Constraining pulsar birth properties with supernova X-ray observations

(work in progress)

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Pulsars and their Wind Nebulae in Supernovae

- inferred Galactic radio pulsar birth rate a large (dominant?) fraction of the Galactic core-collapse supernova rate ⇒ many (most?) ccSNe produce a rotation-powered pulsar

- fast-spinning pulsars/magnetars proposed to power certain types of supernovae, but such scenarios lack an unambiguous observational signature (e.g. Chevalier 2010, and refs. therein)

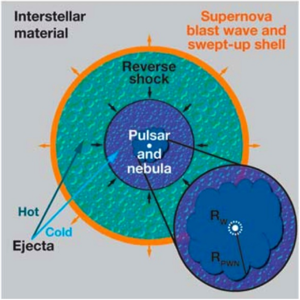
- radio pulsar population synthesis studies (e.g. Faucher-Giguère & Kaspi 2006) suggest log-normal distribution of neutron star surface magnetic field B_*, with $\langle \log B_* \rangle \approx 12.5 \pm 0.5$
- their (FK06) "optimal" model has Gaussian distribution of initial rotation periods P_0, with mean 300 ms and spread 150 ms…
- but distribution "loses memory" of P_0 after $t_{\mathrm{age}} \sim \tau_0 \sim$ kyr

⇒ Model "very young" Pulsar Wind Nebulae

- build on recent modelling of (young) PWN spectral evolution (Zhang et al. 2008, Gelfand et al. 2009, Tanaka & Takahara 2010+, Bucciantini et al. 2011, Torres et al. 2013+…)

"Free expansion" phase of (very) young PWNe

- model PWN as **isobaric bubble** of relativistic $e^{\pm}$ and B
- powered by pulsar wind, carrying the spin-down power $\dot{E}$
- ejecta assumed uniform, with $M_{\rm ej} \simeq 5\,M_{\odot}$, $E_{\rm ej} \simeq 10^{51}$ erg



- solution for constant $\dot{E}$:

  $P_{\rm pwn} \propto \dot{E}^{2/5}\, t^{-13/5}$
- constant magnetic energy fraction η: $\dfrac{B_{\rm pwn}^2}{8\pi} \equiv \eta\, u_{\rm pwn}$

  (if radiative losses negligible)
- median for 9 young PWNe:

  $\eta \approx 0.03$ (Torres et al. 2014)

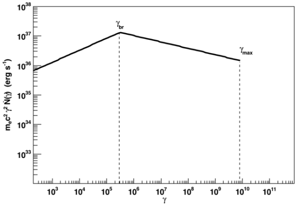
- $$\Rightarrow \quad B_{\rm pwn} \approx 0.4\ {\rm G} \times \sqrt{\frac{\eta}{0.03}} \left(\frac{E_{\rm ej}}{10^{51}\ {\rm erg}}\right)^{-0.45} \left(\frac{t}{\rm yr}\right)^{-1.3}$$
- consequences for $e^{\pm}$ acceleration and synchrotron spectrum?

Accelerated particle spectrum

- $e^\pm$ from pulsar wind accelerated to a broken power law spectrum
- from observations of Crab Nebula, etc., $\gamma_{\rm max}$ set by $t_{\rm cool} \gtrsim t_{\rm gyro}$
- $\Rightarrow$ in very young PWNe,

$$t_{\rm gyro}(\gamma_{\rm max}) \approx 27{\rm s} \left(\frac{t}{\rm yr}\right)^{1.95}$$

- faster than dynamical time



Injection break energy

- $\gamma_{\rm br} \simeq 3 \times 10^5$ is median from 9 PWN models (Torres et al. 2014)
- no trend with age or other parameters (e.g. Bucciantini et al. 2011)
- corresponding synchrotron (injection) break energy:

$$h\,\nu_{\rm br} \;\approx\; 0.18\ {\rm keV} \times \sqrt{\frac{\eta}{0.03}}\; \left(\frac{E_{\rm ej}}{10^{51}\ {\rm erg}}\right)^{-0.45} \left(\frac{t}{\rm yr}\right)^{-1.3}$$

