X-ray Observations of Pulsars and Pulsar Wind Nebulae

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and other collaborators.
1999: Launch of *Chandra* and *XMM-Newton* – New Era in Pulsar and PWN studies

*Chandra* (0.3 – 10 keV; 0.5” resolution, low ACIS background) particularly useful for PWNe

*XMM*: not so good resolution, higher background, but more sensitive, larger field of view, better timing capabilities

*NuSTAR (launched in 2012)*: worse angular resolution, but higher energies (up to 79 keV), low background, good timing capabilities
Tasks enabled by **Chandra** and XMM-Newton
(relevant for PWN and PSR science)

- high-resolution images revealing PWN geometry on (sub)-arcsecond scales
- spatially-resolved spectroscopy on arcsecond scales
- resolving very faint sources and finding extended sources (e.g., faint relic PWNe associated with TeV sources)
- subarcsecond localizations allowing to discover new compact objects (e.g., pulsars) via multiwavelength matching and analysis
- measuring spectra of objects embedded in complex background (e.g., pulsars/PWNe inside SNRs)
- detecting thermal components from PSRs in soft X-rays
Current status of rotation-powered pulsar (RPP) observations in X-rays

255 pulsars observed with Chandra or/and XMM, including 187 ordinary pulsars and 68 recycled pulsars (not counting pulsars in globular clusters).

About 170 pulsars have been detected, including 112 ordinary pulsars and 58 recycled pulsars.

X-ray pulsations detected in ~50 pulsars (~40 of which are ordinary, and ~10 are recycled).
RPPs detected in X-rays (red dots) and $\gamma$-rays (blue stars)
RPPs exist due to constant supply of relativistic e-e+ into magnetosphere.

X-rays come from magnetosphere, PWN, and NS surface.
Emission components in RPPs:

**Nonthermal** – seen from radio to gamma-rays

**Location:**
- Magnetosphere
- PWN (if the PWN is not resolved)

**Thermal** – seen from UV to soft X-rays

**Location:**
- Most of NS surface (heat is stored/produced inside NS)
- Hot polar caps (heated by magnetospheric activity)
Typical (toy-model) X-ray spectra of RRPs

Young RRP (Crab-like) or energetic MSPs

Older RRPs (Vela, B0656, Geminga)

In reality surface temperature distribution is non-uniform (not just 2 components).

The best characterization of it comes from B0656+14.
Pulsars from X-rays to gamma-rays

Energetic MSPs (no thermal component)

Young pulsars

Kuiper & Hermsen (2015)

\[ E^2 \times \text{Flux} \ [\text{MeV}^2 \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{MeV}] \]

\[ E \ [\text{MeV}] \]

\[ E' \times E'' \ [\text{erg cm}^{-2} \cdot \text{s}^{-1}] \]

\[ \text{Photon energy (keV)} \]

