The population of Pulsar Wind Nebulae as observed in TeV γ-rays

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(with numerous H.E.S.S. collaborators, particularly S. Klepser, M. Renaud. . .)

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TeV (Very-High-Energy) γ-ray astronomy

- **GeV** (High-Energy) γ-rays with satellites (e.g. *Fermi*-LAT)
- at high E_γ, limited by calorimeter depth and collecting area

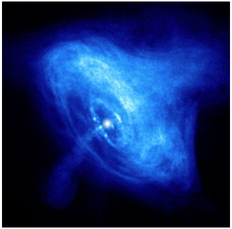
- **TeV**: use Earth's atmosphere as detector, through Cherenkov light from electromagnetic shower (on dark, moonless nights)
- past decade(+) : current generation of *Imaging Atmospheric Cherenkov Telescope* (IACT) experiments
- large mirrors, fine pixels, stereo technique ⇒ high sensitivity

HESS-II IACT system (Namibia)

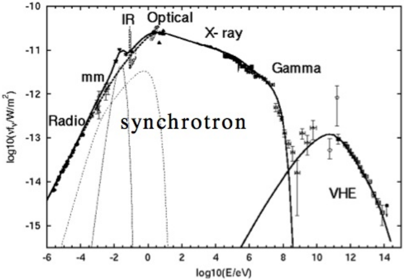
- HESS-I: 4 mirrors of 12 m diameter; HESS-II: +28 m-diameter
- similar principles: MAGIC-II (Canary Isl.), VERITAS (Arizona)

TeV γ-ray spectrum of the Crab Nebula

- “standard candle” of TeV γ-ray astronomy since its discovery



Chandra

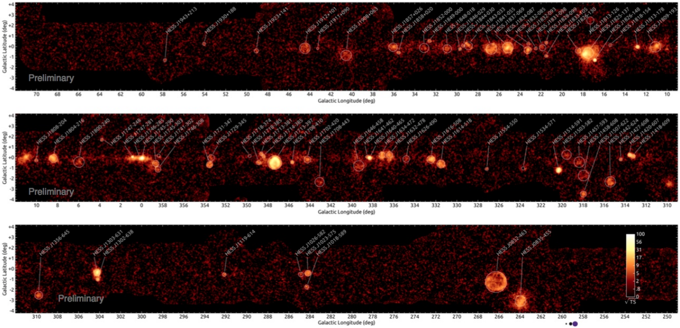


- *synchrotron* emission in most of the electromagnetic spectrum, from $e^{\pm}$ accelerated in the pulsar, wind, termination shock (?)
- TeV γ-ray emission results from *Inverse Compton* scattering of lower-energy photons (synchrotron, CMB, IR, starlight...)
- (hadronic contributions also proposed, e.g. **Horns et al. 2007**)

- PWNe important sources of high-energy cosmic-ray e^{+} (and e^{-})
- main astrophysical candidates to explain $e^{\pm}$ excess measured by PAMELA, *Fermi*-LAT, AMS-02…

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 (>75 in HGPS)
- $\sim$30% identified as pulsar wind nebulae (PWNe) or candidates (HESS PWN population paper in preparation; here preliminary results)

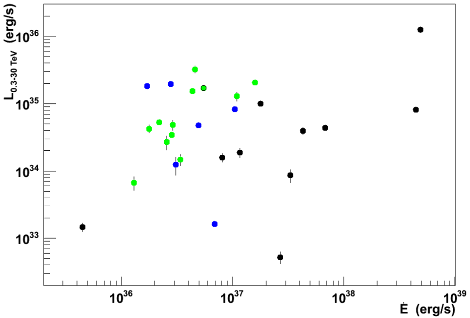
TeV γ-ray luminosity distribution of PWNe

- PWN TeV luminosities $L_\gamma = 4\pi D^2 F_{0.3-30\,\mathrm{TeV}}$, plotted against (current) pulsar spin-down energy loss $\dot{E}$

young PWNe

offset PWNe

candidate PWNe



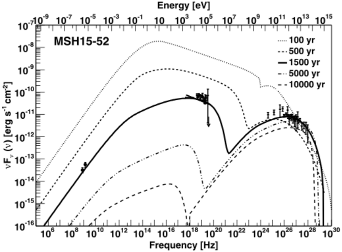
- relatively narrow range of L_γ ($\gtrsim$1 decade, with outliers)
- little correlation with $\dot{E}$, unlike L_X (Grenier 2009, Mattana+ 2009)
- add HESS GPS upper limits $\Rightarrow$ faintening trend significant (Klepser et al., H.E.S.S., 2015 ICRC)

