Pulsar Wind Nebulae observed in TeV gamma-rays and their Galactic environments

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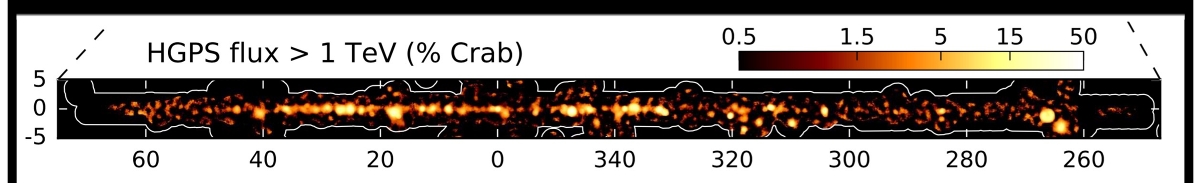
Abstract

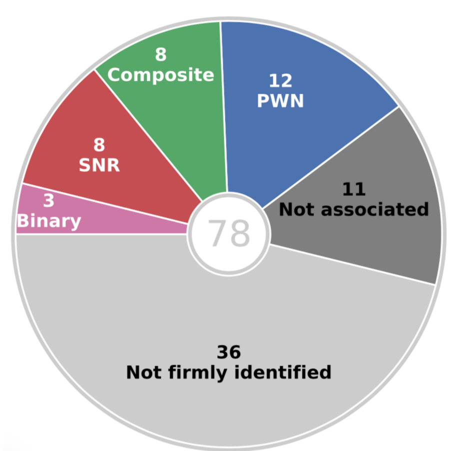
Pulsar Wind Nebulae (PWNe) constitute the largest class of identified Galactic sources of TeV gamma-rays, as revealed by the Galactic Plane Survey with the H.E.S.S. telescopes. This survey allowed a systematic study of a large number of PWNe in TeV gamma-rays, which revealed properties that could only be hinted at previously. In particular, there is a weak but significant trend for the gamma-ray luminosity to decrease with pulsar spin-down power, and apparently to depend on Galactic location. Furthermore, older PWNe are often significantly offset from the associated pulsar, with separations larger than may be readily explained solely by pulsar proper motion.

After reviewing the above properties of TeV-emitting PWNe, we investigate possible explanations in terms of their respective Galactic environments. In particular, we review recent models of the photon density in the Galaxy and its spiral arms, and study their possible influence, in a leptonic (inverse Compton) model, on the observed contrasts in luminosity. We also discuss an explanation of the offsets which relies, in addition to the pulsar proper motion, on density heterogeneity in the surrounding medium. We outline the prospects for the next-generation TeV gamma-ray observatory, CTA, to shed light on these issues.

H.E.S.S. Galactic Plane Survey



H.E.S.S. surveyed the inner Galaxy, $+75° \gtrsim \ell \gtrsim -115°$, in TeV γ-rays (with a highly non-uniform exposure).

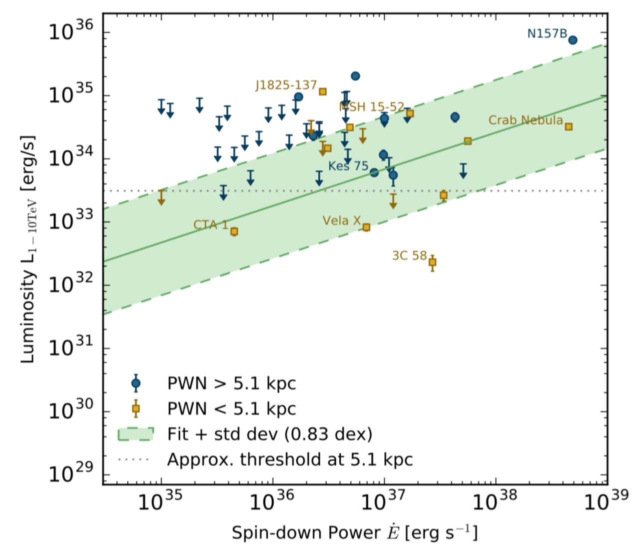


78 sources were detected, of which 40% are firmly identified. The majority of identifications are as Pulsar Wind Nebulae.

