Pulsar wind nebulae: X-ray and multiwavelength observations

Oleg Kargaltsev (University of Florida)
George Pavlov (Penn State University)
Brian Newman (Penn State University)
Zdenka Misanovic (Monash University)
Pulsar Wind Nebulae in Chandra era.

~60 PWNe have been resolved with Chandra to date (Kargaltsev & Pavlov 2008) but some are also found by XMM-Newton.

Subarcsec resolution and low ACIS background make Chandra ideal tool for studying PWNe.

A few nearby, bright PWNe with complex, well-resolved structures are suitable for spatially-resolved spectroscopy.
All active pulsars emit relativistic winds

\( c > c_s \rightarrow \text{shock forms} \)

Downstream of the shock:
subrelativistic flow of relativistic particles in magnetic field and radiation field (e.g. CMBR) \( \rightarrow \) **synchrotron** (radio through MeV) and **IC radiation** (GeV and TeV) \( \rightarrow \) PWN

**Typical parameters**

- Typical energy of synch. photon: \( E_{\text{syn}} = 2 \left( \frac{g}{2 \times 10^7} \right)^2 \left( \frac{B}{10 \, \mu G} \right) \text{ keV} \)

\[ E_{\text{IC}} = 10 \left( \frac{\varepsilon}{4 \times 10^{-4} \text{ eV}} \right) \left( \frac{E_{\text{syn}}}{1 \text{ keV}} \right) \left( \frac{B}{10 \, \mu G} \right)^{-1} \text{ TeV} \]

- Characteristic size: \( R_s = 0.2 \left( \frac{\dot{E}}{10^{37} \text{ erg/s}} \right)^{1/2} \left( \frac{p_{\text{amb}}}{10^{-10} \text{ dyn/cm}^2} \right)^{-1/2} \text{ pc} \)

- Synchrotron cooling time: \( t_{\text{syn}} \sim 1 \left( \frac{E_{\text{syn}}}{1 \text{ keV}} \right)^{-1/2} \left( \frac{B}{10 \, \mu G} \right)^{-3/2} \text{ kyr} \)

- Luminosity: \( L = \eta \dot{E}, \ \eta < 1 \) (efficiency, \( \eta \), depends on wind parameters and outflow geometry; \( \eta_x \sim 10^{-5} - 10^{-1} \) from observations).
Termination shock and PWN shapes depend on pulsar velocity and intrinsic outflow anisotropy.

**Subsonic velocity:**

*Isotropic outflow:* sphere

*Anisotropic outflow:* equatorial + polar = torus + jet(s)

**Supersonic velocity:**

*Isotropic outflow:* bow shock + tail

*Anisotropic outflow:* equatorial + polar = umbrella-like termination shock + structured tail

Real examples will follow…

Del Zanna et al. (2006)

TS – termination shock
CD – contact discontinuity
FS – forward shock
Torus-jet PWNe

In some cases structures are more complex than just torus and jets…
Torus-jet PWNe: Crab

Notice the innermost ring inside the torus: termination shock is resolved by Chandra and HST.

Torus-jet structures are dynamic especially in the vicinity of the termination shock …
Torus-jet PWNe: Vela

Size: $6' \times 5.5' = 0.52 \text{ pc} \times 0.48 \text{ pc} @ d=300 \text{ pc}$

- Nearby, $d=300 \text{ pc} \rightarrow$ well-resolved with Chandra
- Bright enough to provide high-S/N images and spectra
- Rich and puzzling structure with both similarities and differences from the Crab PWN
- Also very dynamical!

To be observed by Chandra for $320 \text{ ks}$.
Vela PWN topology: What are the arcs?

Deepest images of the inner Vela PWN: 160 ks ACIS + 150 ks HRC.

1. The linear sizes of the Inner and Outer Arcs differ by a factor of 1.4; if the arcs are non-coplanar tori, the pulsar is offset from their centers (Helfand et al 2001)
2. Inner arc: shock in the equatorial wind? What is the outer arc?
3. Different from Crab! Because of the different angle between the magnetic and rotation axis?

