281 previously known pulsars, MNRAS352 (2004) 1439–1472.

[11] R. N. Manchester, G. B. Hobbs, A. Teoh, M. Hobbs, The Australia Telescope National Facility Pulsar Catalogue, AJ129 (2005) 1993–2006.

[12] F. Aharonian et al., Observations of the Crab nebula with HESS, A&A457 (2006) 899–915.

[13] S. P. Reynolds, R. A. Chevalier, Evolution of pulsar-driven supernova remnants, ApJ278 (1984) 630–648.

[14] M. J. Rees, J. E. Gunn, The origin of the magnetic field and relativistic particles in the Crab Nebula, MNRAS167 (1974) 1–12.

[15] K. S. Cheng, R. E. Taam, W. Wang, Pulsar Wind Nebulae and the X-Ray Emission of Nonaccreting Neutron Stars, ApJ617 (2004) 480–489.