Pulsar Wind Nebula TeV population, evolution, and the sources of Cosmic-Ray $e^{\pm}$

Yves Gallant[1]

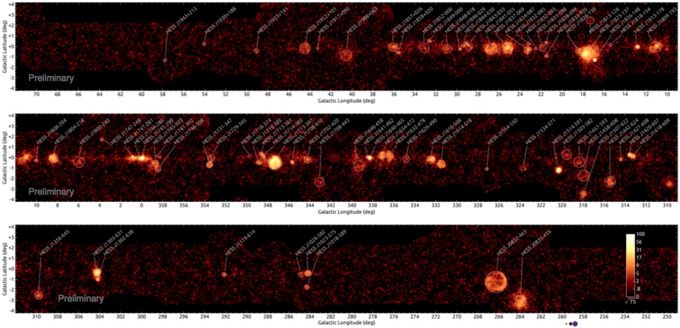
(collaborators: S. Klepser, M. Renaud,
N. Bucciantini, R. Bandiera, E. Amato. . .)

[1] LUPM, CNRS/IN2P3, U. de Montpellier

OCEvU Workshop "The Physics of Relativistic Outflows"
IRAP, Toulouse, March 23, 2016

Galactic TeV γ-ray sources and PWNe

- HESS Galactic plane survey : longitudes $\ell \approx +65°$ 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 >100 Galactic TeV sources known (>75 in HGPS)
- ~30% identified as pulsar wind nebulae (PWNe) or candidates (HESS PWN population paper in preparation)

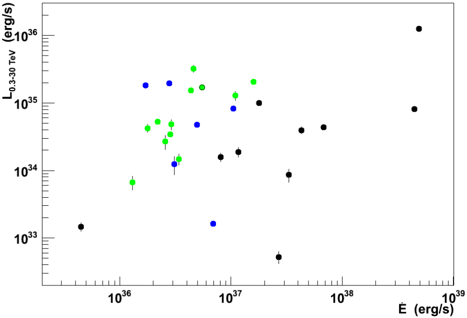
TeV γ-ray luminosity distribution of PWNe

- 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

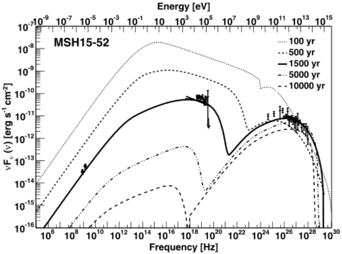


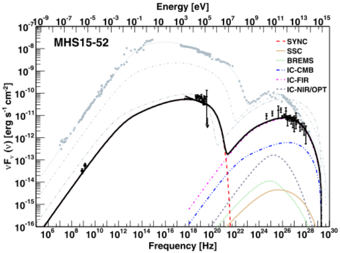
- relatively narrow range of L_γ ($\gtrsim$1 decade); median luminosity for established PWNe is $L_{0.3-30\,\mathrm{TeV}} \approx 4 \times 10^{34}$ erg/s
- no correlation with $\dot{E}$, unlike L_X (Grenier 2009, Mattana et al. 2009)
- TeV γ-rays reflect history of injection since pulsar birth, whereas 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



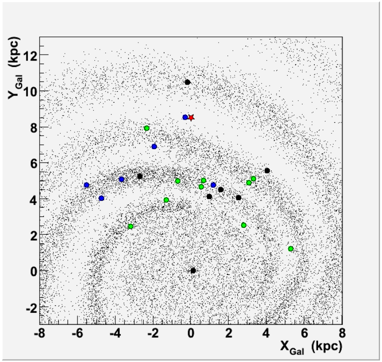


- L_X/L_γ ratio evolution dominated by B-field decrease with age

- shorter lifetimes ⇒ more compact spatial distribution in X-rays

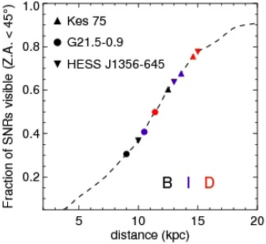
Nébuleuses de pulsars et prospective CTA

- nébuleuses tracent la formation d'étoiles massives (bras spiraux)
- détectabilité avec HESS bonne jusqu'au bras Scutum-Crux
- déficit de nébuleuses TeV dans le bras Sagittaire-Carène?
- ou densité moins élevée de photons-cible (IR et/ou stellaires)?