Tuesday, November 24, 2009
Dynamic Outer Jet of Vela pulsar: closer look

Length ~100 arcsec (4x10^{17} cm @ 300 pc); Luminosity 7 x 10^{30} erg/s (1% L_{PWN})

- Variability:
  1. Sideways shifts/bends; ~ month
  2. Outward moving blobs; \( v \approx 0.6c \)
  3. Blobs brightness varies; ~ week

- Orientation:
  blob speeds + outer jet/counter-jet brightness ratio => jet approaches observer at 30-60 deg angle;
  *(assuming equal intrinsic brightnesses for the jet/counter-jet!)*

- Spectrum: power-law, photon index \( \Gamma = 1.4 \pm 0.1 \)

- Synchrotron emission in magnetic field \( B \sim 100 \mu G \)

Tuesday, November 24, 2009
Vela PWN: more recent results:
Vela PWN (recent series, 3 x 40 ks, 1 week separation)
Vela PWN: spectral structure – particle acceleration

Notice complex structure:
Soft shell surrounding very hard inner features. Harder emission SW from pulsar.

Inner parts of the Vela PWN have extremely hard spectra:

$$S_\nu \propto B^{\Gamma} \nu^{-\Gamma+1}$$

$$p = 2\Gamma - 1$$

$$dn_E = K E^{-p} f(\vec{n}) \, dE \, d\Omega$$

→ $p \approx 1.1-1.2$ in Vela PWN contradicts current particle acceleration models that predict universal $p=2.1-2.2$

Inner parts of the Crab PWN have much softer spectra:

$p \approx 2.6$

Why?
Bowshock-tail PWNe

Again, in several cases structures are more complex than just tail and bow. Older pulsars more often exhibit bowshock-tail PWNe since they move in low-pressure ISM:

\[ p_{\text{ram}} = \rho v^2 >> p_{\text{amb}} \rightarrow \text{supersonic motion} \rightarrow \text{bow shock with apex at} \]

\[ r_h = \left( \frac{E\dot{t}}{4\pi c p_{\text{ram}}} \right)^{1/2} = 1.3 \times 10^{16} \left( \frac{E\dot{t}}{10^{35} \text{ erg/s}} \right)^{1/2} n^{-1/2} \left( \frac{v}{300 \text{ km/s}} \right)^{-1} \text{ cm} \]
The longest (>6 pc) pulsar tail in X-rays.

The 6-pc tail length and synchrotron cooling in B~20 μG imply $V_{\text{flow}} \sim 15,000$ km/s >> than $V_{\text{PSR}} \sim 300$-800 km/s.

$\text{d} \sim 4 \text{ kpc}$
$\dot{E}=5.1 \times 10^{35} \text{ erg/s}$

- Flow in the tail is supersonic.
- Chandra images indicate substructure within the tail: internal shocks or instabilities?

Close-up view of the “head” and the tail near the pulsar.

Kargaltsev et al. (2008)
Mouse PWN vs. J1509-5850 PWN (multiwavelength comparison):

Observations ahead of models: numerical MHD models (Bucciantini et al. 2005) produce images that could be compared to observations but simulations go out just to a ~10 termination shock radii.

J1509 and Mouse PWNe different:
• X-ray radio correlation in Mouse vs. anticorrelation in J1509 PWN
• Anticorrelation is difficult explain by synch. cooling only
• In Mouse magnetic field parallel to the tail, in J1509 tail it is perpendicular.

Mapping magnetic field is very important!
**Stephen Ng**: Magnetic filed structure of bow-shock PWNe via radio polarimetry.

Tuesday, November 24, 2009
Bowshock-tail PWNe: 3-Myr-old PSR J1929+10

\[ \dot{E} = 3.9 \times 10^{33} \text{ erg/s} \quad \text{d} \sim 360 \text{ pc} \]

XMM-Newton: 15'-long X-ray tail

Chandra: A hint of variability!

Becker et al. (2006)

Misanovic, Pavlov & Garmire (2008)

Opens a possibility to measure flow speed just downstream of the termination shock.
Other PWNe

Difficult to assign to either torus-jet or bowshock-tail type.

