Evolved Pulsar Wind Nebulae as Sources of (Mostly Leptonic) Cosmic Rays

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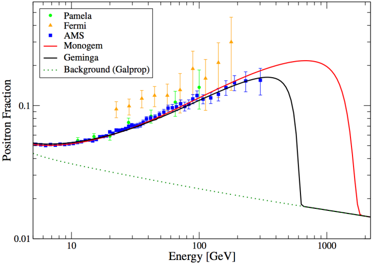
Cosmic Ray Origin – beyond the standard models
San Vito di Cadore, September 22, 2016

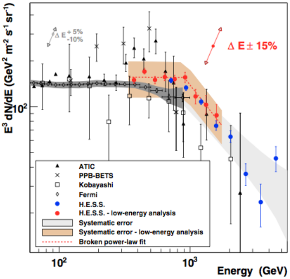
Cosmic-ray positrons and PWNe
PWN evolution and $e^{\pm}$ energy losses
PWN population seen in TeV γ-rays
High-energy hadrons in PWNe

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
- purely SNR origin unlikely; DM signature? (→ M. Malkov)
- **pulsars** proposed as cosmic $e^{\pm}$ sources by Aharonian et al. (1995), Chi et al. (1996), Zhang & Cheng (2001)…

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 (but actual mechanism poorly understood; → M. Lemoine)
2. high-energy $e^{\pm}$ are **confined** in PWN, cannot readily escape PWN & SNR and propagate as cosmic rays in the ISM;

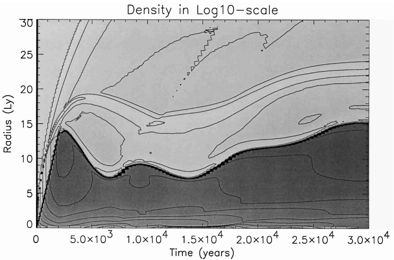
   requires consideration of **adiabatic** and **synchrotron** losses during PWN evolution; full description very complicated

How bad can it be?

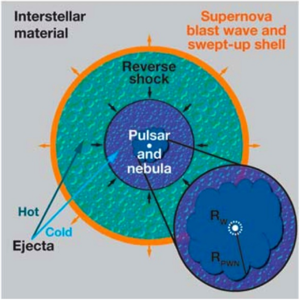
- here: quantify effect of adiabatic and synchrotron losses, assuming $e^{\pm}$ remain confined in PWN until it dissipates in ISM (i.e. neglect **diffusive** escape from PWN and SNR)
- build on recent modelling of PWN spectral evolution (Zhang et al. 2008, Gelfand et al. 2009, Tanaka & Takahara 2010+,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

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)

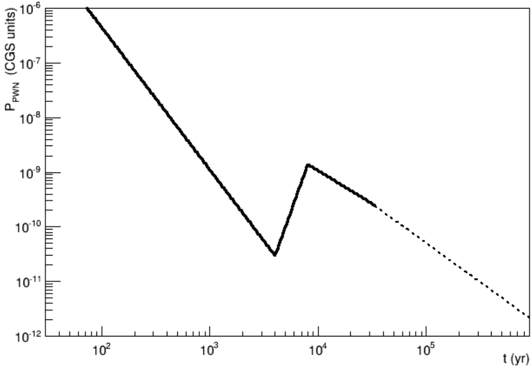


(Gaensler & Slane 2006)

- 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, $t_{\rm rs} \approx 4\,{\rm kyr}$