- injected (uncooled) particle spectral indices below and above break: $p_1 \approx 1.5$, $p_2 \approx 2.5$ (median values from Torres et al. 2014)

Emerging synchrotron spectrum

- synchrotron cooling break (where $t_{\rm cool} = t$):

$$\nu_{\rm cool} \approx 1.2 \times 10^{10}\ {\rm Hz} \times \left(\frac{\eta}{0.03}\right)^{-1.5} \left(\frac{E_{\rm ej}}{10^{51}{\rm erg}}\right)^{1.35} \left(\frac{t}{\rm yr}\right)^{1.9}$$

- $\nu_{\rm cool} \ll \nu_{\rm br}$: essentially all accelerated particle energy quasi-instantaneously radiated away, with νF_ν peak at $\nu_{\rm br}$
- with above indices, $\nu F_\nu \big|_{\nu_{\rm br}} \approx \frac{1}{8}\,\dot{E} \quad (\text{for } \eta \ll 1)$
- fraction in X-rays: $L_{2-10\,{\rm keV}} \approx 0.09\ \dot{E}\ (t/{\rm yr})^{-0.325}$

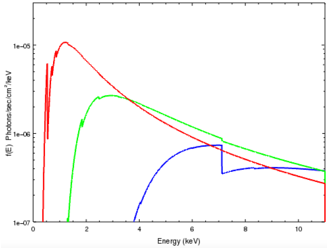
X-ray absorption in the ejecta

- absorption column:

$$N_{\rm H} = 4.3 \times 10^{24}\ {\rm cm}^{-2} \times \left(\frac{M_{\rm ej}}{5\,M_\odot}\right)^2 \left(\frac{t}{\rm yr}\right)^{-2}$$

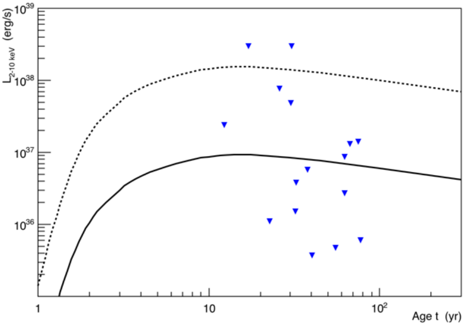
- emerging X-ray spectrum at $t = 3$, 10 and 30 yr
- emerges earlier in hard X-rays

phabs ⋆ power law



Constraints on $\dot{E}_0$ from observations

- Perna et al. (2008) obtained upper limits (and detections) for supernova X-ray fluxes from archival observations
- compare with predicted emerging 2-10 keV X-ray fluxes
- N.B. Non-emerging PWN flux is deposited in the ejecta



- late-time (>10 yr) type IIP upper limits:
  - conflict with $\dot{E}_0 = 3 \times 10^{38}$ erg/s in ∼50% of SNe
  - conflict with $\dot{E}_0 = 5 \times 10^{39}$ erg/s in ∼90% of SNe

Inferred constraints on pulsar birth periods P_0

- standard pulsar spindown:

$$\dot{E} \equiv 3.3 \times 10^{40}\,\mathrm{erg/s} \left(\frac{B_*}{3 \times 10^{12}\,\mathrm{G}}\right)^2 \left(\frac{P}{10\,\mathrm{ms}}\right)^{-4}$$

- for typical $B_* = 3 \times 10^{12}$ G, above limits on $\dot{E}_0$ imply that $P_0 \gtrsim 30$ ms in ∼50%, and $P_0 \gtrsim$ **15 ms** in ∼90% of SNe

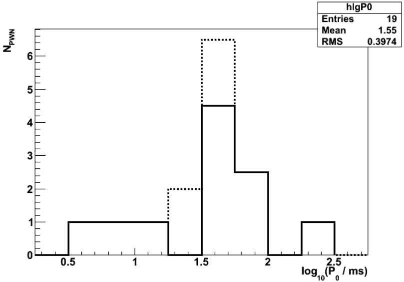
Other approaches

- number of ultra-luminous X-ray sources in external galaxies (Medvedev & Poutanen 2013, and refs. therein): $\langle P_0 \rangle \gtrsim 10$–$40$ ms
- *Caveat:* depends on assumed L_X vs. $\dot{E}$ for young PWNe
- viability of short-P_0 pulsars as sources of UHE cosmic rays?