Possibly some of them are very remote. Some have few counts. But some morphologies are really bizarre.

Why?

Upstream flow and TS properties depend on the angle between the rotation and magnetic axis? Or environmental effects?
Population properties:

- Huge scatter in X-ray efficiencies $\frac{L_x}{\dot{E}} \Rightarrow L_x$ depends on “hidden” parameters.
- There is an upper boundary $L_x(\dot{E})$ when “hidden” parameters deliver maxim. efficiency.
Surprisingly tight correlation between pulsar and PWN luminosities! Even if both are powered by the same synchrotron mechanism, the electron number densities, energies and magnetic fields differ by many orders of magnitude between the pulsar magnetosphere and the post-shock region.
Some recent and unusual results on X-ray PWNe:

A population of underluminous PWNe

Tuesday, November 24, 2009
More than 30 extended TeV sources have been found by H.E.S.S., VRITAS, MAGIC of which ~50% are unidentified.

Young pulsars found in the vicinity of most of these UnID TeV sources strongly suggesting the connection.

What fraction of the TeV source population is due to pulsars/PWNe? What is the contribution of the pulsars/PWNe to the production of the galactic cosmic rays?

High-resolution X-ray observations provide efficient way to identify TeV sources powered by pulsar winds especially if there is no known radio pulsar.
TeV PWNe and “crushed plerion” model.

If the SNR shock becomes asymmetric (due to the interaction with the outside environment), the reverse shock will also be asymmetric and can “crush” a PWN pushing it to one side from the pulsar (Blondin et al. 2001).
VERITAS results: Boomerang PWN (PSR J2229+6114)

Acciari and VERITAS collaboration (2009)

Chandra ACIS

Tuesday, November 24, 2009
TeV PWN candidates.

<table>
<thead>
<tr>
<th>#</th>
<th>TeV Source</th>
<th>Counterpart</th>
<th>(d^a)</th>
<th>(\tau^b)</th>
<th>(E_{36}^c)</th>
<th>(D^d)</th>
<th>(f_{\gamma}^e)</th>
<th>(\Gamma_{\gamma}^f)</th>
<th>(L_{\gamma}/E_{\gamma}^g)</th>
<th>(\Gamma_{X}^h)</th>
<th>(f_{\gamma}/f_{X}^i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>J0534+220</td>
<td>B0531+21/Crab</td>
<td>2</td>
<td>1.2</td>
<td>461</td>
<td>(&lt; 6)</td>
<td>1.0</td>
<td>2.39 ± 0.03</td>
<td>0.007</td>
<td>2.12 ± 0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>J1833-105</td>
<td>J1833-1034/G21.5-0.9</td>
<td>5</td>
<td>5.0</td>
<td>33.1</td>
<td>(&lt; 6)</td>
<td>0.02</td>
<td>2.08 ± 0.22</td>
<td>0.004</td>
<td>1.89 ± 0.02</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>J1846-029</td>
<td>J1846-0258/Kes75</td>
<td>7</td>
<td>0.7</td>
<td>8.12</td>
<td>(&lt; 6)</td>
<td>0.02</td>
<td>2.26 ± 0.15</td>
<td>0.03</td>
<td>2.03 ± 0.02</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>J0835-455</td>
<td>B0833-45/Vela-X</td>
<td>0.3</td>
<td>11</td>
<td>6.92</td>
<td>60</td>
<td>0.75</td>
<td>1.45 ± 0.09</td>
<td>0.01</td>
<td>2.1 ± 0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>J1514-591</td>
<td>B1509-58/MSH 15-52</td>
<td>5</td>
<td>1.6</td>
<td>17.7</td>
<td>12</td>
<td>0.15</td>
<td>2.270.03</td>
<td>1.3</td>
<td>1.6 ± 0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