Gotthelf & Bogdanov 2017
Pulsars from optical to X-rays

Diamond, X-rays

Kargaltsev & Pavlov 2007

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title=Geminga,
    xlabel=Log $\nu$, Hz,
    ylabel=Log $F_\nu$, $\mu$Jy,
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    ymin=-1.5, ymax=1.5,
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    xtick={14,15,16,17,18},
    ytick={-1.5,-1,-0.5,0,0.5,1,1.5},
    grid=major,
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\addplot[] coordinates {
(15,0)
};
\addplot[dashed] coordinates {
(15,-1.5)
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\addplot[dotted] coordinates {
(15,-1)
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\addplot[red] coordinates {
(15,-0.5)
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\addplot[blue] coordinates {
(15,0.5)
};
\addplot[green] coordinates {
(15,1)
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\addplot[red,mark options={fill=red}] coordinates {
(15,-1.5)
};
\addplot[blue,mark options={fill=blue}] coordinates {
(15,-1)
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\addplot[green,mark options={fill=green}] coordinates {
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};
\addplot[red,mark options={fill=red}] coordinates {
(15,0.5)
};
\addplot[blue,mark options={fill=blue}] coordinates {
(15,1)
};
\addplot[green,mark options={fill=green}] coordinates {
(15,1.5)
};
\legend{measured}
\end{axis}
\end{tikzpicture}
\end{center}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title=B0656+14,
    xlabel=Log $\nu$, Hz,
    ylabel=Log $F_\nu$, $\mu$Jy,
    xmin=14, xmax=18,
    ymin=-1.5, ymax=1.5,
    legend pos=north east,
    xtick={14,15,16,17,18},
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};
\addplot[green,mark options={fill=green}] coordinates {
(15,1.5)
};
\legend{measured}
\end{axis}
\end{tikzpicture}
\end{center}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title=Vela,
    xlabel=Log $\nu$, Hz,
    ylabel=Log $F_\nu$, $\mu$Jy,
    xmin=14, xmax=18,
    ymin=-1.5, ymax=1.5,
    legend pos=north east,
    xtick={14,15,16,17,18},
    ytick={-1.5,-1,-0.5,0,0.5,1,1.5},
    grid=major,
    \]
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\addplot[green] coordinates {
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\addplot[red,mark options={fill=red}] coordinates {
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(15,1)
};
\addplot[green,mark options={fill=green}] coordinates {
(15,1.5)
};
\legend{measured}
\end{axis}
\end{tikzpicture}
\end{center}
NuSTAR extends soft X-ray spectra

Weak comptonization of the thermal photons or nonthermal emission (synchrotron)?

Geminga

Mori et al. 2014

MSP J0437-4715

Guillot et al. 2016

Toward higher energies, an extension of the BB+BKPL model ($\Gamma_2 \sim 1.4$) is roughly consistent with the phase-averaged Fermi spectrum with $\Gamma \sim 1.3$ (Abdo et al. 2010). “The Geminga pulsar should have two spectral breaks in its multi-wavelength non-thermal spectrum.”

$\Gamma_{\text{NuStar}} = 1.46-1.65$ (depending on the choice of thermal model)

The PL photon index that we found for J0437 is consistent with the photon flux detected by Fermi above 0.1 GeV when extending to gamma-ray energies: $(4.4 \pm 0.1) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$. However, this may simply be a coincidence since the gamma-ray emission and the hard X-ray non-thermal emission have different origins.

More NuSTAR observations of Fermi pulsars (preferably with detected optical/NIR emission) are needed!
Pulsations in X-rays from XMM-Newton

0.2 – 12 keV

J0537-69, magnetospheric, 16 ms
Crab, magnetospheric, 33 ms
B0540-69, magnetospheric, 51 ms
Vela, magnetospheric+thermal(?), 89 ms
B1509-58, magnetospheric, 151 ms
B0656+14, entirely thermal (?), 197 ms

(Martin-Carrillo et al 2012)
X-ray – UV pulsations

Geminga

B0656+14

Vela

Thermal pulsations can help constrain magnetic inclination angle if the viewing angle is known.

NUV, 4.3 – 7.2 eV

FUV, 7.3 – 11 eV

Soft X-rays, ~0.3 – 1 keV

Harder X-rays, ~2 – 8 keV

(Kargaltsev & Pavlov 2007)
Population properties: $L_X$ vs. $\dot{E}$

Becker & Trumper 1997 (27 pulsars)
Possenti et al. 2002 (39 pulsars)
Posselt et al. 2012
Kargaltsev et al. 2012
Li et al. 2008

Population properties: $L_X$ vs. $\dot{E}$
Topics to explore further:

The nature of nonthermal X-ray emission, region of magnetosphere where it is produced, connection to GeV emission;

Relation between the magnetospheric and PWN X-ray efficiencies;

Connection between the non-thermal X-ray and gamma-ray lightcurves;

Relation between the magnetospheric emission efficiency and magnetic inclination angle;

Possibly higher X-ray efficiencies of older pulsars (more of these need to be observed) and the reason behind;

Origin of complex soft X-ray (and FUV) lightcurves (e.g., Vela pulsar).
Pulsar wind nebulae in X-rays

Search for pulsar wind nebula in NASA ADS beta
All active pulsars emit relativistic winds

\[ v \sim c > c_s \rightarrow \text{shock forms} \]

