Evolution of Pulsar Wind Nebulae Inside Supernova Remnants

Collaborators:
Patrick Slane (CfA)
John Blondin (NCSU)
Christopher Kolb (NCSU)
Niccolo Bucciantini (INAF)
Jack Hughes (Rutgers)
Eli Dwek (GSFC)
Rick Arendt (GSFC)
Steve Reynolds (NCSU)
Kazik Borkowski (NCSU)
Yosi Gelfand (NYU Abu Dhabi)
Daniel Castro (GSFC)
Paul Plucinsky (CfA)
John Raymond (CfA)
George Sonneborn (GSFC)

Tea Temim
(NASA GSFC/UMCP)
Structure of a Composite SNR

Slane 2016
Evolutionary Stages

**Early evolution:** PWN drives a shock into the inner SN ejecta

\[ R_{PWN} \approx 1.5 E_0^{1/5} E_{SN}^{3/10} M_{ej}^{-1/2} t^{6/5} \]

(see Chevalier 1984)

**Late evolution:** PWN interacts with the SN reverse shock, usually asymmetrically (e.g., Blondin et al. 2001, van der Swaluw et al. 2004)

- Pulsar motion
- Non-uniform ISM

*Slane 2016*
What We Can Learn

- Young systems: PWNe sweeping-up SN ejecta
  - Probe SN ejecta (progenitor type and explosion mechanisms)
  - SN dust (origin of dust in galaxies, high $z$)
- Older systems: PWNe interacting with the SNR reverse shock
  - SN ejecta, ISM/CSM environment, explosion asymmetry
  - Injected particle population, fate of energetic particles, Galactic cosmic ray population
Crab Nebula: Ejecta & Dust

Based on $M_{ej} = 4.6 \, M_\odot$ and $v_{ej} = 1700 - 1800 \text{ km/s}$ (1200 km/s for the filaments) $\rightarrow$ low energy electron-capture SN with $E_{51} \sim 0.1$

Yang & Chevalier 2015

$M_d \sim 0.1 \, M_\odot$

- Most of the dust mass is in the larger grains $> 0.1 \, \mu m$

- Consistent with Type IIP SN - higher density and slower ejecta allow larger grains to form (e.g., Kozasa et al. 2009)

Mass and temperature of swept-up ejecta (Bocchino et al. 2001, Slane et al. 2004) and the presence of slow H-rich material (Fesen et al. 1988) suggest an age of ~ 2400 yr and a Type IIP progenitor, similar to the Crab (Chevalier 2005)
Emission lines broadened to 1000 km/s
PWN overtakes ejecta with $v_s \sim 25$ km/s

$\sim 20 \, M_\odot$ progenitor

*(Kim et al. 2013, Gelfand et al. 2015)*
G54.1+0.3

Dust composition: $\text{Mg}_{0.7}\text{SiO}_{2.7}$
($\text{MgO}/\text{SiO}_2 = 0.7$)

Same as in Cas A
(Arendt et al. 2014)

$M_d \leq 0.3 \, M_\odot$
$\Rightarrow$ 20 – 30 $M_\odot$ progenitor

Temim et al. 2016, in prep
G21.5-0.9: PWN-Shocked Ejecta

- SNR age < 1000 yr

- X-ray shell: dust scattering halo and synchrotron emission from particles accelerated by the forward shock.

- See new results from deep Chandra observations: Poster S3.2 (B. Guest)

e.g., Slane et al. 2000, Bocchino et al. 2005, Matheson & Safi-Harb 2010
G21.5-0.9: PWN-Shocked Ejecta

[Fe II] 1.64 μm (VLT/ISAAC)

Zajczyk et al. 2012
G21.5-0.9: *Herschel* Spectroscopy

- **[C II] 157 μm**

- Line at rest shown in blue $\rightarrow$ limb brightened emission from shocked ejecta
- Red and blue shifted line emission in red $\rightarrow$ line of sight shocked ejecta

Ejecta velocity = 400 km/s
Kes 75: First detection of SN ejecta

Pulsar age ~ 800 yr, among youngest in the Galaxy (Gotthelf et al. 2000)

Large SNR size/expansion velocity, and clumpy CSM are characteristic of a WR progenitor (e.g. Helfand et al. 2003)

MIPS 24 µm
Chandra X-ray
Kes 75: A dusty shell?