TeV sources firmly associated with pulsars

<table>
<thead>
<tr>
<th>#</th>
<th>TeV Source</th>
<th>Counterpart</th>
<th>(d^a)</th>
<th>(\tau^b)</th>
<th>(E_{36}^c)</th>
<th>(D^d)</th>
<th>(f_{\gamma}^e)</th>
<th>(\Gamma_{\gamma}^f)</th>
<th>(L_{\gamma}/E_{\gamma}^g)</th>
<th>(\Gamma_{X}^h)</th>
<th>(f_{\gamma}/f_{X}^i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>J1825-137</td>
<td>B1823-13</td>
<td>4</td>
<td>21.4</td>
<td>2.84</td>
<td>60</td>
<td>0.17</td>
<td>2.2–2.4</td>
<td>3.8</td>
<td>1.9 ± 0.3</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>J1420-607</td>
<td>J1420-6048</td>
<td>6</td>
<td>13.0</td>
<td>10.4</td>
<td>7</td>
<td>0.07</td>
<td>2.17 ± 0.06</td>
<td>2.1</td>
<td>0.5 ± 1.2</td>
<td>4.5</td>
</tr>
<tr>
<td>8</td>
<td>J1837-069</td>
<td>J1838-0655</td>
<td>6</td>
<td>22.7</td>
<td>5.55</td>
<td>14</td>
<td>0.13</td>
<td>2.27 ± 0.06</td>
<td>7.6</td>
<td>1.6 ± 0.4</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>J1809-193</td>
<td>J1809-1917</td>
<td>3.5</td>
<td>51.3</td>
<td>1.78</td>
<td>60</td>
<td>0.14</td>
<td>2.2 ± 0.10</td>
<td>2.9</td>
<td>2.3 ± 0.3</td>
<td>3.6</td>
</tr>
</tbody>
</table>

TeV sources with likely pulsar associations

<table>
<thead>
<tr>
<th>#</th>
<th>TeV Source</th>
<th>Counterpart</th>
<th>(d^a)</th>
<th>(\tau^b)</th>
<th>(E_{36}^c)</th>
<th>(D^d)</th>
<th>(f_{\gamma}^e)</th>
<th>(\Gamma_{\gamma}^f)</th>
<th>(L_{\gamma}/E_{\gamma}^g)</th>
<th>(\Gamma_{X}^h)</th>
<th>(f_{\gamma}/f_{X}^i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>J1718-385</td>
<td>J1718-3825</td>
<td>4</td>
<td>89.5</td>
<td>1.25</td>
<td>18</td>
<td>0.015</td>
<td>2.1 ± 0.10</td>
<td>0.8</td>
<td>1.7 ± 0.2</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>J1804-216</td>
<td>B1800-21</td>
<td>4</td>
<td>15.8</td>
<td>2.22</td>
<td>24</td>
<td>0.25</td>
<td>2.72 ± 0.06</td>
<td>7.2</td>
<td>–</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>12</td>
<td>J1857+026</td>
<td>J1856+0245</td>
<td>9</td>
<td>21.0</td>
<td>4.60</td>
<td>14</td>
<td>0.16</td>
<td>2.39 ± 0.08</td>
<td>57</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>13</td>
<td>J1303-631</td>
<td>J1301-6305</td>
<td>6</td>
<td>11.0</td>
<td>1.68</td>
<td>20</td>
<td>0.17</td>
<td>2.44 ± 0.05</td>
<td>33</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>14</td>
<td>J1702-420</td>
<td>J1702-4128</td>
<td>5</td>
<td>55.1</td>
<td>0.34</td>
<td>36</td>
<td>0.24</td>
<td>2.31 ± 0.15</td>
<td>90</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>15</td>
<td>J1616-508</td>
<td>J1617-5055</td>
<td>6</td>
<td>8.1</td>
<td>16.0</td>
<td>16</td>
<td>0.19</td>
<td>2.35 ± 0.06</td>
<td>3.8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>16</td>
<td>J1834-087</td>
<td>J1833-0827</td>
<td>5</td>
<td>147.0</td>
<td>0.58</td>
<td>9</td>
<td>0.08</td>
<td>2.45 ± 0.16</td>
<td>21</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>17</td>
<td>J1912+101</td>
<td>J1913+1011</td>
<td>5</td>
<td>169.0</td>
<td>2.88</td>
<td>45</td>
<td>0.09</td>
<td>2.7 ± 0.2</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>18</td>
<td>J1858+020</td>
<td>J1857+0143</td>
<td>5</td>
<td>71.0</td>
<td>0.45</td>
<td>18</td>
<td>0.04</td>
<td>2.17 ± 0.12</td>
<td>2.3</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

