The Time Evolution of Pulsar Wind Nebulae

Okkie de Jager, S. Ferreira (NWU, South Africa)

Contents

- Galactic Latitude distribution of HESS sources
  - Methanol Maser – leading to core collapse stars
  - Molecular gas (CO)
  - Offset PWN statistics (reverse shocks due to anisotropic ISM density)
  - Conversion efficiencies – Photon index distribution – the cooling effect.

- MHD Simulation Code
  - Evolution of Magnetic field strength of PWN.

- Importing Time dependent Radiation model

- Multiwavelength SED of G21.5-0.9.

- Time evolution of MWL spectrum of G21.5-0.9

- Evolutionary Tracks in X-rays and TeV

- The Calirometric-Relic effect.

- KES 75

- Conclusions
Galactic (b) distribution of HESS Sources: L>200 deg & L<60 deg (Southern Hemisphere)


⇒ Tracers for massive star formation leading to core collapse SNRs.

⇒ Several stages may co-exist. Older ones become TeV sources and younger ones still in star formation.
Galactic (b) distribution of HESS Sources: L>200 deg & L<60 deg (Southern Hemisphere)

Dame et al. (2001) Observed CO emission as tracers of molecular clouds where star formation takes place. Integrated over all longitudes.

**FWHM:** 0.5 deg

**FWHM:** 2 deg
Blondin et al. (2001); Ferreira & de Jager (2008)

Dame et al. (2001) observed CO emission as tracers of molecular clouds where star formation takes place. Integrated over all longitudes.

Galactic Plane – High Density

Early reverse shock

Galactic Plane – High Density

Lower Density

SNR Explosion in Anisotropic Media

FWHM: 2 deg

Galactic Latitude

Galactic Longitude

FWHM: 50

-10°

0°

10°

0°

10°

-10°
Ferreira & de Jager (2008)
The return time of the Reverse Shock scales with ISM density as

\[ T_R \sim (\text{density})^{-1/3}. \]
# PWNe Offset from Pulsars

de Jager & Djannati-Atai (2008); Hessels et al. (2008)

## Table 1. HESS VHE γ-ray Sources Possibly Associated with PWNe

<table>
<thead>
<tr>
<th>HESS Source</th>
<th>Size(^a) (arcmin)</th>
<th>Pulsar / PWN</th>
<th>Offset (arcmin)</th>
<th>(P_{\text{spin}}) (ms)</th>
<th>(\tau_c) (kyr)</th>
<th>(E) (\times 10^{36}) (ergs s(^{-1}))</th>
<th>(d) (kpc)</th>
<th>(L_\gamma/E) (1–10 TeV) (%)</th>
<th>Assoc. Ref.</th>
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</table>
PWNe Offset from Pulsars

Mostly Young Crab-Type

Velocity-Type

Δ (Pulsar Offset/TeV Source Radius)
Photon Index Distribution
The X-ray connection

Vela X

HESSJ1718-385
Numerical Scheme for SNR and PWN
(see Chevalier (2005) for analytical approach)

Euler equations
\[
\begin{align*}
\frac{\partial}{\partial t} \rho + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v} + P \mathbf{I}) &= 0, \\
\frac{\partial}{\partial t} \left( \frac{\rho}{2} \mathbf{v}^2 + \frac{P}{\gamma - 1} \right) + \nabla \cdot \left( \frac{\rho}{2} \mathbf{v}^2 + \frac{\gamma P}{\gamma - 1} \right) &= 0
\end{align*}
\]

For the initial and boundary conditions of the SNR:
\[
\begin{align*}
v &= \frac{r}{t} = v_{ej} r / r_{ej}, \\
v_{ej} &= \sqrt{\frac{10}{3} \frac{E_{ej}}{M_{ej}}}, \\
\rho_{ej} &= \frac{3 M_{ej}}{4 \pi r_{ej}^3}, \\
r_{ej} &= 0.1 \text{ pc
\text{ adiabatic index of } 5/3}
\end{align*}
\]

For the PWN we allow input power to decrease as a dipole spinning down. Magnetic field generation in PWN according to Faraday induction. Not fully MHD since field is calculated kinematically from flow (Scherer & Ferreira 2005).

\[
L(t) = \frac{L_0}{(1 + \frac{t}{\tau})^2}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) = 0
\]

Numerical scheme of LeVeque (2002), Ferreira & de Jager (2008), using wave propagation approach to solve hyperbolic differential equations. See also van der Swaluw et al. (2001), Bucciantini et al. (2003). One fluid approach since post shocked flow downstream is non-relativistic \(v < c/3\) (van der Swaluw et al. 2001).
Evolutionary radiation model, constrained by MHD results.