Downstream of the shock: subrelativistic magnetized flow of relativistic particles

Nonthermal power-law spectra:
- **synchrotron** (radio through MeV) and
- **IC radiation** (GeV and TeV) \( \rightarrow \text{PWN} \)

Typical energy of synch. photon:

\[ E_{\text{syn}} = 2 \left( \Gamma / 2 \times 10^7 \right)^2 \left( B / 10 \mu G \right) \text{keV} \]

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

Characteristic size:

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

Synchrotron cooling time:

\[ t_{\text{syn}} \sim 1 \left( E_{\text{syn}} / 1 \text{keV} \right)^{-1/2} \left( B / 10 \mu G \right)^{-3/2} \text{kyr} \]

IC cooling time:

\[ t_{\text{IC}} \sim 10 \left( E_{\text{syn}} / 1 \text{keV} \right)^{-1/2} \left( B / 10 \mu G \right)^{1/2} \left( U_{\text{rad}} / 0.26 \text{ eV/cm}^{-3} \right)^{-1} \text{kyr} \]

Luminosity:

\[ L = \kappa \dot{E}, \quad \kappa < 1 \quad \text{(efficiency, } \eta, \text{ depends on wind parameters and outflow geometry; } \kappa_X \sim 10^{-5} - 10^{-1} \text{ from observations).} \]
Thanks to Chandra some PWNe have been now studied in detail.
Bright X-ray PWNe suitable for spatially resolved spectroscopy observed by Chandra

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Exposure (ks)</th>
<th>$F_X \ (10^{-11} \text{ cgs})$</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crab</td>
<td>565 (57)</td>
<td>2000</td>
<td>ring, torus, jets</td>
</tr>
<tr>
<td>2</td>
<td>Vela</td>
<td>630 (22)</td>
<td>6.1</td>
<td>arcs, jets</td>
</tr>
<tr>
<td>3</td>
<td>G21.5–0.9 (J1833-1034)</td>
<td>738 (82)</td>
<td>3.8</td>
<td>tori, jets</td>
</tr>
<tr>
<td>4</td>
<td>MSH 11–62</td>
<td>472 (9)</td>
<td>3</td>
<td>arcs, jet, tail(?)</td>
</tr>
<tr>
<td>5</td>
<td>G320.4–1.2 (B1509–58)</td>
<td>331 (10)</td>
<td>5.3</td>
<td>arcs, jet, tail(?)</td>
</tr>
<tr>
<td>6</td>
<td>Kes 75 (J1846-0258)</td>
<td>383 (8)</td>
<td>1.5</td>
<td>jets, torus</td>
</tr>
<tr>
<td>7</td>
<td>G11.2–0.3 (J1811-1925)</td>
<td>480 (12)</td>
<td>0.6</td>
<td>jets, torus (?)</td>
</tr>
<tr>
<td>8</td>
<td>3C58 (J0205+6449)</td>
<td>392 (4)</td>
<td>0.7</td>
<td>jets, loops, torus</td>
</tr>
<tr>
<td>9</td>
<td>G54.1+0.3 (PSR J1930+1852)</td>
<td>326 (5)</td>
<td>0.5</td>
<td>torus, jets</td>
</tr>
<tr>
<td>10</td>
<td>Snail/G327.1–1.1</td>
<td>386 (4)</td>
<td>0.3</td>
<td>tail, prongs</td>
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<tr>
<td>11</td>
<td>MSH 15–56 (G326.3–1.8)</td>
<td>56 (1)</td>
<td>0.83</td>
<td>amorphous morphology</td>
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<tr>
<td>12</td>
<td>N157B (J0537–6910)</td>
<td>48 (1)</td>
<td>0.6</td>
<td>torus, tail/trail</td>
</tr>
<tr>
<td>13</td>
<td>Mouse (J1747–2958)</td>
<td>154 (5)</td>
<td>0.7</td>
<td>equatorial outflow, tail</td>
</tr>
<tr>
<td>14</td>
<td>Lighthouse (J1101–6101)</td>
<td>302 (7)</td>
<td>0.2</td>
<td>misaligned outflow</td>
</tr>
<tr>
<td>15</td>
<td>Geminga</td>
<td>680 (14)</td>
<td>0.075</td>
<td>equatorial &amp; lateral outflows</td>
</tr>
<tr>
<td>16</td>
<td>CTB 80 (B1951+32)</td>
<td>85 (1)</td>
<td>0.6</td>
<td>torus, tail(?)</td>
</tr>
<tr>
<td>17</td>
<td>J1509–5850</td>
<td>413 (5)</td>
<td>0.05</td>
<td>bow shock, jets, tail</td>
</tr>
<tr>
<td>18</td>
<td>Mushroom (B0355+54)</td>
<td>461 (9)</td>
<td>0.03</td>
<td>equatorial outflow, jets, tail</td>
</tr>
<tr>
<td>19</td>
<td>J1741–2054</td>
<td>331 (7)</td>
<td>0.03</td>
<td>bow shock, tail</td>
</tr>
<tr>
<td>20</td>
<td>J0357+3205</td>
<td>134 (4)</td>
<td>0.04</td>
<td>(disconnected) tail</td>
</tr>
<tr>
<td>21</td>
<td>Guitar (B2224+65)</td>
<td>195 (6)</td>
<td>0.006</td>
<td>bow shock, misaligned outflow</td>
</tr>
</tbody>
</table>