- detailed models of young PWNe with synch. and IC spectra
- e.g. Torres et al. (2013, 2014; also Martín et al. 2014)
- *Caveat:* assume all modeled PWNe are in free expansion

Constraints on pulsar birth periods P_0 (II)

- obtain P_0 from parameters L_0, τ_0 and n (with $I = 10^{45}$ g cm^2) [solid: w/TeV, Torres et al. (2014); dashed: + Martín et al. (2014)]



- small number, but logarithmic mean, or median, $P_0 \approx$ **40 ms**
- suggests a “1-σ” range approximately 15–100 ms

- could there be a significant population of young SNRs with “inconspicuous” slower-rotating pulsars and their nebulae?
- unlikely: census of young (< 3 kyr) core-collapse SNRs (Chevalier 2005) shows essentially all to have neutron stars: pulsars, **magnetars** or other *central compact objects* (CCOs)

Magnetars in SNe

- Magnetars (neutron stars with $B_* \sim 10^{14} - 10^{15}$ G, as inferred from spin-down) found in some young supernova remnants

- **if** also born with very short periods ($P_0 \sim$ few ms), could (help) power some classes of super-luminous supernovae
- fast spin coupled with high magnetic field expected in dynamo theory of magnetar formation (Duncan & Thompson 1992)

- fast-spinning magnetars proposed as sources of ultra-high-energy cosmic rays (UHECRs) (e.g. Blasi et al. 2000, Arons 2003, Fang et al. 2012, 2013…)

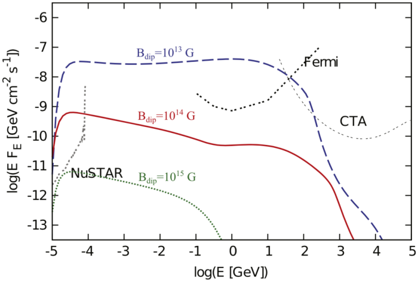
- but with magnetic dipole spindown, memory of initial period lost after spin-down time:

$$\tau_0 \approx 180\,\mathrm{yr} \left(\frac{B_*}{3\times10^{12}\,\mathrm{G}}\right)^{-2} \left(\frac{P_0}{10\,\mathrm{ms}}\right)^{2}$$

- for standard pulsars, $\dot{E}$ approximately constant for decades, but for $B_* \sim 3\times10^{14}$ G, decays in $\tau_0 \sim$ days, or less for short P_0's

Early spin-down of magnetars

- for $t \gg \tau_0$, spin-down history purely determined by B_*
- larger B_* implies earlier spin-down, lower $\dot{E}$ at given time
- fast magnetars deliver large energy early, deposit most in ejecta



predicted spectra
at $t \approx 1$ yr,

for $P_0 = 2$ ms

(Murase et al. 2015)

- are PWN spectral models applicable to magnetars (MWNe)?
- not usually observed around magnetars → talk by D. Torres
- if so, Murase et al. (2015) predict possibly detectable hard X-ray synchrotron emission (and IC emission, for low enough B_*)

Summary and conclusions

Standard pulsars ($B_* \sim 10^{12} - 10^{13}$ G)

- extrapolating models of young pulsar wind nebulae back to SNe,
- efficient radiation of spin-down power around X-ray energies
- for $t \lesssim$ few years, absorbed in ejecta (power for light curve)
- at $t \gtrsim$ few years, X-ray emission detectable for short P_0 pulsars
- available limits consistent with $\langle P_0 \rangle \approx$ **40 ms**, with typical spread about $15 - 100$ ms ($P_0 \lesssim 15$ ms for $\lesssim 10\%$ of cases)

Magnetars ($B_* \sim 10^{14} - 10^{15}$ G)

- higher B_* implies much earlier spin-down ($\sim$ days) after birth
- well before ejecta become transparent to X-rays and below
- young magnetar wind nebulae may be detectable in hard X-rays