Studies of Pulsar Wind Nebulae in TeV γ-rays with H.E.S.S.

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The H.E.S.S Cherenkov Telescope System

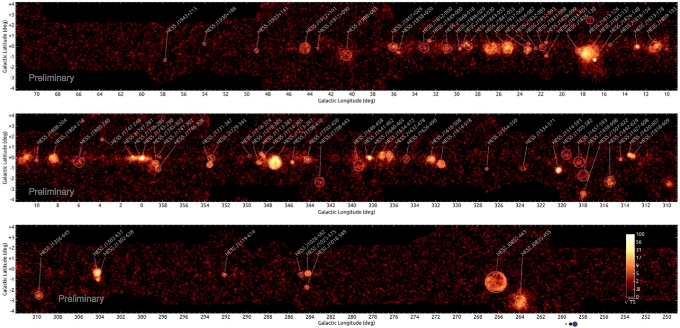
- use Earth's atmosphere as detector, through Cherenkov light from electromagnetic shower (on dark, moonless nights)
- past decade(+) : current generation of *Imaging Atmospheric Cherenkov Telescope* (IACT) experiments
- large mirrors, fine pixels, stereo technique ⇒ high sensitivity

HESS-II IACT system (Namibia)

- HESS-I : 4 mirrors of 12 m diameter ; HESS-II : +28 m-diameter
- Southern hemisphere location ideal to observe inner Galaxy

Galactic TeV γ-ray sources and PWNe

- HESS Galactic plane survey : longitudes $\ell \approx +65^\circ$ to -110°
- long-term, multi-stage survey (2004–2012) ; highly non-uniform
- in time, strategy to achieve more uniform minimal sensitivity

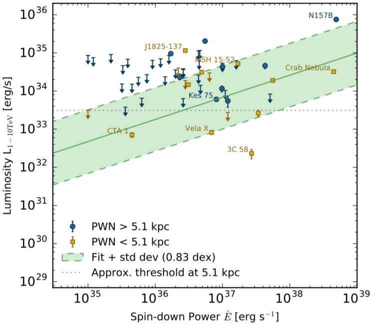


HESS excess map (Donath et al., H.E.S.S., 2015 ICRC)

- currently $\gtrsim$100 Galactic TeV sources known (78 in HGPS)
- $\sim$30% identified as pulsar wind nebulae (PWNe) or candidates **(H.E.S.S PWN population paper :** `arXiv:1702.08280`**)**

TeV γ-ray luminosity distribution of PWNe

- PWN TeV luminosities $L_\gamma = 4\pi D^2\, F_{1-10\,\mathrm{TeV}}$, plotted against (current) pulsar spin-down energy loss $\dot{E}$



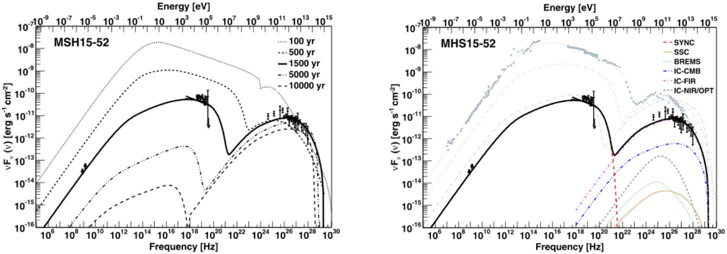
- relatively narrow range of L_γ ($\gtrsim$1 decade, with outliers)

- little correlation with $\dot{E}$, unlike L_X (Grenier 2009, Mattana+ 2009)
- add HESS GPS upper limits ⇒ faintening trend significant
- TeV γ-rays reflect history of injection since pulsar birth, whereas X-rays trace recently injected particles

PWN magnetic evolution and L_X/L_{TeV}

- naive interpretation of L_X/L_{TeV} suggests B decrease with age
- difference of electron lifetime also plays a role (for $B < 30\mu$G, more pronounced as B decreases)