For some of these additional deep CXO observations are needed.

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?

Of course real images are not like this, examples will follow…
Pulsar speed  \( V_{\text{PSR}} = \text{a few times 100 km/s} \)

Speed of sound  \( c_s = (\gamma kT/\mu m_p)^{1/2} \approx 10 \left( T/10^4 \text{ K} \right)^{1/2} \text{ km/s} \)

**Subsonic PSR motion**  \((M < 1)\) is possible only in SNRs (i.e., for very young pulsars/PWNe)

If the unshocked PW were **isotropic**, TS and CD would be spherical surfaces, and the PWN would look like a **round ring** (due to limb brightening) with a characteristic radius

\[
p_{\text{PW}} = p_{\text{amb}} \implies R_0 \approx \left[ \frac{E_{\text{dot}}}{4\pi c p_{\text{amb}}} \right]^{1/2}
\]

\[
R_0 \approx 0.2 \left( \frac{E_{\text{dot}}}{10^{37} \text{ erg/s}} \right)^{1/2} \left( \frac{p_{\text{amb}}}{10^{-10} \text{ dyn/cm}^2} \right)^{-1/2} \text{ pc}
\]

However, we never see such simple round PWN structures
Canonical example: Crab PWN

**Crab pulsar:**  \(E_{\dot{\text{r}}} = 4.5 \times 10^{38} \text{ erg/s}, \text{Age} = 962 \text{ yr}, D=2 \text{ kpc}, V_{t}=140 \text{ km/s}\)

Chandra ACIS images (Weisskopf et al. 2000, 2015).

We do see a **ring**, but it is elliptical, with a bright ‘**torus**’ beyond the ring and fainter ‘**jets**’ along the PSR spin axis.

The spin axis coincides with the **PSR velocity direction** (Ng & Romani 2006)

The unshocked PW is emitted predominantly in the equatorial plane, tilted by 30° to l.o.s.

The jets are likely produced from outer layers of equatorial outflow turned back to the spin axis and confined by magnetic hoop stress (Komissarov & Lyubarsky 2003, 2004; Del Zanna et al 2004, 2006)
Crab’s torus is comprised of ‘wisps’ moving outward with decreasing velocity, \(0.4c - 0.2c\). Similar speeds are seen in the jets. 

Jet’s end wagging on a few year timescale

Hester et al. 2002; Mori et al. 2004, 2006

Weisskopf et al. 2016
Small problem: X-ray and optical wisps do not coincide

Chandra + HST+JVLA synergy: contemporaneous observations

Krassilchtchikov et al. (2016); Dubner et al. (2017)
ALMA image of the Crab PWN

JVLA, 3 GHz

ALMA, 100 GHz

Dubner et al. (2017)
Another outstanding example: **Vela PWN**

Chandra ACIS, 600 ks

$D=0.3 \text{ kpc}, \ E_{\text{dot}} = 7 \times 10^{36} \text{ erg/s}, \ \tau_{\text{sd}} = 11 \text{ kyr}, \ V_{t}=77 \text{ km/s}$

Pulsar motion is transonic; it affects PWN morphology, contrary to Crab.