TeV sources with possible pulsar associations

<table>
<thead>
<tr>
<th>#</th>
<th>TeV Source</th>
<th>Counterpart</th>
<th>(d^a)</th>
<th>(\tau^b)</th>
<th>(E_{36}^c)</th>
<th>(D^d)</th>
<th>(f_{\gamma}^e)</th>
<th>(\Gamma_{\gamma}^f)</th>
<th>(L_{\gamma}/E_{\gamma}^g)</th>
<th>(\Gamma_{X}^h)</th>
<th>(f_{\gamma}/f_{X}^i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>J1747-281</td>
<td>G0.9+0.1</td>
<td>10</td>
<td>–</td>
<td>–</td>
<td>(&lt; 6)</td>
<td>0.02</td>
<td>2.40 ± 0.11</td>
<td>–</td>
<td>2.3 ± 0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>J1418-609</td>
<td>G313.3+0.1</td>
<td>5</td>
<td>–</td>
<td>8</td>
<td>0.06</td>
<td>2.22 ± 0.08</td>
<td>1.7 ± 0.1</td>
<td>3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>21</td>
<td>J1640-465</td>
<td>G338.3-0.0</td>
<td>8</td>
<td>–</td>
<td>9</td>
<td>0.09</td>
<td>2.42 ± 0.15</td>
<td>1.7 ± 0.1</td>
<td>1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>22</td>
<td>J1813-178</td>
<td>G12.82-0.02</td>
<td>4.5</td>
<td>–</td>
<td>9</td>
<td>0.06</td>
<td>2.09 ± 0.08</td>
<td>0.4 ± 0.5</td>
<td>3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>23</td>
<td>J1731-347</td>
<td>G353.6-0.7</td>
<td>3</td>
<td>–</td>
<td>22</td>
<td>0.16</td>
<td>2.26 ± 0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>24</td>
<td>J1713-381</td>
<td>G348.7+0.3</td>
<td>8</td>
<td>–</td>
<td>30</td>
<td>0.66</td>
<td>2.27 ± 0.48</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>25</td>
<td>J0616+225</td>
<td>IC443</td>
<td>1.5</td>
<td>–</td>
<td>12</td>
<td>0.06</td>
<td>3.1 ± 0.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

TeV sources possibly associated with X-ray PWNe (although no radio pulsar has been reported yet)
Equatorial termination shock (TS) resolved in a few PWNe (Crab, Vela).

In addition there may be TSs in polar outflows (Vela).

Several bright PWNe allow spatially-resolved spectroscopy. Spectra measured just downstream of the equatorial TS show different slopes in different PWNe.

Some PWNe (e.g., Vela) show extremely hard PL spectra implying $p \approx 1$ for the electron SED, with electron energies as high as 10 TeV.

There is a very large (>$10^4$) scatter in PWN X-ray efficiencies. “Hidden” parameters affect the efficiencies.

Ram-pressure-confined outflows in the tails of fast moving pulsars have complex structure, average flow speeds can be >15,000 km/s. Expansion, deceleration through internal shocks? Similar to jets in AGNs and YSOs?
Summary (continued):

• Pulsar tails show very different multiwavelengths morphologies and magnetic field topologies (Mouse PWN vs. J1509-5850 tail).

• Moving knots in pulsar tails can allow direct flow speed measurements with Chandra.

• Some PWN structures yet remain to be explained (e.g. “lops” in 3C58, X-ray filament near the Guitar nebula).

• PWNe comprise a large fraction the unidentified TeV source population. High-resolution X-ray observations are most helpful in their identification.