Broadband Emission of Magnetar Wind Nebulae

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Contents

1. Introduction

2. Spectral Evolution of young PWNe

3. A Spectral Model of MWNe
Pulsars in PWNe

- Pulse lumi. ~ a few % × \( L_{\text{spin}} \)
  Most of \( L_{\text{spin}} \) releases as pulsar wind!
- ~ 50 of 2000 pulsars have observable PWNe. \((L_{\text{spin}} > 10^{36}\text{erg/s})\)
- Bow-shock PWNe are around MSP of \( L_{\text{spin}} < 10^{36}\text{erg/s} \)

How about other classes of pulsar?
Magnetar Wind Nebulae?

PWNe are found around High-B radio pulsar.

<table>
<thead>
<tr>
<th>PSR</th>
<th>SNR?</th>
<th>$P$[s]</th>
<th>$\dot{P}$[s/s]</th>
<th>$B$[G]</th>
<th>$L_{\text{spin}}$[erg/s]</th>
<th>$\tau_c$[kyr]</th>
<th>Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E 1547.0-5408</td>
<td>G327.2-0.1</td>
<td>2.07</td>
<td>$2.32 \times 10^{-11}$</td>
<td>$2.2 \times 10^{14}$</td>
<td>$1.0 \times 10^{35}$</td>
<td>1.4</td>
<td>45</td>
</tr>
<tr>
<td>J1834.9-0846</td>
<td>W41 ?</td>
<td>2.482</td>
<td>$8.06 \times 10^{-12}$</td>
<td>$1.4 \times 10^{14}$</td>
<td>$2.1 \times 10^{34}$</td>
<td>4.9</td>
<td>$70 \times 150''$</td>
</tr>
<tr>
<td>J1819-1458</td>
<td>-</td>
<td>4.26</td>
<td>$5.76 \times 10^{-13}$</td>
<td>$5.0 \times 10^{13}$</td>
<td>$2.9 \times 10^{32}$</td>
<td>117</td>
<td>$\sim 13''$</td>
</tr>
<tr>
<td>J1846-0258</td>
<td>Kes 75</td>
<td>0.324</td>
<td>$7.1 \times 10^{-12}$</td>
<td>$4.8 \times 10^{13}$</td>
<td>$8.3 \times 10^{36}$</td>
<td>0.7</td>
<td>40</td>
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<tr>
<td>J1119-6127</td>
<td>G292.2-0.5</td>
<td>0.408</td>
<td>$4.02 \times 10^{-12}$</td>
<td>$4.1 \times 10^{13}$</td>
<td>$2.3 \times 10^{36}$</td>
<td>1.7</td>
<td>6 $\times 15''$</td>
</tr>
</tbody>
</table>

One of young TeV PWN around high-B radio pulsar

**Observed extended emission may be dust-scattering halo for 1E1547.0**

↑ (e.g., Olausen+11)

**MWN candidate**

**HBP(1s) detected**

AXP 1E1547.0-5408

Vink & Bamba09

Kes 75
(PSR J1846-0258)

Kumar & Safi-Harb08

Safi-Harb13
Magnetar Wind

- Magnetars have large surface B-field (\(> 3 \times 10^{14}\text{G}\)) and some have \(L_x > L_{\text{spin}}\) → B-powered emission? e.g., Thompson & Duncan 95

- Magnetars have \(\dot{P}\) → Angular momentum loss!!

Wind loss
\[
\dot{M}_{\text{wind}} \approx R_{LC} \frac{L_{\text{wind}}}{c} \quad \left( = \frac{L_{\text{spin}}}{\Omega} \text{ for RPP} \right)
\]

Photon loss
\[
\dot{M}_{\text{ph}} \approx (R_{NS} + \lambda) \frac{L_{\text{ph}}}{c}
\]

Even \(L_x > L_{\text{spin}}\), wind angular momentum loss would dominate for magnetars from this simple estimate.
What We Learn from MWN

- PWN spectrum tells us spin evolution of pulsar
  $\Rightarrow$ How about MWN?
    - Does a millisecond magnetar exist?

- Difference of wind properties from rotation powered pulsar (RPP).
  - magnetization: $\sigma$? pair multiplicity: $\kappa$?

- Testing fall-back disk model of magnetar. e.g., Chatterjee+00
  - Disk model does not produce MWN because no wind flows out from magnetosphere.

References:
Thompson & Duncan 1993
Rea et al. arXiv:1510.01430
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Spectral Evolution Model

- PWN as uniform sphere
- Constant rate of Expansion applicable to young \(\ll 10\text{kyr}\) PWN
  \[ R_{\text{PWN}} = V_{\text{PWN}} \times t \]
- Introduce a parameter \(\eta\) satisfies (no hadron)
  \[ L_{\text{spin}} = L_{e^\pm} + L_B = (1 - \eta) L_{\text{spin}} + \eta L_{\text{spin}} \]
- B-field evolution as energy conservation
  \[ \int_0^t L_B(t') dt' = \frac{4\pi}{3} R_{\text{PWN}}^3 \frac{B^2(t)}{8\pi} \]