Are the two arcs analogues to Crab torus (‘split torus’) i.e. caused by equatorial outflow. Larger angle ($\alpha$) between spin and magnetic axis?

*Inner and outer “jets”* ($\sim 0.01 \text{ pc}$ and $0.15 \text{ pc}$) aligned with pulsar’s speed. Inner SE jet detached from PSR.

*Why inner and outer jets so different?*

Outflow speed $\sim 0.3-0.7 \ c$ in the outer jet, energy injection rate $\sim 8 \times 10^{33} \text{ erg/s}$.

Magnetic field *a few* $\times 10 \text{ mG}$, electron energies up to $\sim 200 \text{ TeV}$
Vela PWN: 2 months in 2010

8 observations 40 ks each, 1 week separation (Durant et al. 2013)

Outer jet resembles a rotating corkscrew! Turning helix projected onto sky? Precession with 120 d period, launch speed 0.7c? Kink instability?

Bright inner PWN is variable. Are there wisps like those seen like in Crab? A bar on the south-eastern jet is an oblique shock in the equatorial flow? Analog of Crab’s Inner Knot?
Vela PWN: spectral structure

Jets have hard spectra.

Adaptively binned spectral map

See poster by Noel Klingler
Other Torus-jet PWNe

Crab, B0540-69, G21.5-0.9, 3C58, G106.3+2.7, B1509-58, G292.0+1.8, G54.1+0.3, Vela, J2021+3651, B1706-44, B1800-21 --- all are young (< 17 kyr), all in SNRs, M ~<1.

In some cases structures are more complex than just torus and jets...
Very deep look at two PWNe in SNRs

**PSR J1811-1925/G11.2-0.3**
Edot=6.5×10^{36} \text{ erg/s}, \sim2 \text{ kyr}, 5 \text{kpc}
Chandra 400 ks, Borkovski et al. (2016)

**PSR B1509-58/MSH 15-52**
Edot=1.8×10^{37} \text{ erg/s}, \sim1.5 \text{ kyr}, 5 \text{kpc}
Chandra 190 ks, Yatsu et al. (2009)

Jets are much brighter than tori! (and there are more such examples). Are these pulsars close to aligned rotators?
Population properties:

Having detailed spectral maps allows to find the hardest spectra and measure spectral slopes relatively unaffected by cooling.

Photon indices ($\Gamma$) and electron SED slopes ($p = 2\Gamma - 1$)

These slopes may be more directly related to pulsar properties than the volume-integrated slopes.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\Gamma_i$</th>
<th>$p_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>1.80 ± 0.05</td>
<td>2.60 ± 0.10</td>
</tr>
<tr>
<td>Vela</td>
<td>1.33 ± 0.06</td>
<td>1.67 ± 0.12</td>
</tr>
<tr>
<td>G21.5–0.9</td>
<td>1.43 ± 0.09</td>
<td>1.86 ± 0.18</td>
</tr>
<tr>
<td>MSH 11–62</td>
<td>1.10 ± 0.05</td>
<td>1.20 ± 0.10</td>
</tr>
<tr>
<td>B1509–58 (G320.4–1.2)</td>
<td>1.19 ± 0.13</td>
<td>1.38 ± 0.27</td>
</tr>
<tr>
<td>Kes 75 (J1846–0258)</td>
<td>1.85 ± 0.10</td>
<td>2.70 ± 0.20</td>
</tr>
<tr>
<td>G11.2–0.3</td>
<td>1.75 ± 0.1</td>
<td>2.79 ± 0.46</td>
</tr>
<tr>
<td>3C58</td>
<td>1.97 ± 0.07</td>
<td>2.94 ± 0.15</td>
</tr>
<tr>
<td>G54.1+0.3</td>
<td>1.7 ± 0.1</td>
<td>2.30 ± 0.21</td>
</tr>
<tr>
<td>Snail (G327.1–1.1)</td>
<td>1.66 ± 0.06</td>
<td>2.32 ± 0.11</td>
</tr>
<tr>
<td>N157B (J0537–6910)</td>
<td>2.17 ± 0.11</td>
<td>3.34 ± 0.23</td>
</tr>
<tr>
<td>Mouse (J1747–2958)</td>
<td>1.57 ± 0.06</td>
<td>2.14 ± 0.12</td>
</tr>
<tr>
<td>Geminga</td>
<td>1.4 ± 0.1</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>CTB 80</td>
<td>1.7 ± 0.1</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td>J1509–5850</td>
<td>1.43 ± 0.18</td>
<td>1.86 ± 0.36</td>
</tr>
<tr>
<td>Mushroom (B0355+54)</td>
<td>1.54 ± 0.05</td>
<td>2.08 ± 0.10</td>
</tr>
<tr>
<td>J1741–2054</td>
<td>1.5 ± 0.15</td>
<td>2.0 ± 0.3</td>
</tr>
</tbody>
</table>