Two-component (radio/X-ray) injection (Venter & de Jager 2006)

\[ Q(\gamma, t) = \begin{cases} Q_0(t)(\gamma/\gamma_b)^{-p_1} & \text{for } \gamma < \gamma_b \\ Q_0(t)(\gamma/\gamma_b)^{-p_2} & \text{for } \gamma_b < \gamma < \gamma_{\text{max}} \end{cases} \int Q(\gamma, t) \gamma d\gamma = \eta L(t). \]

$L(0)$ (or $P_0$) constrained by $R_{\text{PWN}}/R_{\text{SNR}}$ from MHD

Particle spectrum from Leaky Box approach:
see e.g. Zhang et al. (2008)

\[ \frac{dN(E_e, T_{\text{age}})}{dE_e} = \int_0^{T_{\text{age}}} Q(E_e, t) \exp\left(-\frac{T_{\text{age}} - t}{\tau_{\text{eff}}}\right) dt \]

Effective loss timescales constrained by MHD

Pair production multiplicity from continuity equation (Sefako & de Jager 2003)

The electron continuity equation is given by

\[ \int_0^\infty Q(E) \, dE = \eta_p \frac{I_{\text{GJ}} M}{e}, \quad (3) \]

where $\eta_p$ is the fraction of all pairs escaping through the light cylinder, which contributes to the compact nebular emission. The expression for the Goldreich-Julian current (converted to a rate) from the pulsar polar caps is $I_{\text{GJ}}/e \sim (6E/c)^{1/2}/e$. The pair-creation multiplicity is $M$, as defined earlier.

Maximum particle energy constrained by gyroradius limit ($\epsilon = r_g/R_s$). PWN termination shock radius cancels out (Venter & de Jager 2006; de Jager & Djannati-Atai 2008)

\[ E_{\text{max}}(t) \approx \frac{e}{2} \sqrt{\frac{\sigma L(t)}{(1 + \sigma)c}} \]

\[ = (110 \text{ TeV}) \kappa \left( \frac{\epsilon}{0.2} \right) \left( \frac{\sigma}{0.1} \right)^{1/2} \hat{E}_{36}^{1/2} \]
Adding the effect of birth & braking index

Evolution of average field strength

• $L = 4.7 \times 10^{37} \text{ erg/s}$
• $R_{\text{PWN}} = 1.2 \text{ pc}; R_{\text{SNR}} = 3.3 \text{ pc}$
• Expansion age $870 \pm 200 \text{ yr} \Rightarrow P_0 = 55 \text{ ms}$ given $P = 61.8 \text{ ms}$.
• $\int (-\dot{E}) dt \approx 3.8 \times 10^{48} \text{ erg}$ for $L_0 = 1.1 \times 10^{38} \text{ erg/s}$.
• Requires $n \approx 0.6 \text{ cm}^{-3}$ to reproduce $R_{\text{SNR}} = 3.3 \text{ pc}$ after a kyr.
• Requires $8M_\odot$ ejecta mass to reproduce $R_{\text{PWN}}$ radius.
• Equipartition argument gives $E_{\text{min}} \approx 3.2 \times 10^{47} \text{ erg}$ (Bocchino et al. 2005) and $B_{\text{eq}} = 0.2 \text{ mG}$.
• H.E.S.S. observations give lower field strength (Djannati-Atai et al. 2007) $B \approx 25 \mu\text{G} \Rightarrow$ ten times lower than equipartition.
EVOLUTION MEAN FIELD STRENGTH IN PWN of G21.5-0.9
($L_0 = 10^{38}$ erg/s; $\tau = 3000$ yr; $M_{ej} = 8M_\odot$; $n_{ISM} = 0.6$ cm$^{-3}$)

$B \propto t^{-1}$
RADIATION SPECTRUM OF G21.5-0.9
B=25 µG (T/t); 70% Conversion Efficiency
However, Birth Period and Efficiency are correlated, but Birth Period and Age is also correlated!
- Pair production multiplicity: $2.2 \times 10^5 > M > 0.9 \times 10^5$
- Challenge for standard models?