nébuleuses jeunes

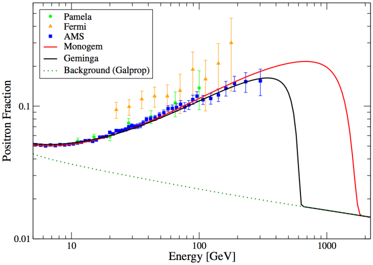
décalées candidates



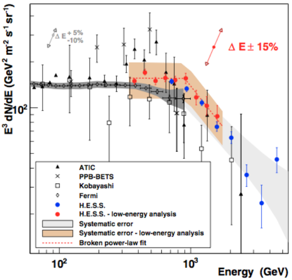
- détectabilité avec CTA jusqu'à 10–15 kpc suivant la luminosité L_γ, taille ℓ, et la configuration choisie (**B**, **I**, **D**)

Cosmic-ray positrons as new "messenger"?

- *PAMELA* (2009) measured positron fraction $e^+/(e^+ + e^-)$ increase with E, inconsistent with secondary propagation origin
- confirmed to higher E: *Fermi*-LAT (2012), AMS-02 (2013, 2014)



(from Linden & Profumo 2013)



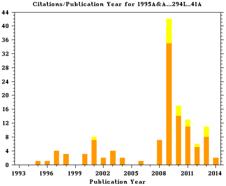
(Aharonian et al. 2009)

- tending to ~20% up to $(e^+ + e^-)$ steepening at $E \sim 1$ TeV?
- spectrum and positron fraction require **primary** $e^\pm$ source
- signature of DM annihilation? But another "natural" scenario…

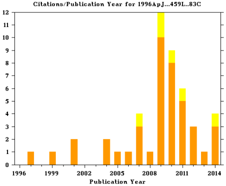
Primary $e^{\pm}$ from pulsars?

- copious $e^{\pm}$ production in pulsar magnetospheres (Sturrock 1970)
- proposed as cosmic e^{+} sources by several authors:

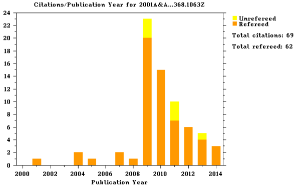
Aharonian et al. (1995)



Chi et al. (1996)



Zhang & Cheng (2001)



- dramatic increase in interest (ADS citations) since 2009!
- more recent studies: Grimani (2004, 2007), Büsching et al. (2008), Hooper et al. (2009), Delahaye et al. (2010)...
- dominant local contribution from Geminga, PSR B0656+14?
- source spectrum of e^{+} for propagation mostly based on purely magnetospheric considerations...

Primary $e^{\pm}$ from Pulsar **Wind Nebulae**!

1. although e^{+} created in magnetosphere, thought to be **accelerated** to $E \gg$ TeV at wind termination shock
2. high-energy $e^{\pm}$ are **confined** in PWN, cannot readily escape PWN & SNR and propagate as cosmic rays in the ISM;

   requires consideration of **adiabatic** and **synchrotron** losses during PWN evolution; full description very complicated

How bad can it be?

- this talk: quantify effect of adiabatic and synchrotron losses, assuming $e^{\pm}$ remain confined in PWN until it dissipates in ISM (i.e. neglect **diffusive** escape from PWN and SNR)
- build on recent modelling of PWN spectral evolution (Zhang et al. 2008, Gelfand et al. 2009, Tanaka & Takahara 2010+, Bucciantini et al. 2011, Torres et al. 2013+...)

PWN model assumptions and parameters

- model PWN as isobaric bubble of relativistic $e^{\pm}$ and B (until late, bow-shock phases)

Pulsar wind

- injection of broken power-law spectrum of $e^{\pm}$, with γ_{break}, low and high spectral indices p_1 and p_2 independent of t
- constant magnetic energy fraction injected in nebula, $\eta \ll 1$
- wind power approximated as constant, $\dot{E} \approx 10^{38}$ erg/s, during free-expansion phase (dynamically unimportant thereafter)

Supernova remnant

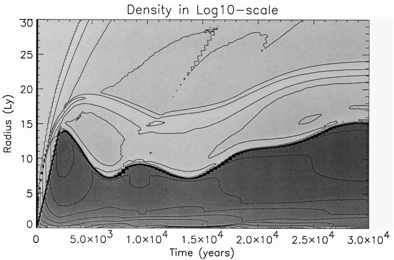
- uniform ejecta, with $M_{\mathrm{ej}} = 5M_{\odot}$ and $E_{\mathrm{ej}} = 10^{51}$ erg
- expanding in uniform interstellar medium, $n_{\mathrm{ism}} = 1\,\mathrm{cm}^{-3}$