Sources identified as composite SNRs are unresolved, but in most of these the PWN is likely the main source of γ-rays. From H.E.S.S. Collaboration (2018a, 2018b).

PWN TeV luminosities

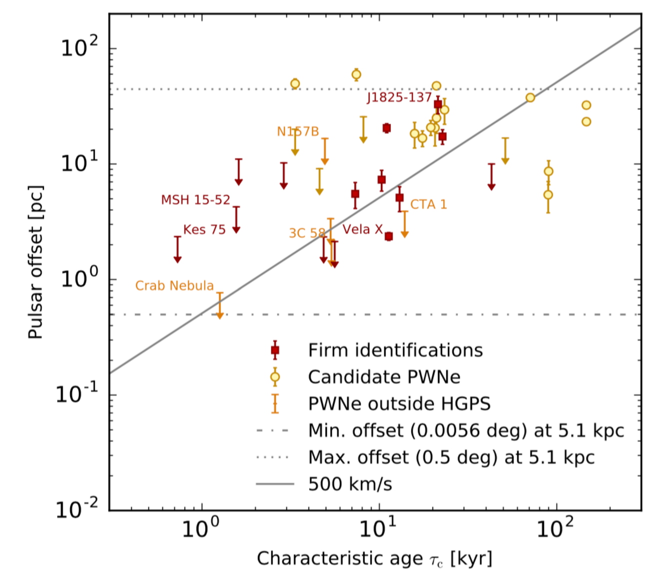
There is a weak but statistically significant trend for TeV PWNe to become less luminous with decreasing pulsar spin-down power (and hence increasing age).



TeV luminosities of PWNe, and upper limits on pulsars without detected PWNe, as a function of spin-down power $\dot{E}$. The inclusion of upper limits yields a statistically significant trend, with $L_{\mathrm{TeV}} \propto \dot{E}^{0.59\pm0.21}$. H.E.S.S. Collaboration (2018b).

PWN TeV offsets

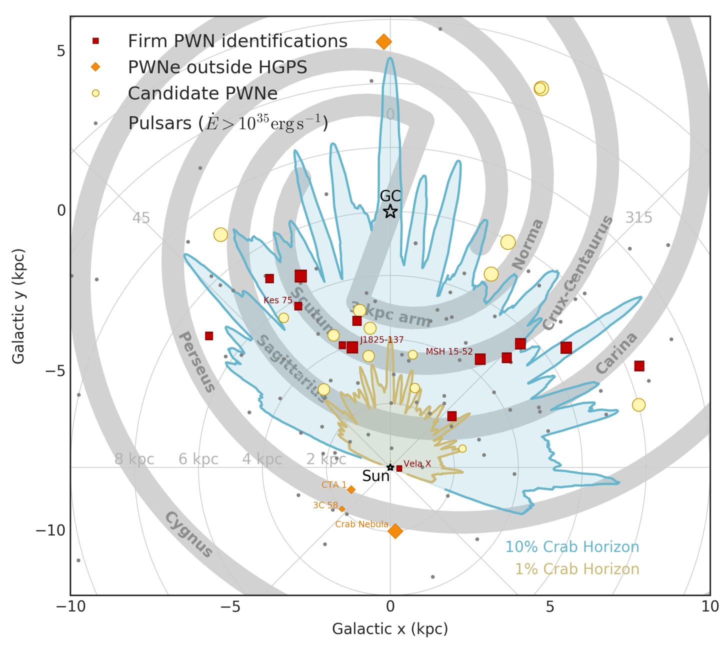
Older TeV PWNe generally show **large** offsets from their pulsar. These cannot be explained solely by typical pulsar proper motions. An additional offset mechanism must be involved.