H.E.S.S.: Djannati-Ataï et al. (2007)
XMM-Newton: Bocchino et al. (2005)
G21.5-0.9 PWN
(300 y)

ENERGY FLUX (erg/cm²/s)

CHANDRA

ISO

H.E.S.S.
(preliminary)

p₁=1.0

p₂=2.6

LOG₁₀(FREQUENCY/Hz)
Evolutionary parameters for SNR expansion into ISM with low density.
The Possenti et al. (2002)
$L_X$-Edot relationship – X-ray Evolution

G21.5-0.9
Low ISM Density
Hessels et al. (2008) TeV/Edot Conversion Efficiency – TeV Evolutionary Track
The **Calirometric-Relic** Effect

When the lifetime of radiating particles

\[ \tau(E_\gamma) \sim (4.8 \text{ kyr}) \left( \frac{B_\perp}{10^{-5} \text{ G}} \right)^{-2} E^{-1/2}_{\text{TeV}}. \]

\[ \tau(E_\gamma) \sim \frac{(100 \text{ kyr})}{[1 + 0.144(B\mu G)^2]E^{1/2}_{\text{TeV}}}, \]

exceeds the pulsar spindown timescale by a large amount

\[ \tau = \frac{3Ic^3}{\Omega_i B_{ns}^2 R_{ns}^6 \sin^2 \alpha}, \]

The apparent conversion efficiency may exceed 100%

If the neutron star surface field strength times the birth rotational frequency is large enough, the pulsar spins down rapidly and may leave an **Unidentified Gamma-Ray Source** with uninteresting pulsar counterpart!
KES 75 (Djannati-Atai et al. 2007)

- $R_{\text{PWN}} = 0.6d_6 \text{ pc}; R_{\text{SNR}} = 2.8d_6 \text{ pc}$
- Requires $n \approx 20 \text{ cm}^{-3}$ (Leahy & Tan 2007)
- $R_{\text{PWN}} / R_{\text{SNR}} \Rightarrow P_0 = 80 - 100 \text{ ms}$ (van der Swaluw & Wu 2001)
- $T_{\text{age}} \approx 800 \text{ yr.}$
- $\int (-\dot{E}) dt \approx 2 \times 10^{48} \text{ erg for } L_0 = 8 \times 10^{38} \text{ erg/s.}$
- H.E.S.S. observations give field strength below equipartition $B \approx 15 \mu \text{G}$ or $W_B = 2 \times 10^{44} \text{ erg}$ (Djannati-Atai et al. 2007; Ng et al. 2008).
Time dependent injection model for MWL spectrum of KES 75 – Observed radio flux consistent with $P_0 = 80$ ms and H.E.S.S. determined field strength. Intrinsic break energy 40 GeV – consistent with X-ray and VHE gamma-ray observations.
Time dependent model for MWL spectrum of KES 75. Radiation break energy smeared by variable field strength.

35% Conversion efficiency of spindown power to leptons.
KES 75 Results

- Energy in field: \( W_B = 2 \times 10^{44} \text{ erg} \) (same as Ng et al. 2008)
- Total particle energy of \( W_E = 3.4 \times 10^{47} \text{ erg} \approx 0.17 \int (-\dot{E}) \, dt \) (some fraction lost to radiation). Clearly particle dominated, unlike Crab Nebula! Small avg. sigma.
- Total number of leptons: \( N_e > 8 \times 10^{48} \) (1 GHz radio frequency lower limit from 1 GeV \( e^\pm \))
- Integrated number of Goldreich Julian pairs: \( N_{GJ} = 1.6 \times 10^{44} \)
- Pair production multiplicity (upper limit from electron energy lower limit of 1 MeV): \( 2.5 \times 10^5 > M > 2.4 \times 10^4 \)
Conclusions

- GeV-TeV emission gives us a handle on macroscopic evolutionary quantities.
- Wide FoV X-ray surveys important.
- Pair production multiplicities are $2.5 \times 10^5 > M > 2.4 \times 10^4$ for KES 75 and $2.2 \times 10^5 > M > 0.9 \times 10^5$ for G21.5-0.9 are exceptional.
- Density of ISM has an impact on the evolution of X-ray to VHE gamma-ray luminosity.
- Some unidentified TeV sources may be old PWN with
  - Relatively high $B_{NS}/P_0$ (calirometric relic effect) and
  - Low ISM density