Jets from Runaway Pulsars

case study: the Lighthouse nebula

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PHAROS Workshop 2018
Jets from Runaway Pulsars

case study: the Lighthouse nebula

outline

- PWNe, PSR jets
- Lighthouse Nebula
  - PWN tail
  - jet & counter-jet
  - SNR association
- other systems
- open questions
Pulsar Wind Nebulae

Pulsar wind structure in the Crab Nebula

PSR J1747-2958 powering the “Mouse nebula”
Gaensler et al. (2004)
Pulsar wind structure in the Crab Nebula

PSR B0531+21 powering the Crab Nebula
Weisskopf et al. (2000)
PWNe - X-ray observations

*torus-jet PWNe*

![Images of PWNe](image)

*Kargaltsev & Pavlov (2008)*
PWNe - X-ray observations

bow-shock PWNe

Kargaltsev & Pavlov (2008)
anisotropic energy flux

\[ f_w = \frac{f_0}{r^2} \left( \sin^2 \theta + \frac{1}{\sigma_0} \right) \]
\[ \sigma_0 = \text{initial magnetization (} \gg 1) \]

“σ problem”

assume some mechanism is converting magnetic energy into kinetic energy at or before the termination shock

residual magnetic field distribution in the wind

\[ B = (4\pi f_0/c)^{1/2} \frac{\xi}{r} \sin \theta \left( 1 - \frac{2\theta}{\pi} \right) \]
\[ \xi = \text{wind magnetization} \]
\[ \sigma \approx 0 \text{ at } \theta = \pi/2 \text{ and } \theta = 0 \]
\[ \sigma \approx \xi^2 \text{ at } \pi/2 \gg \theta \gg 1/\sigma_0, \]

jet formation

- collimation of ultra-relativistic wind is difficult
- alternative (Lyubarski 2002); magnetic hoop stress on shocked pulsar wind. Very effective at middle \( \theta \) (eq. disk “surface layers”) as \( \sigma \) is high, and for which termination shock is closer to origin

Bogovalov & Khangoulyan (2002)

Komissarov & Lyubarsky (2003)
**discovery:** unclassified hard ISGRI source (4th IBIS/ISGRI catalog, *Bird et al. 2010*)

**association** (*Malizia et al. 2011, Pavan et al. 2011, Tomsick et al. 2012*):

- **X-rays:** archival data: *ROSAT, ASCA, Einstein, Swift-XRT, XMM-Newton, Chandra*
- **optical/IR:** STSCI-DSS and 2MASS surveys (source “N” only)
- **radio:** MOST (843 MHz): “compact” source (“N” and/or ”S”); Parkes (288 MHz): no pulsations
- **γ-rays:** EGRET 3EG J1102-6103 (but ~0.6° error circle); no *Fermi-LAT*
Chandra observations (PI: L. Pavan)

Obs-ID: 13787, $t_{\text{obs}} = 50$ ksec

ACIS-I at 0.8’ from “PSR”

- **“PSR”**: R.A. 11:01:44.9
  Dec. -61:01:38.66
- **“PWN”**: extended, 1.2’ from “PSR”
- **main-jet**: 5.5’ from “PSR”
  corkscrew modulation
  strong bend @ 1.4’ (chips?)
- **counter-jet**: 1.5’ from “PSR”

MSH 11-61-A (archival):
Obs-ID: 2754, 3720 $t_{\text{obs}} = 66$ ksec
**Chandra observations**

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{H}}$ ($10^{22} \text{ cm}^{-2}$)</th>
<th>$\Gamma$</th>
<th>$F_{2-10 \text{ keV}}$ ($10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$)</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR</td>
<td>1.0±0.2</td>
<td>1.1±0.2</td>
<td>6.1±0.6</td>
<td>1.09 / 70</td>
</tr>
<tr>
<td>PWN</td>
<td>0.8±0.1</td>
<td>1.9±0.1</td>
<td>6.7±0.5</td>
<td>0.82 / 76</td>
</tr>
<tr>
<td>Main jet</td>
<td>0.8±0.2</td>
<td>1.6±0.2</td>
<td>5.4±0.5</td>
<td>1.08 / 65</td>
</tr>
</tbody>
</table>

$L_{X,\text{jet}} = 3.80 \times 10^{33} d_{7\text{kpc}}^2 \text{ erg s}^{-1}$

$L_{X,\text{PSR}} = 3.85 \times 10^{33} d_{7\text{kpc}}^2 \text{ erg s}^{-1}$

$L_{X,\text{PWN}} = 3.91 \times 10^{33} d_{7\text{kpc}}^2 \text{ erg s}^{-1}$

PSR

PWN

Main jet

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Tuesday, March 20, 2018
**SNR association**