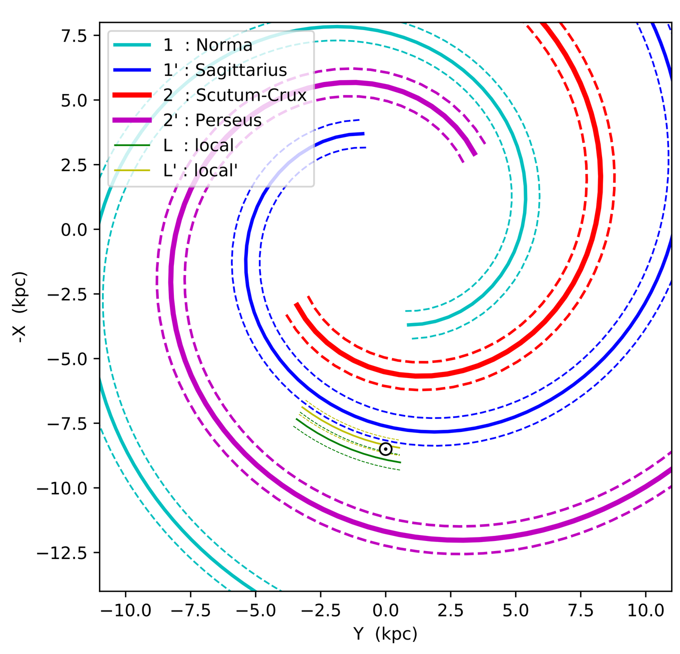
Distance between the TeV PWN centroid and the pulsar, as a function of its characteristic age. The solid line corresponds to a transverse velocity $v_\perp$ of 500 km/s. The majority of systems with $\tau_c \gtrsim 6$ kyr show offsets larger than this. From H.E.S.S. Collaboration (2018b).

Galactic distribution and luminosities of TeV PWNe

PWNe trace recent formation of massive stars, and thus concentrate in the Galaxy's spiral arms. Their detectability in the HESS GPS is quite good up the **Scutum-Crux** (or Centaurus) arm, yet few TeV PWNe are seen in the Sagittarius-Carina arm. A trend of higher TeV luminosities in the inner Galaxy is also apparent.



Best-guess Galactic plane locations of TeV PWNe and candidates. Symbol size is proportional to the logarithm of TeV luminosity. From Klepser et al. (2017).



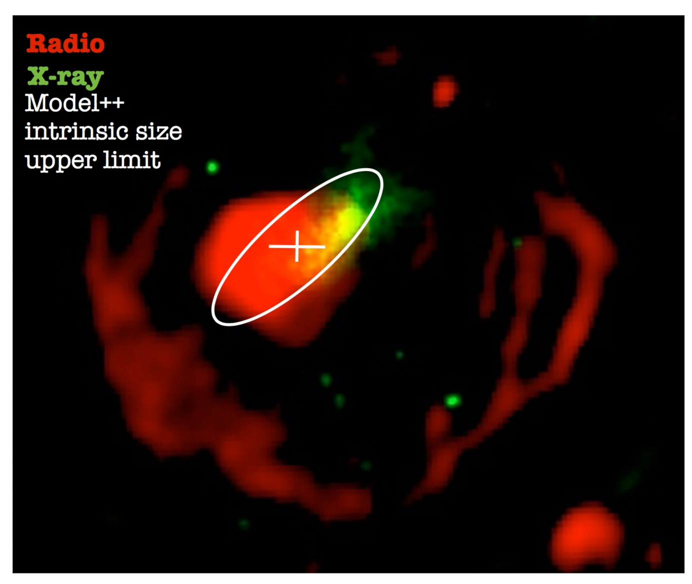
Spiral arm geometry of the Galaxy in the model of Robitaille et al. (2012), used by Porter et al. (2017).

In the model by Robitaille et al. (2012), the Galaxy has 4 spiral arms but 2 are dominant, with enhanced emissivity from young stars: **Scutum-Crux** and Perseus.