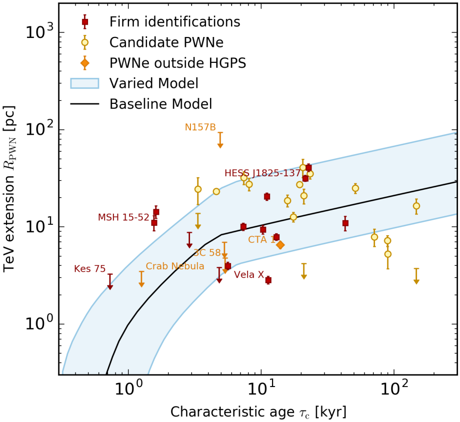
- Torres et al. (2014) model *young* TeV-detected PWNe [see also Tanaka & Takahara (2010,2011), Bucciantini et al. (2011), . . .]
- Crab, G0.9+0.1, G21.5–0.9, MSH 15–52, Kes 75, ..., modelled with broken power-law injection, $1.0 < p_0 < 1.5$, $p_1 = 2.2$–2.8



- L_X/L_γ ratio evolution dominated by B-field decrease with age
- main target photons for Inverse Compton are Galactic far-IR

PWN TeV size evolution

- significant trend of expansion with characteristic age

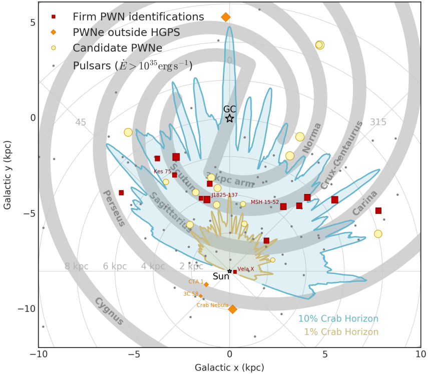


- consistent with PWN supersonic “free” expansion initially, followed by slower subsonic expansion (after reverse shock “informs” PWN about surrounding medium)

Galactic distribution of TeV PWNe

- with simulated SNR distribution (using Cordes & Lazio 2002)
- PWNe trace recent massive star formation (spiral arms)

(Klepser et al. 2017, H.E.S.S.)

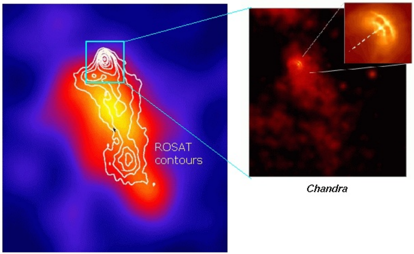


- HESS GPS detectability quite good to Scutum-Crux (Centaurus) arm
- deficit of TeV-emitting PWNe in Sagittarius-Carina arm ?
- PWNe in outer Galaxy (Vela X, 3C 58...) have low luminosities

⇒ correlation of L_{TeV} with ambient (far-IR) photon density ?

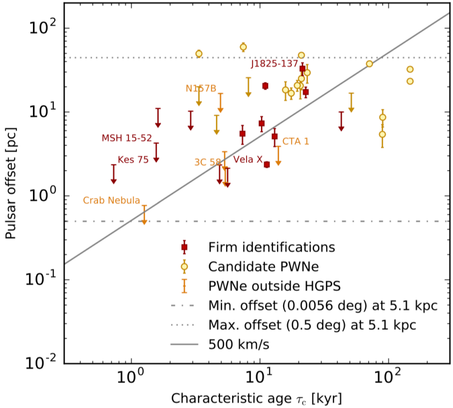
Older, “offset” PWNe

- TeV emission from the **Vela X** nebula (HESS 2006)



- IC emission $\propto$ (approximately uniform) target photon density $\Rightarrow$ direct inference of spatial distribution of electrons
- fainter emission from whole radio nebula (HESS 2012)
- compact X-ray nebula not conspicuous in TeV γ-rays $\Rightarrow$ torii and jets bright in X-rays because of higher magnetic field
- source **offset** from pulsar position ; not due to pulsar motion
- two TeV PWNe in **Kookaburra**, and **HESS J1356–645** are in same category (though no SNR shells)