**IGRJ11013-6103 & MSH 11-61A**

- **core-collapse** SN explosion from massive star \((García et al. 2012)\)
- **no point-like source** inside SNR
- similar column density
  \[
  N_{H, J11} = [0.8 \pm 0.2] \times 10^{22} \text{ cm}^{-2} \\
  N_{H, MSH} = [0.6 \pm 0.2] \times 10^{22} \text{ cm}^{-2}
  \]
  \[\Rightarrow d_{J11} \sim d_{MSH} = 7 \text{ kpc}\]
- age MSH 11-61A = 10-20 kyr
- \(\theta_{MSH - J11} \sim 11 \text{ arcmin}\)
  \[\Rightarrow v_{J11} \sim (1100 - 2200) d_7 \text{ km/s}\]
- \(\theta_{jet} \sim 5.5 \text{ arcmin}\)
  \[\Rightarrow l_{jet} \sim 11.5 d_7 \text{ pc}\]
bow-shock and PWN

⇒ $v_{J11} \geq 1200$ km/s (d = 7 kpc, $L_{sd} \sim 10^{36}$, $n=0.1$)

\[
\delta_{SO} = 0.266 \frac{\cos^2 i}{v_{r,3d_{10}}} \left( \frac{E_{36}}{n_{0.1}} \right)^{1/2}
\]
\[
R(\phi) = \frac{R_{SO}}{\sin \phi} \sqrt{3 \left( 1 - \frac{\phi}{\tan \phi} \right)}
\]
IGR J11014-6103

**ATCA observations**

- $t_{\text{obs}} = 2 \times 12\text{h}; \text{freq.} = 2\text{GHz}$
- MGPS J110149-610104 **clearly resolved**
- PWN extension $\sim$ X-ray extension
- pulsar and jets are **not detected**
- integrated flux density $= 23 \pm 2\text{mJy @ 2GHz}$
- flat-spectrum (typical of PWN in radio)
Chandra & ATCA observations

IGR J11014-6103
Chandra & ATCA observations

IGR J11014-6103

Chandra (0.5-10 keV)

ATCA (2GHz)

Flux in arbitrary units

Distance from the PSR (arcsec)
Chandra & ATCA observations

PWN synchrotron emission

\[ d = 7 \text{ kpc}, \ \theta_{\text{peaks}} \sim 22'', \ \nu_{\text{PSR}} \approx 1000 \text{ km s}^{-1} \]

\[ t_{\text{peaks}} \sim \theta_{\text{peaks}} d / \nu_{\text{PSR}} \]

\[ t_{\text{peaks}} \gtrsim t_{\text{sync}}(E_{e^-}, B_{\text{PWN}}) \approx 422 \frac{E_{e^-}}{B_{\text{PWN}}^2} \text{ s} \]

\[ h\nu_c = 5 \text{ keV} \approx 5.2 B_{\text{PWN}} E_{e^-}^2 \]

\[ B_{\text{PWN}} \gtrsim 20 \mu \text{G}, \ \gamma_{e^-} \gtrsim 3 \times 10^8 \]

\[ \theta_{\text{peaks}} \sim 22'' \]

IGR J11014-6103
PWN nature

- observational evidences
  - lack of any other counterpart within MSH 11-61A
  - IGR J11: "PSR" source + tail towards MSH
  - column density $N_{H, J11} \sim N_{H, MSH}$
  - high-velocity bow-shocked PWN morphology
  - typical radio/X-ray PWN spectra
  - lack of pulsations
    ($\sim 30\%$ Chandra PWN candidates)

- phenomenological correlations
  - $L_x$ (measured) $\approx 1.2 \times 10^{34}$ erg/s (@ 7 kpc)
    $\rightarrow$ young pulsar ($\sim 10^4$ yrs $\sim t_{SNR}$)
  - $\log L_x (2{-}10$ keV) $= 1.34 \log L_{sd} - 15.34$
    $\rightarrow L_{sd} \sim 3.5 \times 10^{36}$ erg/s (OK with $R_{bs}$)

  $\Rightarrow$ X-ray pulsations detected with XMM-Newton
  $P = 62.8$ ms, $L_{sd} \sim 1.4 \times 10^{36}$ erg/s
@ 7 kpc, \( l_{\text{jet}} \geq 11.5 \) pc
(longest Galactic X-ray jets)

- precession-like pattern
- faint counter-jet (Doppler?)

- chance prob. for an external, unrelated feature \( \sim \) negligible:
  - alignment jet/counter-jet
  - flux change @ “PSR” position

- main jet \( \sim 1/3 \) of total flux
- no signatures of bending
  (but diffuse emission @ jet tip?)

 DataGridView J11014-6103 jets

extreme properties as compared to archetypical PWN jets

how can ultra-fast runaway pulsars develop and maintain large-scale jets?
precession model

➤ fit with ballistic jet model
➤ best fit values:

\[ \beta = 0.8 \ c, \]
\[ \tau_{\text{prec}} = 66 \ \text{yrs} \]
\[ \alpha_{\text{prec}} = 4.5^{\circ} \]

inclination = 50\(^{\circ}\)

