The Serendipitous Tale of a Pulsar and an SNR

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PSR J0002+6216

- Discovered in “blind” periodicity searches of Fermi data using the Einstein@Home volunteer computer (Clark et al. 2017)
- Relatively normal gamma-ray pulsar: $P=115$ msec, $B=0.8 \times 10^{12}$ G, $E=1.5 \times 10^{35}$ erg s$^{-1}$
  Characteristic age $\tau_c = 306$ kyr
- Weakly detected in radio (Wu et al. 2018)
  Dispersion measure puts distance at 7 kpc
Targeting unidentified (oops!) Fermi sources

1-hr integration at 20 cm (1-2 GHz) with 12-arcsec resolution

Used special experimental algorithms within CASA

– Wideband AW projection with conjugate beam models and
– Multi-term, multifrequency synthesis
– Multi-scale clean
A middle-aged SNR ($\tau=10 \pm 0.2$ kyrs)

- optical and radio circular shell of radius 17.8 arcmin
- X-rays mixed morphology SNR with evidence for enhanced heavy element abundances
- located in Perseus arm with distance of $d_k=2.0 \pm 0.4$ kpc
Extrapolation of least squares fit of 7-arcmin tail passes within 5-11 arcsec of the geometric center of SNR CTB1, 28±1 arcmin away.

Very small *a posteriori* probability of chance coincidence.

If PSR J0002+6216 is from the SN, predicts proper motion of

$$\mu = \Delta \theta / \tau = 168 \pm 35 \text{ mas/yr at a PA of 113 degrees.}$$
If the association is true, then

- The pulsar is **much** younger than its characteristic age (born spinning slowly)
- The pulsar is moving at ~810 \(d_{kpc}\) km/s.
  
  Recall \(d_{DM}=7\text{kpc}\) and \(d_{SNR}=2\text{kpc}\).

Really desire an independent measure of the pulsar proper motion!
Fermi “instantly” gives us >10 years of data with which to perform pulsar timing.

An error in the position of a pulsar produces an annual sinusoid in the pulse arrival time. So an error in the proper motion produces a linearly-growing sinusoidal error (chirp).

Unfortunately, young pulsars are far from ideal! Plot at right shows the pulsar with only its simple spindown and position modeled. The residual is timing noise.

With Fermi, we have reliably measured proper motions really only for millisecond pulsars (low timing noise).
Unfortunately, we also don’t know what the true pulse profile looks like... We need the profile to get the timing solution, and we need the timing solution to the profile!

So, we tried a range of models of timing noise while jointly fitting a model for the template.

A model with three sinusoidal components fully fit the data, an unusually red timing noise signal.

Fermi Pulsar Timing
Best-fit timing noise and pulsar timing model prefer proper motions that agree in magnitude and direction with the values required by the PWN-SNR direction and the PWN-SNR offset/SNR age!

(This is one of the only gamma-ray pulsars with a measured proper motion – a real testament to the quality of Fermi data.)
Rule out $\mu<63$ mas/yr with 95% confidence

**Measured:**
$\mu=115\pm33$ mas/yr (3.5$\sigma$)
$\theta_\mu=121\pm13^\circ$

**Inferred:**
$\mu=\Delta\theta/\tau=168\pm35$ mas/yr
$\theta_\mu=113\pm2^\circ$

What can we learn from the association?
How pulsars get their kicks (and spins)

Highest $V_{PSR}$ provide severe constraints on models

- $x$ binary disruption

- $x$ electromagnetic ("Rocket effect")

- ✔ neutrino-driven ($E_0=10^{53}$ erg)
  - $V_{PSR}$ aligned with $\Omega$

- ✔ ejecta-driven (hydro recoil; $E_k=10^{51}$ erg)
  - $V_{PSR}$ anti-aligned with $V_{ejecta}$

Wongwathanarat, Janka and E. Müller (2013)
Hydrodynamic or Ejecta-driving Kicks

Originate in large-scale asymmetries seen in CC SNe explosion modeling

Signature in the SNR morphologies and (heavy element) ejecta distribution

What does the SNR CTB1 tells us?

Evidence for asymmetry in CTB 1

X-rays are offset to NW but mixed morphology so SNR is likely dominated by ISM
X-ray spectra have enhanced heavy element abundances
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High PSR velocity requires very asymmetric explosion
  – i.e. $M V_{PSR}^2 = 20\% E_k$

Asymmetry Parameter

In general, bow shock nebulae provide a “clean” probe of the pulsar wind. Resolving the bow shock is a direct probe of the ISM density/pressure. Radio and X-ray spectra characterize the injected particles and their evolution downstream.
New observations

C & X band VLA observations

10X higher resolution
A new, very high-velocity (>1000 km/s) pulsar associated with a middle-aged supernova remnant provides insight into, and hopefully some constraints on, core collapse and pulsar kicks.

- PSR was not born spinning rapidly ($P_0 \approx 113 \text{ ms}$)
- highly asymmetry SN was required to give PSR its natal “kick”

A new bow shock nebulae, potentially one of the closest with such a high Mach number, provides a new way to probe pulsar winds and the ISM.

- Physical properties are similar to a subset of bow-shock PWN that includes The Duck, The Mouse and the Frying Pan

Hoping for Chandra imaging of the PWN head to detect the youngest injected electrons and measure flow properties.

VLBA+VLA+Effelsberg VLBI observations will determine parallax and more accurate proper motion (in two years).

Future high-frequency VLA observations can resolve the head to measure standoff distance and Mach disk; polarimetry to study magnetic field in downstream flow.
The Distance to PSR J0002+6216

\[ \text{DM}_e = 2n_eR_s \sqrt{1 - \left( \frac{R}{R_s} \right)^2} \]

<table>
<thead>
<tr>
<th>Distance (kpc)</th>
<th>DM$_e$ (pc cm$^{-3}$)</th>
<th>EM$_e$ (pc cm$^{-6}$)</th>
<th>A$_v$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>4x10$^4$/L$_{pc}$</td>
<td>0.9</td>
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<tr>
<td>2</td>
<td>130</td>
<td>1.7x10$^4$/L$_{pc}$</td>
<td>1.3</td>
</tr>
<tr>
<td>3.5</td>
<td>50</td>
<td>2500/L$_{pc}$</td>
<td>2.1</td>
</tr>
</tbody>
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Bottom line:

- d=2 kpc is the closest distance that satisfies all constraints
- Agrees with empirical relation between L$_\gamma$ and $\dot{E}$
If the association is real why is $\tau_{\text{SNR}} \ll \tau_c$?

$\tau_c$ assumes $P_o \ll P$

$n=3$ (dipole) \hspace{1cm} $P_o = P \sqrt{1 - \frac{\tau_{\text{SNR}}}{\tau_c}}$

PSR J0002+6216 was born with a period $P_o \sim 113$ ms

Consistent with there being a wide distribution of pulsar birth periods (10-300 ms)

Agrees with results of CC models of massive stars

\[ t_{\text{true}} = \frac{P}{(n-1)\dot{P}} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right], \text{ if } n \neq 1. \]