Pulsar birth velocity

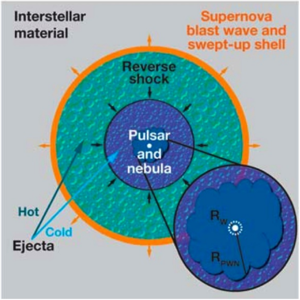
- assume typical pulsar 3D velocity $V_{\mathrm{psr}} = 400\,\mathrm{km/s}$ (e.g. Hobbs et al. 2005, Faucher-Giguère & Kaspi 2006)

Initial PWN phases in composite SNRs

- PWN first expands in unshocked SN ejecta (“free expansion”)
- four shocks: pulsar wind termination, PWN expansion, SNR reverse and forward shocks



density vs *r* and *t*
(Bucciantini et al. 2003)

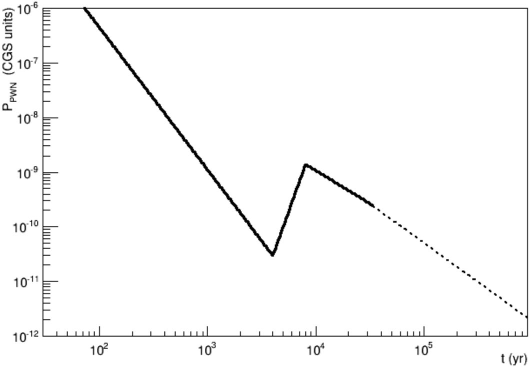


(Gaensler & Slane 2006)

- reverse shock eventually contacts PWN at SNR center
- PWN is initially “crushed” by shocked ejecta pressure
- in spherically symmetric simulations (e.g. MHD by Bucciantini et al. 2003), several reverberations before slower, steady expansion

Time evolution of PWN pressure (I)

- initial **free expansion** phase: $P_{\rm pwn} \propto t^{-13/5}$ (constant $\dot{E}$)
- lasts until reverse shock hits, $t_{\rm rs} \approx 4\,{\rm kyr}$



compression phase,

assumed $\Delta t = t_{\rm rs}$

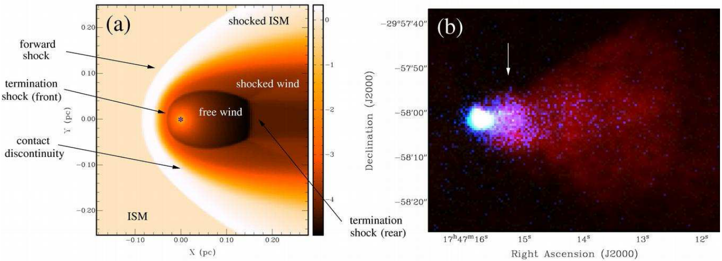
- subsonic expansion phase, in pressure equilibrium with remnant in **Sedov** (then radiative) phase: $P_{\rm pwn} = P_{\rm Sed} \propto t^{-6/5}$
- particles injected at $t < 30\,{\rm kyr}$ follow this evolution until $P_{\rm pwn} \approx P_{\rm ism}$: *relic* PWN

Bow-shock PWN phases

- pulsar motion becomes **supersonic** relative to hot interior (in a Sedov SNR) at

$$t_{\rm bow} = 32 \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{1/3} \left(\frac{n_0}{1\,{\rm cm}^{-3}}\right)^{-1/3} \left(\frac{V_{\rm PSR}}{400\,{\rm km/s}}\right)^{-5/3} \,{\rm kyr}$$

- leaves SNR and forms bow-shock PWN in **ISM** at $t_{\rm cross} = 2\,t_{\rm bow}$ (van der Swaluw et al. 1998)



hydrodynamic simulation

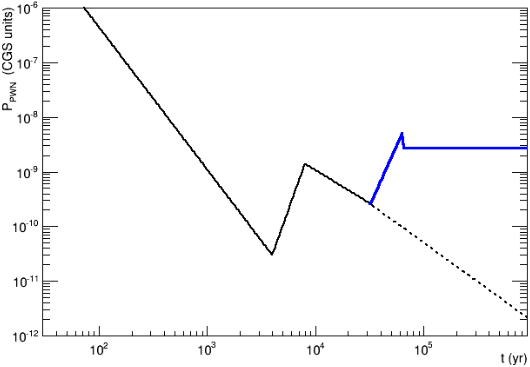
"Mouse" in X-rays and radio

(from Gaensler & Slane 2006)