See poster by Noel Klingler

Kargaltsev et al. 2017 (2017arXiv171102656K)
$\Gamma$ measured from innermost regions

Kargaltsev et al. 2017 (2017arXiv171102656K)

$\Gamma$ is spatially averaged

Li et al. 2008
Swift XRT can also be used to find pulsar, PWNe, and GeV/TeV source counterparts.

To be observed with XMM-Newton and Chandra.

Galactic plane surveys with Swift XRT, Chandra ACIS, and XMM-Newton EPIC must be carried out while these observatories are operational.

Swift XRT is doing Galactic Plane Survey Pilot (PI Kouveliotou): (10 deg < |l| < 30 deg and |b| < 0.5 deg)
Connection between pulse shapes and PWN morphologies

See poster by Noel Klingler

Both are likely to depend on two internal parameters (viewing angle $\zeta$ and magnetic inclination angle $\alpha$) in addition to $E_{\text{dot}}$, Mach number and velocity direction.

Important angles are:

$\alpha$ – angle between the rotation and magnetic axis

$\zeta$ – angle between the rotation axis and the line of sight

$\beta$ – closest approach of line of sight to magnetic axis

$\alpha + \beta = \zeta$
Typical assumptions about the PSR lightcurves

• Radio comes from the plasma filled region just above magnetic poles. Pencil beam? This seems to be too simplistic to accommodate the data. One must, at least, resort to nested cones or fan beam configurations.

• Thermal X-rays come from polar cap. Still Ok but in some cases pulse fractions are very high (magnetized atmosphere?).

• Gamma-rays come from somewhere further away in the magnetosphere.

Possible examples of implications from gamma-ray/radio lightcurves:

• Single (or absent) radio pulse, weak or no gamma-rays -> both the line of sight and the magnetic dipole axes are close to the rotation axis

• Strong gamma-rays, no radio -> orthogonal rotator viewed at some substantial angle with respect to the rotation axis
Lightcurve modeling (Watters et al. 2009):

Complex task but knowing $\zeta$ helps a lot!

Gap thickness $w = \eta \propto E_{\text{SD}}^{-1/2}$

TPC (within dashed lines) and OG (shaded) emission regions

from Dyks & Rudak 2003
Lightcurve modeling: Pierbattista et al. (2016):

Triangles actual pulsars
Dots simulated pulsars
PWN morphology: some expectations

- Asymmetry between two jets or the ellipticity of the ring projection tells about $\zeta$

- PWNe often show equatorial and polar components. Can their relative strengths be indicative of the angle $\alpha$?

- One can expect PWN luminosity (all or equatorial component?) to be correlated with the size of the reconnection layer near the equatorial plane (absent for aligned rotator)

- Spectral slopes that are different for different PWNe may be reflecting acceleration efficiency and correlate with $\alpha$. 
J2021+3651 PWN is very similar to Vela PWN, it just has slightly larger viewing angle $\zeta$.

Magnetic inclination angle is likely similar for both pulsars. For Vela $\alpha=43-70$ deg.

