A nearby, fast-moving pulsar with a very unusual X-ray trail

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with P. Caraveo, M. Marelli, D. Salvetti, N. Sartore, R. Mignani, A. Belfiore, P. Saz Parkinson
Fermi-LAT discovers pulsars

Fermi-LAT 2PC – talk by D. Smith
The soft X-ray side

Systematic follow-up campaign for RQ PSRs (Chandra, XMM-Newton, Swift/XRT, Suzaku)

Goals: → are RQ PSRs and RL PSRs different?
       → detailed study of interesting targets

Status: → 76 Fermi PSRs with X-ray counterpart
       → 27 RL – 24 RQ – 25 MS

       Chandra and Suzaku “mini-surveys” ongoing

       → deep obs of PSR J0007+7303, PSR J0357+3205,
           PSR J2021+4026, PSR J1813-1246, PSR J2055+2539

       (Caraveo et al. 2010; De Luca et al. 2011,2013; Marelli et al. 2012a,b,2013;
        Weisskopf et al. 2011; Fermi-LAT 2PC; Sarazin et al. in prep; Marelli et al. in prep)
The radio quiet PSR J0357+3205

P = 444 ms
E_{dot} = 6 \times 10^{33} \text{erg/s}
B = 2.3 \times 10^{12} \text{G}
\tau = 0.54 \text{Myr}

b = -16^\circ
d \sim 500 \text{pc}
S_{1400} < 4 \, \mu\text{Jy}
A faint PSR with a parsec-long X-ray tail

Tail $L_X \sim 1.5 \cdot 10^{-3} \cdot \text{Erot}$

not detected in NVSS

9 arcmin --> 1.3 pc @ 500 pc

Chandra/ACIS 77 ks

De Luca et al. 2011
ApJ 733, 104
Tail: weird brightness profile

De Luca et al. 2011
ApJ 733, 104
Weird brightness profile – 2

No hints for diffuse emission surrounding the PSR

De Luca et al. 2011
ApJ 733, 104
A very deep observation with XMM

11 AGN → Galactic NH

$2.10 \pm 0.09 \times 10^{21} \text{ cm}^{-2}$

Bright artifacts due to $X \text{ Per}$
The XMM view of the PSR counterpart

Composite BB+PL spectrum

\[ kT = 94 \pm 8 \text{ eV} \]
\[ R = 0.5 \pm 0.1 \text{ km} \]
\[ \Gamma = 2.28 \pm 0.15 \]
\[ NH = (1.2 \pm 0.4) \times 10^{21} \text{ cm}^{-2} \]

Pulsation search hampered by time jumps

Marelli et al. 2013
ApJ 765, 36
No hints of spectral evolution

\[ \Delta \Gamma < 0.2 \text{ at } 3\sigma \text{ c.l. along both axes} \]
Any issue with the NH?

Non-thermal model for the PWN yields large NH.

Thermal Bremsstrahlung model yields better results.

Marelli et al. 2013
ApJ 765, 36
Measuring the proper motion

Chandra multi-cycle program

Relative astrometry on field sources within 4 arcmin from aimpoint

<table>
<thead>
<tr>
<th></th>
<th>2011 vs. 2009a</th>
<th>2011 vs. 2009b</th>
<th>2009a vs. 2009b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time baseline</td>
<td>2.16 yr</td>
<td>2.16 yr</td>
<td>1 day</td>
</tr>
<tr>
<td>Number of ref. srcs</td>
<td>11(^a)</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Uncertainty on X(_{shift}) (pixels)</td>
<td>0.09</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>(\chi^2) (dof)</td>
<td>13.6 (10)</td>
<td>15.6 (9)</td>
<td>7.8 (15)</td>
</tr>
<tr>
<td>Uncertainty on Y(_{shift}) (pixels)</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>PSR Y displacement (pixels)</td>
<td>0.54 ± 0.11</td>
<td>0.50 ± 0.10</td>
<td>0.04 ± 0.10</td>
</tr>
</tbody>
</table>

De Luca et al. 2013
ApJ 765 L19
The proper motion of PSR J0357+3205

- Proper motion: $165 \pm 30$ mas/yr
- Position Angle: $314^\circ \pm 8^\circ$
- PA of tail’s axis: $315.5^\circ \pm 1.5^\circ$
- (projected) PSR velocity: $390 \text{ km/s at } 500 \text{ pc}$

Origin of the tail linked to PSR velocity

De Luca et al. 2013
ApJ 765 L19
No Balmer-dominated bow-shock

Deep observation with Gemini telescope in Hα

Upper limit to bow-shock
$5 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$

Neutral fraction
$X_{\text{ISM}} < 0.01$

De Luca et al. 2013
ApJ 765 L19
Is the trail a ram pressure-confined PWN?

seems most “natural” explanation for an elongated tail aligned with PSR proper motion

**Cons:**
- where is the pulsar wind termination shock?
- how to explain brightness profile?
- ... as well as lack of spatial/spectral evolution?
- any problem with PSR energetics?
- NH ≈ inconsistent with PSR
Is the trail a thermally emitting nebula?

- free-free emission from ISM, shock-heated by the fast moving PSR. The first seen example?
- Order of mag estimates: $v_{\text{psr}} \sim 1900 \text{ km/s}$, $d=300-900 \text{ pc}$, $i=68^\circ-83^\circ$, $\rho_{0,\text{ISM}} = 0.15-0.3 \text{ cm}^{-3}$, $T_{0,\text{ISM}}=1-9 \times 10^5 \text{ K}$

- **could explain** alignment with proper motion
  peak away from PSR position (long $t_{\text{heat}}$)
  lack of spectral evolution (long $t_{\text{cool}}$)
  NH (vs. PSR and Galactic)

**Cons**?
- very low metallicity from the fit
- medium denser than typical hot phase of ISM
- Morphology of the tail?
Conclusions

Nature of PSR J0357+3205 trail is puzzling. Possibly thermal?

Population of energetic, nearby PSRs unveiled by Fermi will teach us a lot about pulsar winds and their interaction with the ISM

A new peculiar case from Fermi:

a low-Edot RQ PSR with an 11 arcmin-long tail

Coming soon!