MIPS 24 μm
Chandra X-ray

Herschel 70 μm Chandra X-ray

Temim et al. 2016, in prep
Kes 75: *Herschel* Spectroscopy

[O I] 63.18 μm line, FWHM = 1000 km/s

Ejecta expansion velocity of ~ 500 km/s

Temim et al. 2016, in prep
Kes 75: *Herschel* Spectroscopy

Temim et al. 2016, in prep

Ejecta velocity of $\sim 500$ km/s

[O I] 63.18 $\mu$m line image

[O I] 63.18 $\mu$m line, FWHM = 1000 km/s

*Chandra, Herschel 70 $\mu$m*
Transitional Stage: Reverse Shock Reaching the PWN

G292.0+1.8
NASA/CXC/S.Park et al.
Distribution of ejecta knots puts RS at the boundary of the radio PWN
MSH 11-62
Slane et al. 2012

Age ~ 1200 yrs

PWN morphology and modeling of the system suggest that the reverse shock has begun compressing the PWN
G11.2-0.3
Borkowski et al. 2016

- Expansion rate $\rightarrow$ age = 1400 – 2400 yrs
- Possibly a stripped-envelope SN that swept up previously lost mass into dense shell

Radio PWN & thermal X-rays anticorrelated $\rightarrow$ RS has reheated all ejecta and compressed the PWN

400 ks Chandra image
Evolved Systems

Vela SNR

MSH 15-56

G327.1-1.1
SNR G327.1-1.1: Crushed PWN in an evolved SNR

X-ray (blue)
Radio (red)

$R_{\text{SNR}} = 8.5'$

Temim et al. 2009

Sedov
$(d = 9 \text{ kpc})$
$R = 22 \text{ pc}$
$n_0 = 0.12 \text{ cm}^{-3}$
Age = 17k yr
$T = 0.3 \text{ keV}$
$v_s = 500 \text{ km/s}$

$N_H = 2 \times 10^{22} \text{ cm}^{-2}$

$v_{\text{PSR}} = 400 \text{ km/s}$
Also a $\gamma$-ray source

Acero et al. (2011)
SNR G327.1-1.1: Crushed PWN in an evolved SNR

X-ray (blue)
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$R_{SNR} = 8.5'$

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Also a $\gamma$-ray source

Temim et al. 2009 (NASA/CXC/SAO)
Chandra 350 ks observation

X-ray emission from relic PWN, mixed-in ejecta

Thermal X-ray emission from SNR shell, $T = 0.3$ keV

Outflow ahead of the pulsar?