Total magnetic energy injected

Magnetic energy inside PWN
Spectral Evolution Model

- Injection of non-thermal $e^\pm$ plasma (broken power-law)

$$(1-\eta)L_{\text{spin}} = L_{e^\pm} = \int Q_{\text{inj}} \gamma mc^2 d\gamma$$

- Evolution of energy distribution of $e^\pm$

$$\frac{\partial}{\partial t} N(\gamma, t) + \frac{\partial}{\partial \gamma} \dot{\gamma}(\gamma, t)N(\gamma, t) = Q_{\text{inj}}(\gamma, t)$$

Calculate Syn. & IC spectral evolution
Crab

Most observed & studied object (one parameter $\eta$)

- Observed flux@1kyr
  $\eta \sim 5 \times 10^{-3}$ (85 $\mu$G)

- SSC dominates in $\gamma$-rays.

- Flux evolution is consistent.

Model can reproduce observations
Young PWNe

Applicable to other young PWNe < 10 kyr

One-zone model is enough to get
- mean B-field inside PWN.
- spin-evolution of central pulsars
- predictions to γ-ray flux
- η ~ 10^{-3} for all except for Kes 75
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Simplified One-zone Model

- Spin-down evolution
- Expansion of MWN
- B-field inside MWN
- $e^{\pm}$ injection

\[ t_c = \frac{n-1}{2}(t_{\text{age}} + \tau_0) \approx \frac{n-1}{2}t_{\text{age}} \]

\[ L_{\text{spin}}(t) \approx L_{\text{spin,now}} \left( \frac{t}{t_{\text{age}}} \right)^{-\frac{n+1}{n-1}} \]

\[ R(t) = R_{\now} \left( \frac{t}{t_{\text{age}}} \right)^{\alpha_R} \]

\[ B(t) = B_{\now} \left( \frac{t}{t_{\text{age}}} \right)^{\frac{\alpha_B}{2}} \]

-1.2 < $\alpha_R$ < -1.0, -5 < $\alpha_B$ < -3 from past studies (e.g., Gelfand+09, Tanaka&Takahara10, 11, 13, Bucciantini+11)

\[ L_{e^{\pm}}(t) \sim L_{\text{spin}}(t) \]

$e^{\pm}$ energy distribution

\[ \frac{\partial}{\partial t} n(\gamma, t) + \frac{\partial}{\partial \gamma} \gamma n(\gamma, t) = Q(\gamma, t) \]

adiabatic + synchrotron + inverse Compton coolings
Kes 75

Young RPP with magnetar-like activity

\[ L_{\text{spin}} = 8 \times 10^{36} \text{erg/s}, \quad B_{\text{NS}} = 4.8 \times 10^{13} \text{G}, \quad \tau_c = 0.7 \text{kyr} \]

<table>
<thead>
<tr>
<th></th>
<th>model 1</th>
<th>model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d )</td>
<td>6kpc</td>
<td>10.6kpc</td>
</tr>
<tr>
<td>( \tau_0 )</td>
<td>0.2kyr</td>
<td>3yr</td>
</tr>
<tr>
<td>( E_{\text{rot}} )</td>
<td>( 1.5 \times 10^{48} \text{erg} )</td>
<td>( 2.1 \times 10^{50} \text{erg} )</td>
</tr>
<tr>
<td>( B_{\text{PWN}} )</td>
<td>20 ( \mu \text{G} )</td>
<td>24 ( \mu \text{G} )</td>
</tr>
<tr>
<td>( \eta )</td>
<td>( 5 \times 10^{-5} )</td>
<td>( 6 \times 10^{-6} )</td>
</tr>
</tbody>
</table>
AXP 1E1547.0-5408

Assuming \((u_{IR}, u_{opt}) = (1.0, 2.0) [eV/cc]\)

\[L_{spin} = 1 \times 10^{35} \text{erg}, \quad B_{NS} = 2.2 \times 10^{14} \text{G}, \quad \tau_c = 1.4 \text{kyr}\]

- Results are insensitive to \(\alpha_B \& \alpha_R\).
- X-ray upper limit gives constraints \(B_{\text{now}} < 25 \mu G\).
- CTA would detect MWN around 1E1547.0 when \(B_{\text{now}} < 3 \mu G \& u_{IR} > 1.0 \text{eV/}cc\)
  - larger value is expected
- \(\eta < 10^{-3}\) is consistent with Kes 75.
- \(P_0 < 100 \text{msec}\) is presumed.
Summary

- Pulsar & Pulsar Wind Nebula
  - Most of $L_{\text{spin}}$ lost by pulsar wind
  - $\sigma$- & $\kappa$- problem about physics of pulsar magnetosphere
  - One-zone model of PWNe tells us spin-evolution of central pulsars

- A Spectral model of MWNe
  - Angular momentum loss of magnetar $\Rightarrow$ magnetar wind?
  - Deep obs. of 1E1547.0 by CTA can examine the hypothesis.
  - $\eta \ll 10^{-3}$ is consistent with High-B radio pulsars.
  - Constraint on $P_0$ is not strong $< 100\text{msec}$
  - Detections of MWN in multi-wavelength are required to constrain magnetar evolution properties.