- wind termination shock balance with ram pressure: $P_{\rm ts} \approx \rho V_{\rm psr}^2$

Time evolution of PWN pressure (II)

- $t > t_{\rm bow} \approx 30\,$kyr: **supersonic** bow-shock PWN in (Sedov) SNR
- fresh particles injected at post-shock pressure (then expand)



$t > 2\,t_{\rm bow}$:
bow-shock
PWN in **ISM**

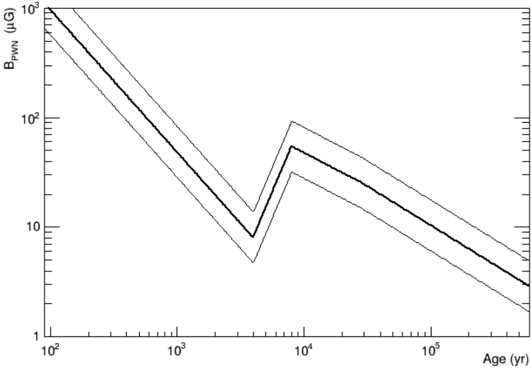
$$P_{\rm ts} \approx \rho_{\rm ism} V_{\rm psr}^2$$

- adiabatic expansion (or compression) of relativistic gas:

$$P \propto n^{4/3} \quad \Rightarrow \quad \left(\frac{\gamma_{\rm inj}}{\gamma_f}\right) = \left(\frac{P_{\rm inj}}{P_{\rm ism}}\right)^{1/4}$$

Synchrotron losses : magnetic field evolution

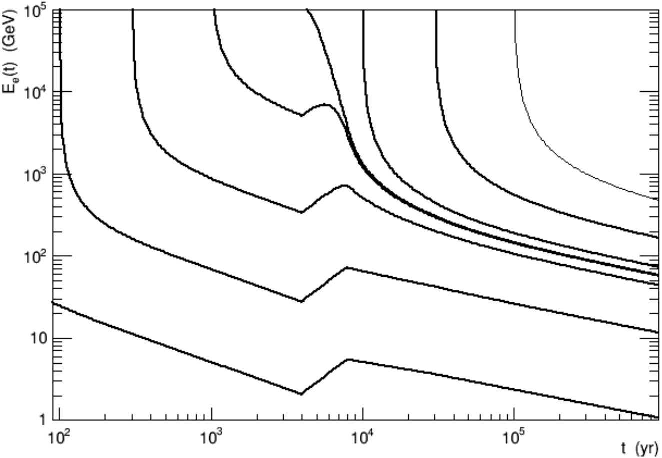
- magnetic field and relativistic gas have same energy density behavior in expansion and compression $\Rightarrow$ magnetic fraction η conserved (when radiative losses dynamically unimportant)



- $\eta = 0.03$ (0.01, 0.1) : typical value, e.g. median in models of 9 PWNe by Torres et al. (2014)
- peak $B_{\rm pwn}$ value after compression similar to that in young PWN, but acting over $t \sim 10^4$ yr…

Evolution of $e^{\pm}$ energy

- adiabatic and synchrotron losses (for pre-bow-shock phases)
- particles injected with $E \to \infty$ at $\log t_{\rm inj} = 1.5, 2, 2.5, \ldots, 5$



- early synchrotron burn-off: $e^{\pm}$ w/$t_{\rm inj} \lesssim 100\,$yr don't contribute
- compression phase burns off earlier $e^{\pm}$ to $E_f \lesssim 50\,$GeV

Summary and Prospects

- PWN L_{TeV} distribution relatively independent of age or $\dot{E}$
- Galactic distribution traces recent star formation, target photons
- cosmic-ray positrons can be created in pulsar magnetospheres, then accelerated and confined in Pulsar Wind Nebulae
- we quantify the effect of adiabatic and synchrotron losses, assuming good $e^{\pm}$ confinement (late escape into the ISM)
- compression phase burns off all earlier $e^{\pm}$ to $E_f \lesssim 50\,\text{GeV}$: only late PWN phases contribute to high-energy CR $e^{\pm}$
- synchrotron losses less problematic for bow-shock phases: higher post-shock B, but rapid flow time to P balance
- *Caveats:* parameter uncertainties, e.g. η; compression burn avoided if $e^{\pm}$ escape PWN before
- further observational and theoretical studies of *late-phase* (compressed and bow-shock) PWNe will help clarify issues
- combination of γ-ray (IC) and synchrotron morphologies can help disentangle spatial extent of $e^{\pm}$ and B