Higher $N_H$ in the west

T. Temim, P. Slane, C. Kolb, J. Blondin, J. Hughes, N. Bucciantini, 2015
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**HD Model of a PWN Expanding Inside a Supernova Remnant**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR Properties:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D$ (kpc)*</td>
<td>SNR distance</td>
<td>9.0</td>
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<tr>
<td>$R_{SNR}$ (pc)*</td>
<td>SNR radius</td>
<td>22</td>
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<tr>
<td>$v_s$ (km/s)*</td>
<td>Shock velocity</td>
<td>500</td>
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<tr>
<td>$t$ (yr)*</td>
<td>SNR age</td>
<td>17400</td>
</tr>
<tr>
<td>$n_0$ (cm$^{-3}$)</td>
<td>Average ambient density</td>
<td>0.12</td>
</tr>
<tr>
<td>$E_{51}$ ($10^{51}$ erg)</td>
<td>Explosion energy</td>
<td>0.5</td>
</tr>
<tr>
<td>$M_{ej}$ ($M_\odot$)</td>
<td>SN ejecta mass</td>
<td>4.5</td>
</tr>
<tr>
<td>PWN Properties:</td>
<td></td>
<td></td>
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<tr>
<td>$R_{PWN}$ (pc)*</td>
<td>PWN radius</td>
<td>5.0</td>
</tr>
<tr>
<td>$v_p$ (km/s)</td>
<td>Pulsar velocity</td>
<td>400 (north)</td>
</tr>
<tr>
<td>$L_{X(2-10)}$ (erg/s)</td>
<td>PWN X-ray luminosity</td>
<td>$7.2 \times 10^{34}$</td>
</tr>
<tr>
<td>$E_0$ (erg/s)</td>
<td>Initial spin-down luminosity</td>
<td>$2.8 \times 10^{38}$</td>
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<tr>
<td>$n$</td>
<td>Pulsar braking index</td>
<td>3.0</td>
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<tr>
<td>$\tau_0$ (yr)</td>
<td>Spin-down timescale</td>
<td>2000</td>
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<tr>
<td>$B$ ($\mu$G)</td>
<td>PWN magnetic field</td>
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<tr>
<td>Density Gradient:</td>
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<tr>
<td>$x$</td>
<td>Density contrast of 12.5</td>
<td>1.08</td>
</tr>
<tr>
<td>$H$ (pc)</td>
<td>Characteristic length scale</td>
<td>5.2</td>
</tr>
<tr>
<td>Orientation</td>
<td></td>
<td>East/West</td>
</tr>
</tbody>
</table>

Parameters in blue adjusted to produce the desired PWN morphology and SNR/PWN dimensions at the estimated SNR age of ~ 17,000 yr.

Time dependent pulsar spin-down power driving the PWN:

$$\dot{E} = \dot{E}_0 \left(1 + \frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$
SNR Age: 00200 yr

Pulsar velocity 400 km/s

ISM density gradient

Modified VH-1 (Blondin et al. 2001)
Morphology Comparison

Displacement of “relic” PWN → orientation of density gradient

Trail thickness → pulsar’s spin down luminosity

Orientation of trail → combination of gradient and pulsar motion direction

Temim et al. 2015
Broadband Spectrum of the PWN at 17,000 yrs

• Model for radiative evolution of the PWN - Gelfand et al. (2009)
• Input parameters from observational constraints and HD model
  → $B = 11 \mu G$ and an electron energy break at 300 GeV
Age of particles injected by the pulsar at SNR age of 17,000 yr

Photon index in the trail steepens from 1.76 to 2.28:
\[ \Delta \Gamma = 0.52 \pm 0.17 \]

Synchrotron lifetime \( \sim 1700 \) yr

\( \Rightarrow \) Expect spectral steepening of 0.5 over a synchrotron lifetime

Temim et al. 2015
Simulation shows mixing of ejecta and PWN gas throughout the disrupted nebula, consistent with observations (LaMassa et al. 2008)
New *Chandra* observation of the PWN region provides 15 yr baseline to measure the pulsar’s velocity

See Poster S1.4 (J. Devin) on γ-ray emission from MSH 15-56
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Conclusions

• Multi-wavelength observations of PWNe inside SNRs at various stages of evolution have significantly improved our understanding of composite SNRs

• Young PWN expanding into SN ejecta give insight into PWN/SNR dynamics, properties of the SN ejecta and dust, and nature of the SN progenitor

• New HD simulations of evolved systems give insight into the structure and evolution of composite SNRs and clues on what physical parameters determine the morphology of the systems → information about ambient ISM, SN ejecta, pulsar properties, energetic particle population

• Future studies combining HD and radiative evolution models with detailed observational constraints will improve our understanding of the PWN/SNR interaction
$M_d \geq 0.3 \ M_\sun$

Largest after SN 1987A

20 – 30 $M_\sun$ progenitor

Temim et al. 2016, in prep