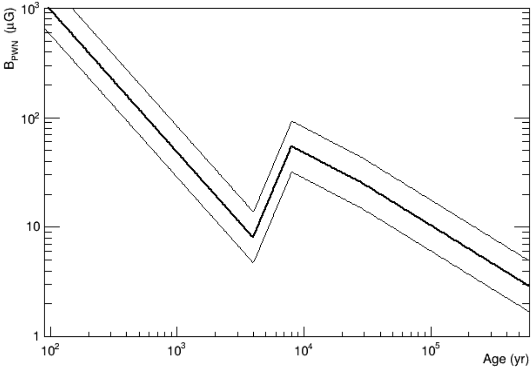
compression phase,

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

Synchrotron losses : magnetic field evolution

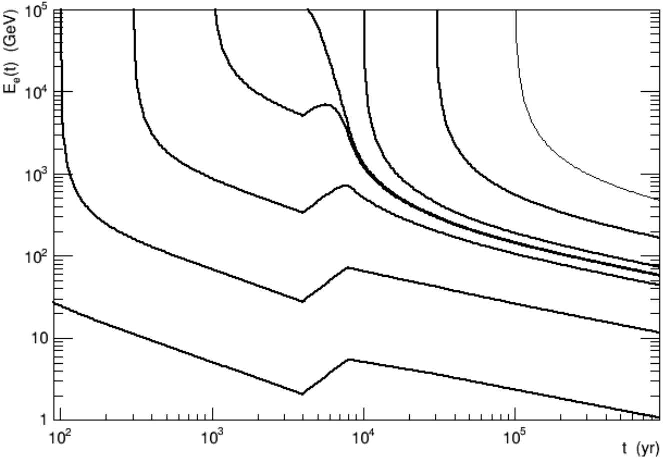
- magnetic field and relativistic gas have same energy density behavior in expansion and compression ⇒ magnetic fraction η conserved (when radiative losses dynamically unimportant)



- $\eta = 0.03$ (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 $\log t_{\rm inj} = 1.5, 2, 2.5, \ldots, 5$



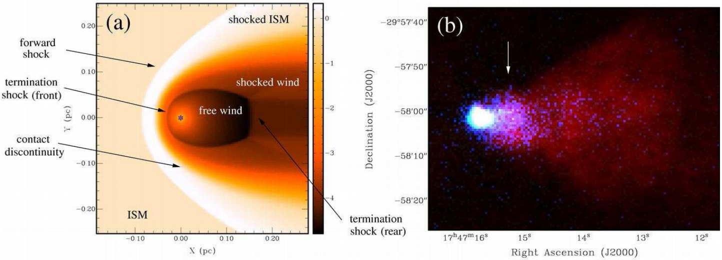
- early synchrotron burn-off: $e^\pm$ w/$t_{\rm inj} \lesssim 100\,$yr don't contribute
- compression phase burns off earlier $e^\pm$ to $E_f \lesssim 50\,$GeV

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

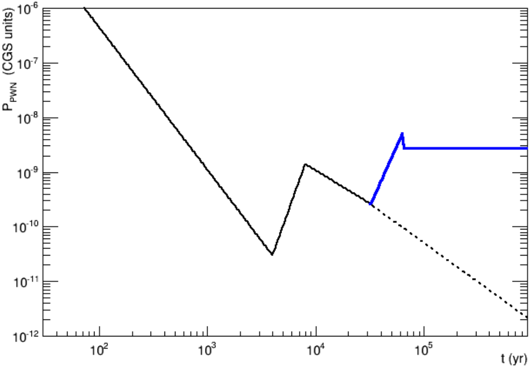
“Mouse” in X-rays and radio

(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:

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

- fast advection from high-B region ⇒ fewer radiative losses

Summary on PWNe as $e^{\pm}$ sources

- 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 $E_f \lesssim 50\,\mathrm{GeV}$: only late PWN phases contribute to high-energy CR $e^{\pm}$
- synchrotron losses less critical for bow-shock phases: higher post-shock B, but rapid advection (→ Blasi & Amato 2010)

- *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

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

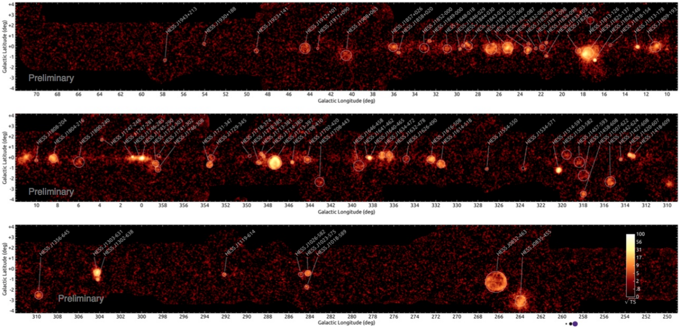
- **TeV**: use Earth's atmosphere as detector, through Cherenkov light from electromagnetic shower (on dark, moonless nights)
- past decade(+) : current generation of *Imaging Atmospheric Cherenkov Telescope* (IACT) experiments
- large mirrors, fine pixels, stereo technique ⇒ high sensitivity

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)

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)

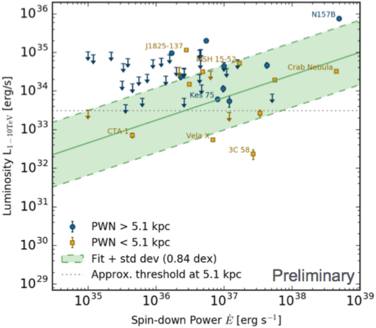
- currently $\gtrsim$100 Galactic TeV sources known (78 in HGPS)
- $\sim$30% identified as pulsar wind nebulae (PWNe) or candidates (H.E.S.S PWN population paper *submitted*; here preliminary results)