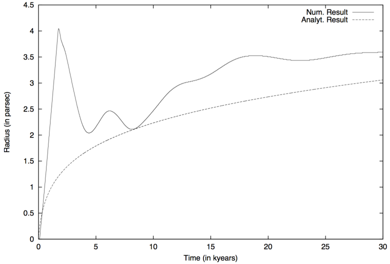
TeV PWN offsets vs. age



- older TeV PWNe have **large** offsets
- cannot be explained by typical pulsar proper motions (observed distribution implies $v_\perp < 500\,\mathrm{km/s}$ for most)
- suggests alternative asymmetric PWN “crushing” scenario. . .

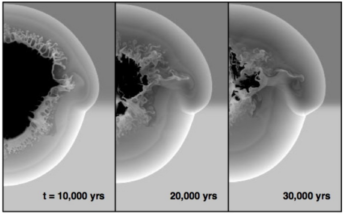
PWNe in older composite SNRs

- reverse shock eventually contacts PWN at SNR center
- PWN is initially "crushed" by shocked ejecta pressure
- in spherically symmetric simulations (e.g. van der Swaluw et al. 2001), several reverberations before slower, steady expansion



PWN r vs. t

2D asymmetric evolution



- in more realistic 2D, Rayleigh-Taylor instabilities can mix plerion and ejecta (Blondin, Chevalier & Frierson 2001)
- asymmetries in medium can shift or "offset" PWN from pulsar → talk by P. Slane
- eventually settles to "subsonic" expansion inside Sedov-phase remnant (e.g. van der Swaluw et al. 2001)

Summary on TeV properties of PWNe

- H.E.S.S. Galactic Plane Survey yields new inferences on the population of Pulsar Wind Nebulae in TeV γ-rays (H.E.S.S. Collaboration 2017 : `arXiv:1702.08280`)

PWN TeV γ-ray luminosities

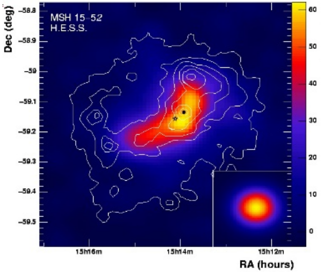
- weak but significant decreasing trend with pulsar $\dot{E}$ or age (in contrast to X-ray synchrotron luminosity, from shorter-lived electrons)
- often dominated by inverse Compton on ambient far-IR photons
- PWNe more readily detected in inner than outer Galaxy

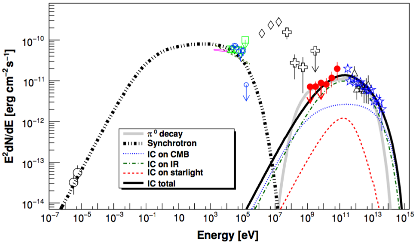
TeV PWN sizes and offsets

- clearly resolved trend of PWN expansion with age
- older PWNe are offset, more than due to pulsar velocities
- plausibly due to “crushing” by asymmetric reverse shock
- implications for late evolution and bow-shock stage onset ?

γ-rays from the PWN in MSH 15–52

- composite SNR MSH 15–52 (a.k.a. G 320.4 –1.2) contains the nebula of young PSR B1509–58 ($\tau \approx 1600$ yr, $\dot{E} = 1.8 \times 10^{37}$ erg/s)
- X-rays : bright, nonthermal PWN plus thermal emission from SNR
- H.E.S.S. (2005) discovered emission coincident with the X-ray PWN ; *Fermi*-LAT (2010) subsequently detected its emission



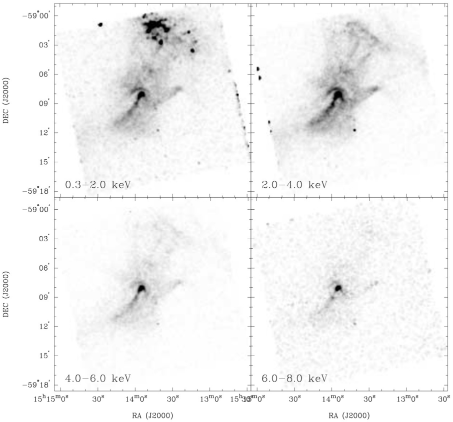


(← Aharonian et al. 2005 ; ↑ Abdo et al. 2010)

- one-zone spectral models favor $B \approx 17\,\mu$G, require high FIR photon density $U_{FIR} \sim 2\,\mathrm{eV/cm^3}$ for dominant IC contribution
- what can we learn about morphology from more H.E.S.S. data ?