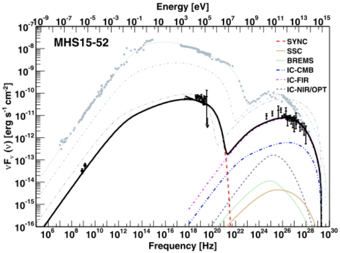
- TeV γ-rays reflect history of injection since pulsar birth, whereas X-rays trace recently injected particles

PWN magnetic evolution and $L_X/L_{\rm TeV}$

- naive interpretation of $L_X/L_{\rm TeV}$ 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

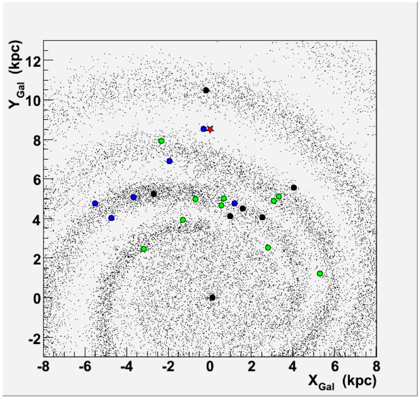
Galactic distribution of TeV PWNe

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

young PWNe

offset PWNe

candidate PWNe



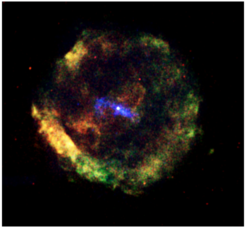
- HESS GPS detectability quite good to Scutum-Crux arm
- deficit of TeV-emitting PWNe in Sagittariux-Carina arm?
- PWNe in outer Galaxy (Vela X, 3C 58...) have low luminosities

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

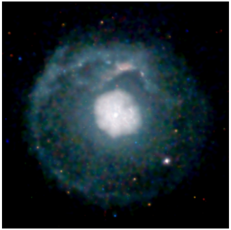
TeV morphology: composite SNR evolution

- pulsars are born in (core-collapse) supernovae (type II / Ib,c)
- Crab Nebula unusual in that SN remnant shock not detected : purely “**plerionic**” (center-filled) SNR
- more generally, PWNe inside classical, **shell-type** SNR : “**composite**” SNR

X-ray (*Chandra*) images



G 11.2–0.3



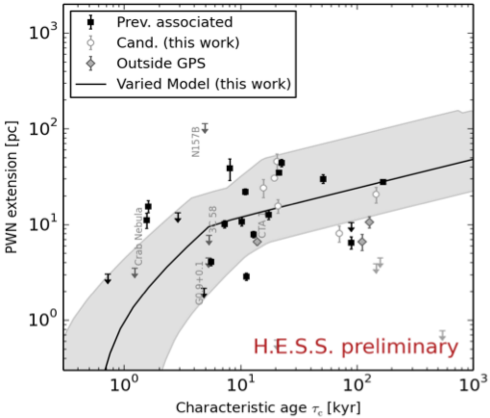
G 21.5–0.9

Kes 75

- thermal X-ray emission from shocked supernova ejecta
- non-thermal (synchrotron) emission near two acceleration sites :
  - blast wave of initial explosion : SNR shell (forward shock)
  - pulsar (wind termination shock) : pulsar wind nebula

PWN TeV size evolution

- significant trend of expansion with characteristic age

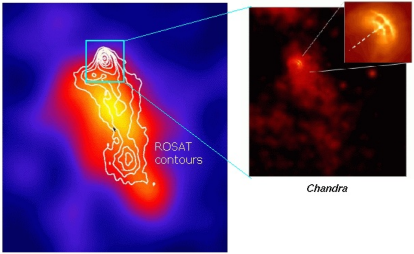


(Klepser et al., 2015 ICRC)

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

Older, “offset” PWNe

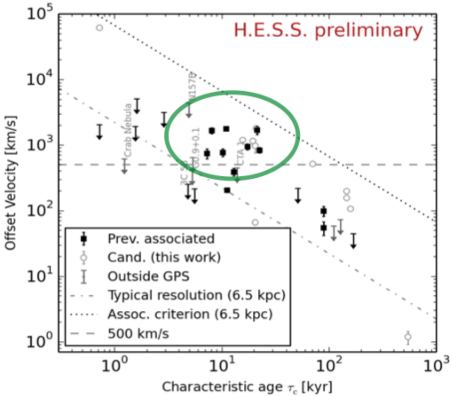
- TeV emission from the **Vela X** nebula (HESS 2006)