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In the diagram:
- Vela: $\zeta=65$ deg
- J2021+3651: $\zeta=80$ deg
Van Etten et al. 2008

\[ \epsilon_{\text{PWN}} = 1.45 \pm 0.09 \]

\[ \epsilon_{\text{PWN}} = 1.30 \pm 0.05 \]

\[ \zeta = 65 \text{ deg} \]

\[ \zeta = 80 \text{ deg} \]

\[ \alpha = 53 \text{ deg} \]

smaller $\alpha$ compared to two PSRs below

\[ \Gamma_{\text{PWN}} = 1.40 \pm 0.1 \]

\[ \Gamma_{\text{PWN}} = 1.30 \pm 0.05 \]

\[ \Gamma_{\text{PWN}} = 1.45 \pm 0.09 \]

Van Etten et al. 2008
Single pulse in gamma-rays: $\zeta \sim \alpha = 40-50$ deg

Very faint or non existent X-ray PWN

Birzan et al. 2016
Outlook

• Some of this work (determining $\zeta$ from PWN morphologies) has been done in Ng & Romani (2008) but it is worth revisiting this topic using additional constraints from larger sample of PWNe.

• Once it would be possible to infer $\alpha$ more or less reliably from the lightcurve modeling, one can check if there is correlation between $\alpha$ and PWN X-X-ray efficiency or $\Gamma$.

• It would be good to explore more the relation between the relative strength of the polar and equatorial components and pulsar’s $\alpha$ (Bühler & Giomi 2016).
Supersonic PSR motion: SPWNe

Pulsars that have left their parent SNRs always move supersonically ($M \sim 10 - 100$) \( \Rightarrow \quad p_{\text{ram}} = \rho v^2 \gg p_{\text{amb}} \)

→ bow-like structure with CD apex at

\[
    r_{\text{CD}} = \left( \frac{E_{\dot{\text{ot}}}}{4\pi c \rho_{\text{ram}}} \right)^{1/2}
\]

\[
    r_{\text{CD}} = 1.3 \times 10^{16} \left( \frac{E_{\dot{\text{ot}}}}{10^{35} \text{ erg/s}} \right)^{1/2} n^{-1/2} (v/300 \text{ km/s})^{-1} \text{ cm}
\]

Schematic picture:

Forward bow shock (FS) and shocked ISM between FS and CD can be observed in Balmer lines

X-rays come from shocked PW between TS and CD, should look like a ‘head-tail’ PWN.
Examples of SPWNe

Most of them show strongly elongated structures.

**Jets:** Polar outflows along spin axis, often seen on both sides of PSR;

**Tails:** Fast outflows behind moving pulsar confined by ram pressure;

**Trails:** Tails slowed down by interaction with ISM matter (do we see any?);
Supersonic PWNe (SPWNe) with deep Chandra ACIS exposures
(See poster by Maxim Lyutikov explaining these morphologies)
In some cases (with good quality Chandra images) it is tempting to interpret the fine structure of the SPWNe in a way similar to subsonic torus-jet PWNe. B0355+14 Geminga

This enables independent tests of the viewing geometry inferred from pulsar lightcurve modeling.
Connection to the pulsar magnetosphere geometry

PSR J1509-5850

Similar lightcurves imply similar (α, ζ) angles, helps to interpret PWN features and vice versa!

PSR B1706-44
Summary: Some outstanding problems

• What is the reason for the great diversity of X-ray PWNe? Different Mach numbers alone cannot explain it. PW anisotropy + axis orientations?
• What is the true nature of “jets”? Why are some jets in subsonic/transonic PWNe brighter than tori? Is the “backflow model” universally applicable?
• What is the nature of misaligned outflows? They apparently cannot be explained with the (M)HD approach. Kinetic approach required?
• Are the apparent helical motions in some jets (or misaligned outflows) indeed connected with pulsar precession or instabilities?
• Why some very extended structures (e.g., tails) show strong synchrotron cooling while others do not. Why some structures show very hard spectra? Reacceleration (e.g., due to reconnections) required?
• What is the true topology of some puzzling PWNe (Vela, Geminga, …)?
• Why are some PWNe so underluminous or even absent?