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 $\dot{E}$

(Klepser et al. 2016; H.E.S.S., submitted)

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

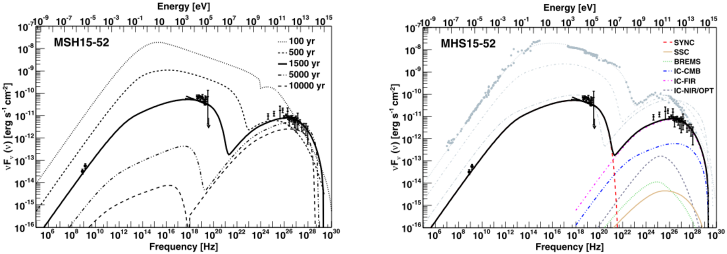


- little correlation with $\dot{E}$, unlike L_X (Grenier 2009, Mattana+ 2009)
- add HESS GPS upper limits $\Rightarrow$ faintening trend significant (Klepser et al. 2016; H.E.S.S., submitted)
- TeV γ-rays reflect history of injection since pulsar birth, whereas X-rays trace recently injected particles

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

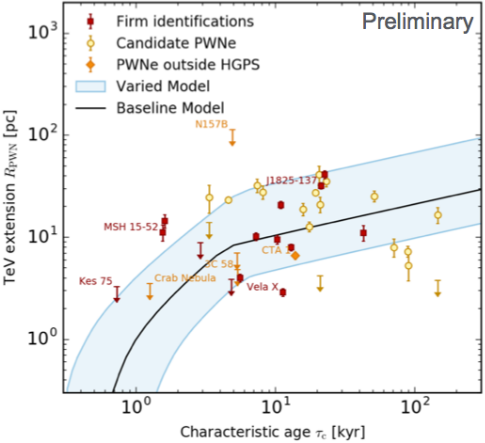


- L_X/L_γ ratio evolution dominated by B-field decrease with age

- main target photons for Inverse Compton are Galactic far-IR

PWN TeV size evolution

- significant trend of expansion with characteristic age



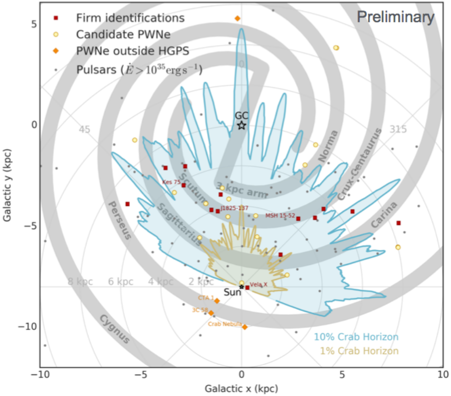
(Klepser et al. 2016; H.E.S.S., submitted)

- 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. 2016; H.E.S.S., submitted)

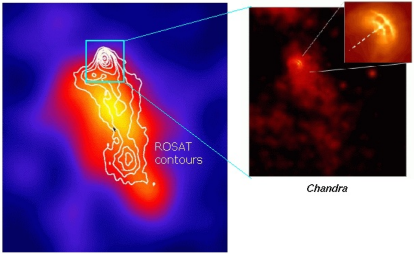


- HESS GPS detectability quite good to Scutum-Crux (Centaurus) arm
- deficit of TeV-emitting PWNe in Sagittarius-Carina arm?
- PWNe in outer Galaxy (Vela X, 3C 58...) have low luminosities

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

Older, “offset” PWNe

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

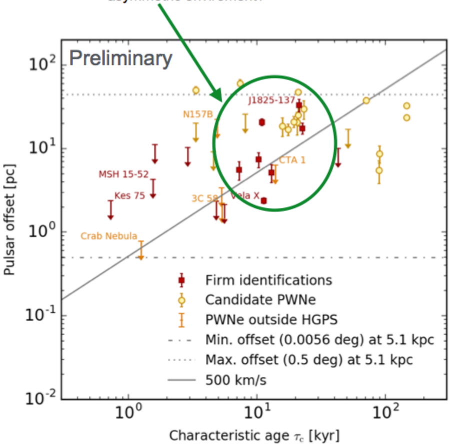


- IC emission $\propto$ (approximately uniform) target photon density $\Rightarrow$ direct inference of spatial distribution of electrons
- fainter emission from whole radio nebula (HESS 2012)
- compact X-ray nebula not conspicuous in TeV γ-rays $\Rightarrow$ torii and jets bright in X-rays because of 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

Offset through crushing or
asymmetric enviroment?