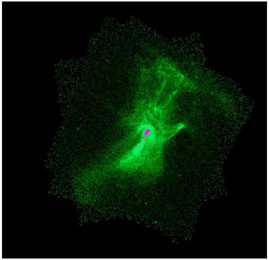
X-ray morphology and synchrotron template

- *Chandra* revealed complex PWN morphology, with prominent arc (torus ?), jet(s), and thermal knots (in RCW 89)



(← Gaensler et al. 2002)

synchrotron template



- additional ∼200 ks of archival *Chandra* ACIS data
- **4–7 keV** band to exclude thermal emission, reduce background
- exposure-corrected mosaic → synchrotron template

H.E.S.S.-I data set and analysis method

Current H.E.S.S. data analyzed

- H.E.S.S.-I data (2004–2014) with offset $< 2.5^\circ$ from source : 93 h live time (48 h exposure-corrected)
- model event analysis (de Naurois & Rolland 2009) ; $E_\gamma \gtrsim 0.3$ TeV
- excess $\sim 5\,500$ events, total significance $> 50\,\sigma$
- (all results cross-checked with an independent analysis and reconstruction chain — from the H.E.S.S. Galactic Plane Survey)

Morphological analysis procedure

- generate raw count, background, exposure maps and PSF
- use *Sherpa* for 2D fit of model to raw count data :

$$\mathtt{prediction} = (\mathtt{model} * \mathtt{PSF}) \times \mathtt{exposure} + \mathtt{backgd}$$

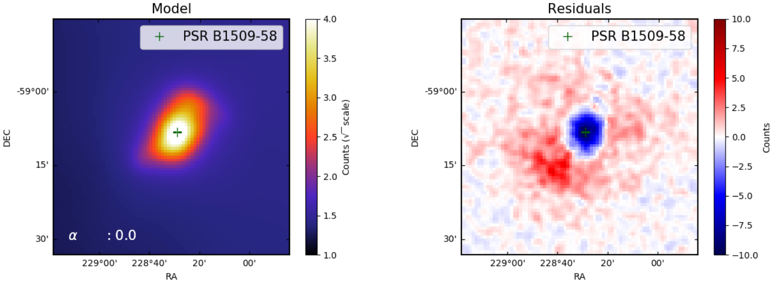
- assess models using Akaike Information Criterion (AIC) (Akaike 1973) : $\mathrm{AIC} \equiv -2\log L + 2\,k$,

  where $-2\log L =$ Cash (1979) statistic, for k parameters in model

(more details on data and results : **Tsirou et al., proc. ICRC 2017**)

γ-ray morphology vs. synchrotron template

- how well does γ-ray morphology match the X-ray template ?



- negative residuals in central regions around PSR B1509–58 (emission from pulsar itself was subtracted from X-ray template)
- positive residuals at larger distances from pulsar

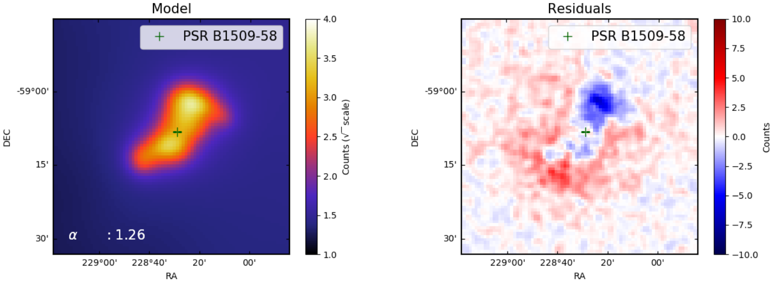
- $\Rightarrow$ magnetic field B stronger in central regions of nebula :