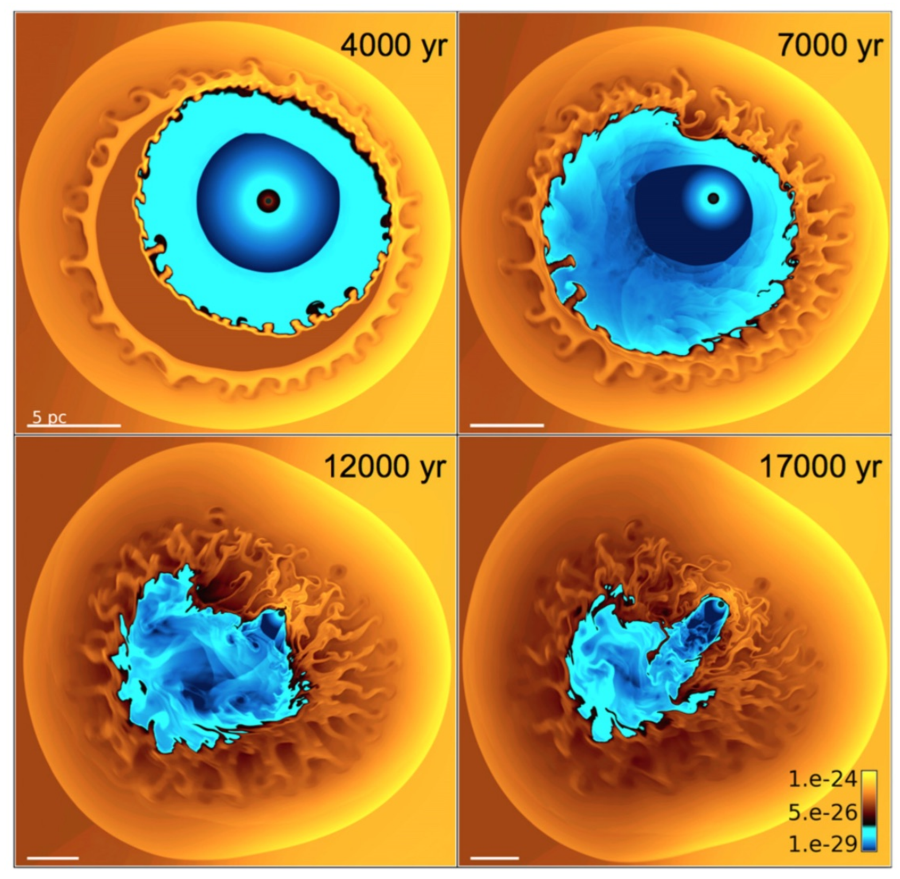
PWN offsets from asymmetric medium around SNR

A gradient in the surrounding interstellar medium density was proposed by Blondin et al. (2001) to explain the offset of the Vela X PWN from its pulsar. It leads to "crushing" and displacement of the nebula away from the higher density.

G 327.1–1.1



Multi-wavelength image of the composite SNR G 327.1–1.1, where radio is in red and X-rays in green. The white ellipse illustrates the morphology seen in TeV γ-rays by HESS. From Acero et al. (2011).

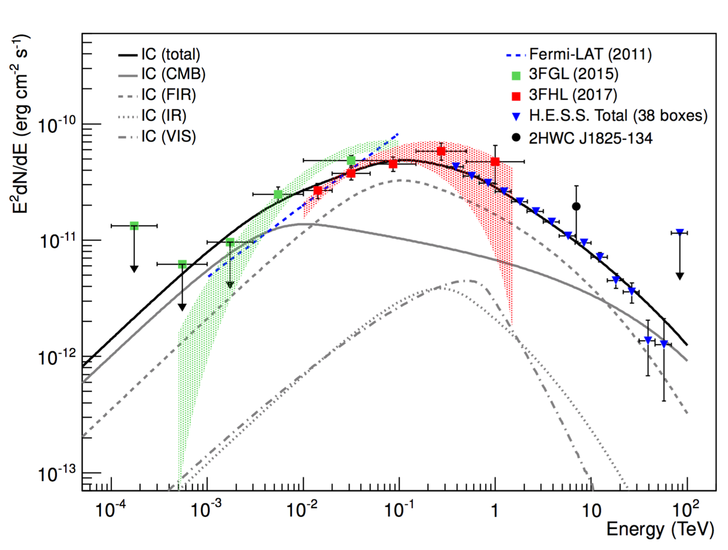


Hydrodynamical simulations of the PWN/SNR system by Temim et al. (2015). The pulsar has a proper motion of 400 km/s towards the top, and the density increases to the right.