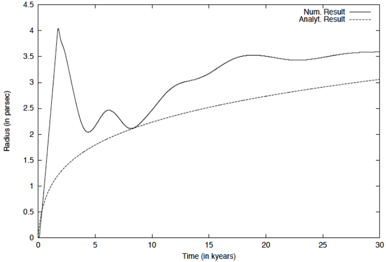


(Klepser et al. 2016; H.E.S.S., submitted)

- 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. . .

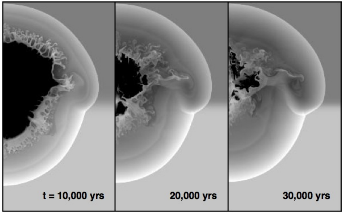
PWNe in older composite SNRs

- 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
- 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

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

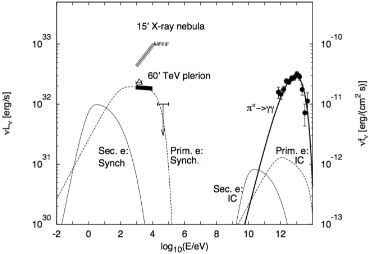
TeV PWN sizes and offsets

- 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?

Accelerated hadrons in Pulsar Wind Nebulae

- for one sign of $\boldsymbol{\Omega} \cdot \boldsymbol{B}_*$, ions ($Fe$) can be extracted from neutron star surface at polar caps
- ion component in relativistic wind generally minor by number, but can be dominant in energy (depending on *multiplicity*)

- Horns et al. (2006) proposed dominantly hadronic TeV γ-ray emission in Vela X
- but required density unrealistically high (LaMassa et al. 2008)

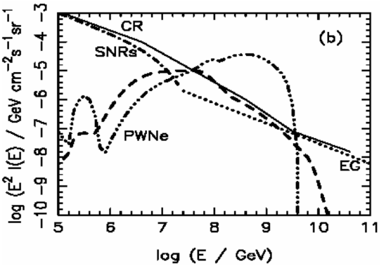


- prediction of hadronic scenario: accompanying neutrinos

- Di Palma, Guetta & Amato (2016) predicted neutrino flux for ∼30 PWNe and candidates, based on TeV γ-ray flux
- Vela X and MSH 15-52 predictions near IceCube upper limits
- Crab dominantly leptonic; KM3Net could constrain “cold” or power-law wind ions

(Hadronic) Cosmic Rays from PWNe?

- nuclei (*Fe*) from neutron star can be accelerated to high energies
- but number of such nuclei limited to *Goldreich-Julian* flux ⇒ cannot account for bulk of Galactic cosmic rays $\lesssim 10^{16}$ eV
- PWN evolution yields very hard spectrum ($dN/dE \propto E^{-1}$)
- best model from Bednarek & Bartosik (2004): dashed line
- predicts increasingly heavy composition above ∼3 PeV knee



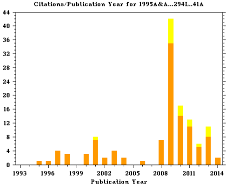
- possible origin for ∼100 PeV "second knee" component
- *Caveat:* depends sensitively on distribution of birth periods P_0
- **UHECRs** for $P_0 \sim 1$ ms (Blasi et al. 2000; → M. Lemoine)
- *Caveat:* no evidence for (non-recycled) pulsars with $P_0 \lesssim 10$ ms (Perna et al. 2008; Medvedev & Poutanen 2013)

Supplementary slides

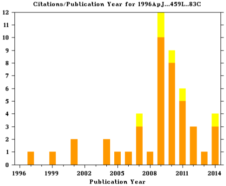
Primary $e^\pm$ from pulsars?

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

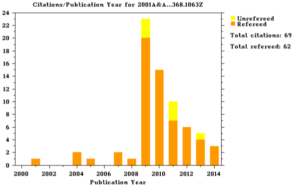
Aharonian et al. (1995)



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…

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

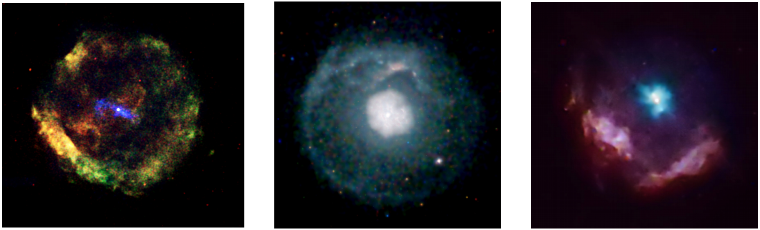
Pulsar birth velocity

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

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