$$L_{\text{synch}} \propto N_e\, B^2 \qquad \text{vs.} \qquad L_{\text{IC}} \propto N_e\, U_{\text{rad}} \; ,$$

with target photon density $U_{\text{rad}} \approx$ uniform in nebula

Beyond the one-zone models

- modify synchrotron template by modeling non-uniform B : fit to $F_{\text{synch}} \times R^{\alpha}$ (where R is projected distance from pulsar)



- significantly better fit of γ-ray morphology : $\Delta\text{AIC} = 400$
- best-fit value $\alpha = 1.26 \pm 0.06_{\text{stat}}$ (preliminary, sys. not quantified)
- $F_{\text{synch}} \propto \nu^{1-\Gamma} B^{\Gamma} \Rightarrow$ $B \propto R^{-\zeta}$ with $\zeta \approx 0.5\text{–}0.6$ (using $\Gamma \approx 2.2$) (compared with $\zeta \approx 1$ at large R according to Kennel & Coroniti 1984)

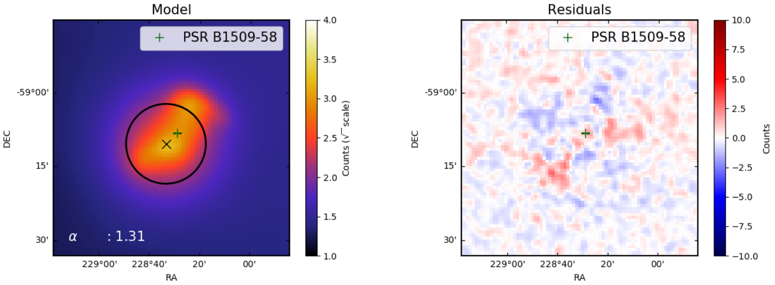
- positive residuals still remain at larger distances to the pulsar…

Beyond the X-ray nebula

- extended emission described by added Gaussian component :

$$\texttt{model} = A \cdot \texttt{Xray} \times R^{\alpha} + B \cdot \texttt{gauss2d}(\sigma, X_{\text{cen}}, Y_{\text{cen}})$$

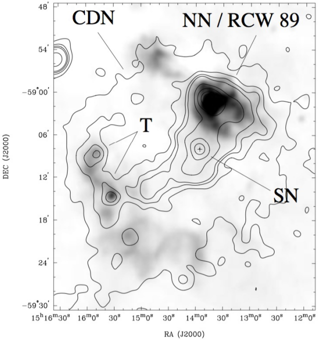
- significantly improved fit : ΔAIC ≈ 1000 with previous model
- other morphological models (e.g. shell, disk) did not yield better fit

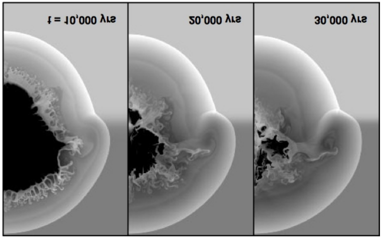


- best-fit Gaussian intrinsic extension $\sigma = 6.9' \pm 0.2'_{\text{stat}} \pm 0.3'_{\text{sys}}$ (much broader than PSF ; uncertainties included in sys. err.)
- Gaussian centroid position[$\times$] offset from pulsar[$+$] towards SE (away from Galactic plane)
- physical origin of this extended component ?