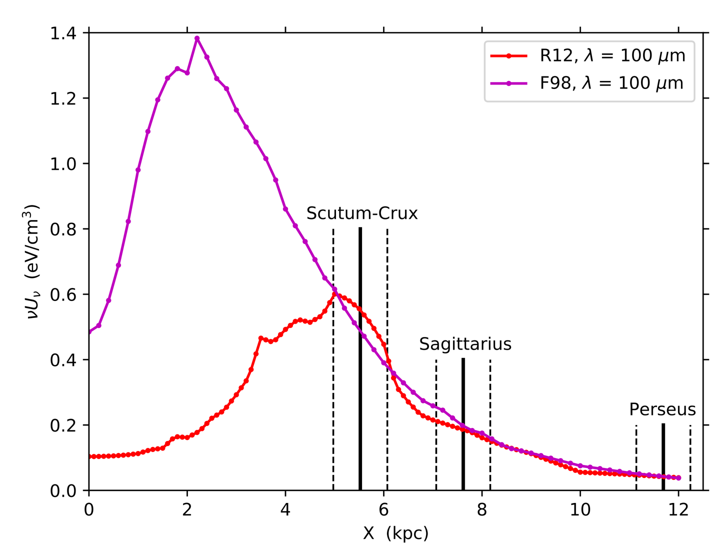
Interstellar radiation fields and TeV PWN luminosity

Recent radiative transfer models of the Galactic interstellar radiation field (ISRF) by Porter et al. (2017) and Popescu et al. (2017) posit a stellar emissivity distribution and self-consistently compute absorption by dust and re-emission in the far infrared (FIR).

In standard leptonic models of PWN emission, with such an ISRF along with the Cosmic Microwave Background (CMB), inverse Compton scattering of the FIR component is the dominant emission mechanism in TeV γ-rays, for PWNe in the inner Galaxy such as HESS J1825–137.



Inverse Compton emission model and contributions for HESS J1825–137, along with the latest H.E.S.S. data and published *Fermi*-LAT points. The stellar (VIS) target photon contribution is negligible due to Klein-Nishina effects. From H.E.S.S. Collaboration (2019).



ISRF energy density in the FIR as a function of Galactocentric radius (X with $Y = Z = 0$), for the two models of Porter et al. (2017). Model R12 includes the spiral arm structure in stellar emissivity.

Galactocentric variation of the FIR target photon density may explain the PWN TeV luminosity trend, although the amplitude of the FIR variation appears smaller. If so, a sufficiently large TeV PWN sample, as expected from the Cherenkov Telescope Array (CTA), could probe the Galactic FIR photon density distribution.

Summary and prospects

The TeV γ-ray luminosities of PWNe tend to mildly decrease with pulsar spin-down power, hence with increasing age, and appear less luminous in the outer Galaxy. Older TeV PWNe are generally offset from their pulsar, with displacements larger than can be explained solely by pulsar proper motions.

Self-consistent models of the interstellar radiation field predict an enhanced FIR photon density in the inner spiral arms. This may explain the TeV luminosity trend, although the FIR density contrast appears smaller; including spiral arm structure in the dust distribution should increase the predicted FIR photon density contrast.

Gradients in interstellar medium density may combine with pulsar proper motion to explain the observed offsets. This requires large density contrasts, for which observational evidence is limited. Alternatively, asymmetric particle escape from the nebula may play a role.

References

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