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

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- TeV-emitting PWN population
- PWNe and cosmic-ray positrons
- PWN evolution phases
- Adiabatic and synchrotron losses
Galactic TeV $\gamma$-ray sources and PWNe

- HESS Galactic plane survey: longitudes $\ell \approx +65^\circ$ to $-110^\circ$
- 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)
- $\sim 30\%$ identified as pulsar wind nebulae (PWNe) or candidates (HESS PWN population paper in preparation)
TeV $\gamma$-ray luminosity distribution of PWNe

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

- relatively narrow range of $L_\gamma$ ($\sim 1$ decade); median luminosity for established PWNe is $L_{0.3-30\,\text{TeV}} \approx 4 \times 10^{34}$ erg/s
- no correlation with $\dot{E}$, unlike $L_X$ (Grenier 2009, Mattana et al. 2009)
- TeV $\gamma$-rays reflect history of injection since pulsar birth, whereas X-rays trace recently injected particles
PWN magnetic evolution and $L_X/L_{\text{TeV}}$

- naive interpretation of $L_X/L_{\text{TeV}}$ 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, $1.0 < p_0 < 1.5, p_1 = 2.2–2.8$

- $L_X/L_\gamma$ ratio evolution dominated by $B$-field decrease with age
- shorter lifetimes $\Rightarrow$ 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)?

- détectabilité avec CTA jusqu’à 10–15 kpc suivant la luminosité $L_\gamma$, taille $\ell$, et la configuration choisie (B, I, D)
Cosmic-ray positrons as new “messenger”?  

- **PAMELA** (2009) measured positron fraction $e^+/\left(e^+ + e^-\right)$ 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 $\sim 20\%$ up to $\left(e^+ + e^-\right)$ steepening at $E \sim 1$ TeV?
- spectrum and positron fraction require **primary** $e^\pm$ source
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)

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 $\gamma_{\text{break}}$, 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 $M_{\text{ej}} = 5M_\odot$ and $E_{\text{ej}} = 10^{51}$ erg
▶ expanding in uniform interstellar medium, $n_{\text{ism}} = 1 \text{ cm}^{-3}$

**Pulsar birth velocity**

▶ assume typical pulsar 3D velocity $V_{\text{psr}} = 400$ 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 in Log10-scale](image)

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

- 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

![Diagram](image)

(Gaensler & Slane 2006)
Time evolution of PWN pressure (I)

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

\[ P_{\text{pwn}} (\text{CGS units}) \]

![Graph showing pressure evolution with time](chart)

- compression phase, assumed
  \[ \Delta t = t_{\text{rs}} \]

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

- Pulsar motion becomes **supersonic** relative to hot interior (in a Sedov SNR) at
  
  
  \[ t_{\text{bow}} = 32 \left( \frac{E_{\text{SN}}}{10^{51} \text{erg}} \right)^{1/3} \left( \frac{n_0}{1 \text{ cm}^{-3}} \right)^{-1/3} \left( \frac{V_{\text{PSR}}}{400 \text{ km/s}} \right)^{-5/3} \text{ kyr} \]

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

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**Hydrodynamic simulation “Mouse” in X-rays and radio**

(from Gaensler & Slane 2006)

- Wind termination shock balance with ram pressure: \( P_{ts} \approx \rho V_{\text{psr}}^2 \)
Time evolution of PWN pressure (II)

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

- $t > 2 t_{bow}$: bow-shock PWN in ISM
  \[ P_{ts} \approx \rho_{ism} V_{psr}^2 \]

- adiabatic expansion (or compression) of relativistic gas:
  \[ P \propto n^{4/3} \Rightarrow \left( \frac{\gamma_{inj}}{\gamma_f} \right) = \left( \frac{P_{inj}}{P_{ism}} \right)^{1/4} \]
Synchrotron losses: magnetic field evolution

- Magnetic field and relativistic gas have the same energy density behavior in expansion and compression ⇒ magnetic fraction $\eta$ 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 $B_{\text{pwn}}$ 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 $\log t_{\text{inj}} = 1.5, 2, 2.5, \ldots, 5$

- early synchrotron burn-off: $e^\pm$ with $t_{\text{inj}} \lesssim 100$ yr don’t contribute
- compression phase burns off earlier $e^\pm$ to $E_f \lesssim 50$ GeV
Summary and Prospects

- PWN $L_{\text{TeV}}$ 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 $E_f \lesssim 50$ 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. $\eta$; 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 $\gamma$-ray (IC) and synchrotron morphologies can help disentangle spatial extent of $e^\pm$ and $B$