SNR parameters and reverse shock interaction

- PSR B1509–58 characteristic spin-down time $\tau \approx 1600\,\mathrm{yr} > t_{\mathrm{age}}$
- large pulsar-shell radius (∼20 pc) to SE can be explained by low medium density, high explosion energy and/or low ejecta mass
- high density to NW (RCW 89) : $n_{\mathrm{H}} \sim 1$–$5\,\mathrm{cm}^{-3}$ (Gaensler+ 1999) ⇒ well in Sedov-Taylor phase ; reverse shock is crushing PWN





(← Gaensler et al. 1999 ; ↑ Blondin et al. 2001)

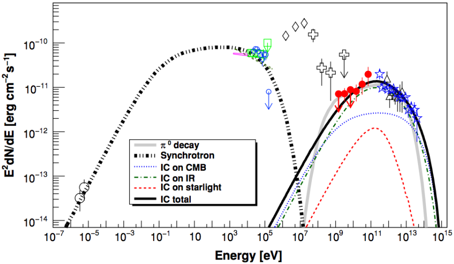
→ talk by P. Slane

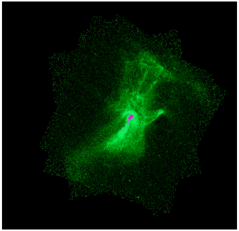
- low density to SE : $n_{\mathrm{H}} \sim 0.01\,\mathrm{cm}^{-3}$ (away from Galactic plane) ⇒ still in transition from free-expansion phase
- ongoing interaction and displacement of (relic) PWN to SE

Extended γ-rays from “crushed” relic PWN ?

- but no corresponding emission detected in synchrotron…

Spectrum and $e^{\pm}$ energies



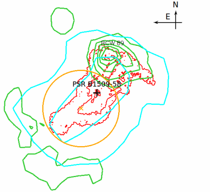


- equipartition (one-zone model) suggests $B \approx 20\,\mu$G
- then $h\nu_{\rm synch} > 4\,$keV corresponds to $E_e \gtrsim 100\,$TeV
- synchrotron lifetime $\lesssim 300\,$yr $\Rightarrow$ “fresh”, recently-injected $e^{\pm}$

- dominant target photons component for IC is Galactic IR
- for $T \approx 25\,$K, $E_\gamma > 0.3\,$TeV corresponds to $E_e \gtrsim 2\,$TeV
- *Fermi*-LAT morphology compatible with Gaussian of radius $8.8' \pm 1.4'$, compatible position… $\Rightarrow$ lower-E_e component ?
- “relic” nebula unobservable in X-rays (and multi-TeV γ-rays) ?

Alternative scenario : $e^{\pm}$ escape into ejecta

- if halo spectrum similar to other component, can estimate B
- lack of corresponding synchrotron suggests γ-ray halo is in low-B medium $\Rightarrow$ SN ejecta
- reverse shock interaction $\Rightarrow$ complicated geometry (PWN / ejecta boundary, mixing ?) ; ejecta shocked ?



Diffusion into ejecta ?

- halo size $R_h \approx 8\,\mathrm{pc}$ $\Rightarrow$ diffusion coefficient $\kappa \sim 10^{28}\,\mathrm{cm^2 s^{-1}}$
- (assumes most injection at $t = 0$, ignores advection $\Rightarrow$ UL on κ)
- large diffusion coefficient, comparable to that in ISM : diffusion into non-turbulent medium ? Unshocked ejecta ?

- κ expected to depend on E_e ; energy-dependent morphology ?
- a crucial process for PWNe as sources of cosmic-ray $e^{\pm}$!

Summary and prospects on MSH 15–52

Morphological analysis

- detailed 2D morphological analysis of H.E.S.S.-I γ-ray data (Tsirou et al. 2017, ICRC proceedings)
- using a *Chandra* map as synchrotron template, empirically find compatibility with $B \propto R^{-\zeta}$, with $\zeta \approx 0.5$–0.6
- significant additional extended emission, modeled as a Gaussian with extent $\sigma \sim 7'$, containing $\sim 65\%$ of total flux

Nature of the extended emisson ?

- morphology suggests relic, offset PWN from reverse shock interaction ; would require a steep spectrum in TeV γ-rays
- could also be $e^{\pm}$ which have escaped from PWN into ejecta

Future work prospects

- investigate energy-dependent morphology in TeV γ-rays ; could help discriminate between above possibilities
- more detailed numerical modeling to help understand spectrum