- 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

- here plotted in terms of corresponding "velocity" $\equiv$ offset / τ_c

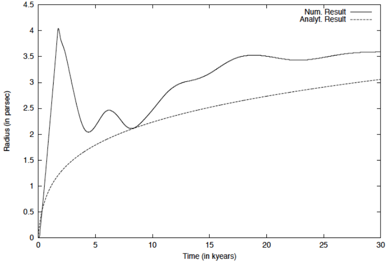


(Klepser et al., 2015 ICRC)

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

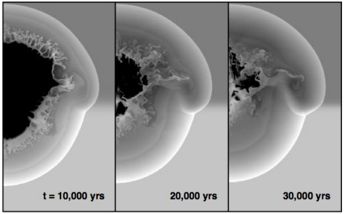
PWNe in older composite SNRs

- 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



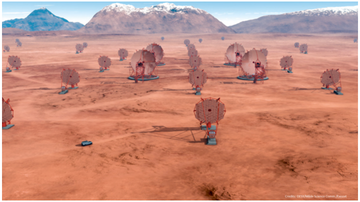
PWN r vs. t

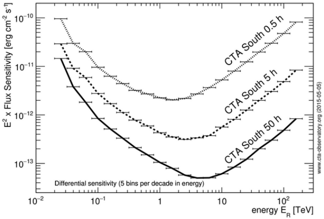
2D asymmetric evolution



- 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
- eventually settles to "subsonic" expansion inside Sedov-phase remnant (e.g. van der Swaluw et al. 2001)

CTA (Cherenkov Telescope Array) project



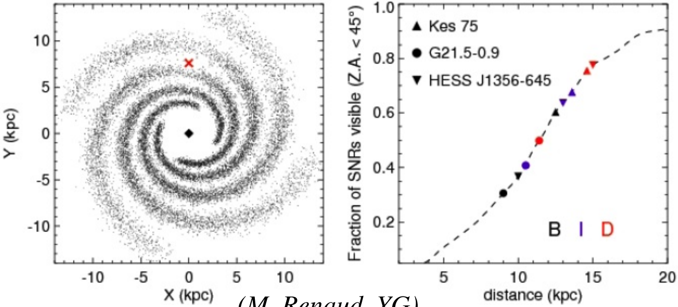


- next generation of imaging atmospheric Cherenkov telescopes
- one order of magnitude sensitivity improvement over current generation of IACT instruments (e.g. HESS or MAGIC)
- energy range from few $\times$ 10,GeV to few $\times$ 100 TeV
- two sites : Northern and Southern Hemisphere
  (latter better for Galactic physics $\Rightarrow$ higher energy)

Galactic PWN population seen by CTA

- PWNe with Crab luminosity detectable to LMC (in 50 hours)!
- fainter, inner Galactic TeV PWNe ($L_{0.3-30\,\mathrm{TeV}} \sim 10^{34}$ erg/s)
- simulate Galactic (core-collapse) SNR distribution
- Ignore displacement from pulsar birth place due to velocity kick

Horizon of **detectability**



(M. Renaud, YG)

- fainter PWNe detectable to 10–15 kpc (depend. on object, config.)
- if all PWNe shine several $\times$ 10^4 yr in TeV, several 100 PWNe! (Dubus et al. 2013)

Summary and prospects

- H.E.S.S. Galactic Plane Survey is yielding new inferences on the population of Pulsar Wind Nebulae in TeV γ-rays

PWN TeV γ-ray luminosities

- vary little 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

TeV PWN sizes and offsets

- clearly resolved trend of PWN expansion with age
- older PWNe are offset, more than due to pulsar velocities
- due to "crushing" by asymmetric reverse shock?

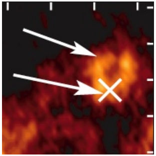
Prospects with CTA

- could detect PWNe across a major fraction of the Galaxy
- population study of star formation / spiral arm environment

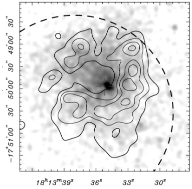
Supplementary slides

Subsequently identified young PWNe in SNRs

The progressive identification of **HESS J1813–178**

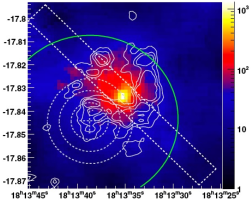


- Brogan et al. (2005) revealed its coincidence with a shell-type radio SNR (and *ASCA* source)



- *Chandra* revealed a pulsar candidate (Helfand et al. 2007)

- *XMM* revealed an extended non-thermal nebula inside the shell (Funk et al. 2007a)



- *XMM* found pulsed emission, $\dot{E} = 5.6 \times 10^{37}$ erg/s (Gotthelf & Halpern 2009)