➤ byproduct: internal Doppler

⇒ jet brightness profile recovered
IGR J11014-6103 jets

jet synchrotron emission

\[ d = 7 \text{ kpc}, \theta_{\text{jet}} \sim 5.5'' , \nu_{\text{jet}} \approx 0.8 \text{ c} \]

\[ t_{\text{travel}} \sim \theta_{\text{jet}} d_7 (\sin i)^{-1} / \nu_{\text{jet}} \]

\[ t_{\text{sync}}(E_{e^-}, B_{\text{jet}}) \approx 422 E_{e^-}^{-1} B_{\text{jet}}^{-2} \text{ s} \]

no spectral break \( \Rightarrow t_{\text{travel}} \lesssim t_{\text{sync}}(E_{e^-}, B_{\text{jet}}) \)

synchrotron characteristic frequency:

\[ h\nu_c = 5 \text{ keV} \approx 5.2 B_{\text{PWN}} E_{e^-}^2 \]

Larmor radius:

\[ r_L \approx 1.75 \times 10^{25} E_{e^-} B_{\text{jet}}^{-1} \text{ cm} \]

\[ R_{\text{jet}} \sim 2.3 \times 10^{17} d_7 \text{ cm} \geq r_L \]

\[ \Rightarrow B_{\text{jet}} \approx (10 - 50) \mu \text{G}, \gamma_{e^-} \approx (1.5 - 3.0) \times 10^8 \]

(assuming equipartition \( \Leftrightarrow \) minimum energy condition: \( B_{\text{jet}}^{\text{equip}} \approx 15 \mu \text{G} \)
Jet bending in binary systems

problem: why jets are not bended?

- IGR J11 jets $\geq 11.5$ pc (see also Guitar Nebula) with **no clear signature of bending**
- curvature radius from Euler equation for a cold, relativistic plasma:

$$R_{\text{curv}} \propto \frac{L_{\text{jet}} (R_{\text{jet}})^{-2}}{\rho_{\text{ISM}} (v_{\text{psr}})^2}$$

$\Rightarrow$ jet has to be **powerful**

$\Rightarrow$ and/or has to be **extremely well-collimated**

$\Rightarrow$ **how does a high pulsar proper motion affect jet-launching and propagation?**

Jet bending in binary systems

*(from Soker & Bisker 2006)*
re-observations of the Lighthouse Nebula

➤ 250 ksec Chandra observations (Pavan, Bordas, Pülhofer et al. 2016)
re-observations of the Lighthouse Nebula

- *Chandra* pointings optimised for main-jet studies (e.g. avoiding chip gaps, dead columns)
- **spatial discontinuity**: not an instrumental effect, but intrinsic to the jet
- several “stripes” developing almost parallel to the main jet. Low S/N, no firm constraints on geometry
- jet "bending": close to the pulsar, but still outside the shocked wind region
- helical (precession) model: good fit for outer regions, failing for the “gap” close (50”- 90”) to the pulsar
- limits on pulsar proper motion: $\mu_{\text{PSR}} \leq 0.3\"$ in line with 0.03”/yr for $v_{\text{PSR}} = 1000$ km/s at $d = 7$ kpc

*Pavan et al. (2016) from Kargaltsev et al. (2017)*
The “Guitar Nebula”

- powered by PSR B2224+65
  - \( L_{sd} \approx 1.2 \times 10^{33} \text{ erg/s} \)
  - age \( \approx 10^6 \text{ yrs} \)
- runaway pulsar: velocity = 800 km/s
- extended (2') jet-like feature ~ 1.2 pc
- feature is moving along with PSR
- hints of counter-feature
- jet origin:
  - ballistic, relativistic jet
  - \textit{diffusion of energetic e^+/e^- into ISM + confinement by organized, planar ambient magnetic field} (Bandiera 2008)

other systems

PWN J1509-5850

- powered by PSR J1509-585054
  - $L_{sd} \approx 1.8 \times 10^{35} \text{ erg/s}$
  - age $\approx 1.5 \times 10^5 \text{ yrs}$
- runaway pulsar: velocity = 200-600 km/s
- extended (2') jet-like feature $\sim 9 \text{ pc}$

The Mushroom

- powered by PSR B0355+54
  - $L_{sd} \approx 1.7 \times 10^{34} \text{ erg/s}$
  - age $\approx 5 \times 10^5 \text{ yrs}$
- runaway pulsar: velocity = 62 km/s
- extended (2') jet-like feature $\sim 1.1 \text{ pc}$

Kargaltsev et al. (2017)
3D MHD simulations of fast moving PWN

**goal**

- probe particle escape + diffusion into ambient magnetic field scenario (Bandiera 2008)
- make use of PLUTO code (Mignone 2007)
- flow approximated as a **relativistic gas of one particle species**, and with Taub equation of state.
- **non-uniform resolution** in the computational domain. total number of cells $NX = 468$, and $NY = NZ = 336$.

**(preliminary) results:**

- **“kinetic jets”** readily produced, and are highly **asymmetric**
- ISM B-field lines are **draped around the PWN**. A narrow layer at near-equipartition values forms at the contact discontinuity (Dursi & Pfrommer 2008)
- contact discontinuity becomes rotational disc. with B-fields of similar strengths at both sides $\Rightarrow$ **reconnection**
- efficiency of reconnection at the contact discontinuity will depend on the **relative orientation of PWN and ISM fields**

Barkov et al. (in prep)
summary

- increasing observational evidences of **large-scale, ~linear features** produced in fast-moving PWNe

- **pulsar jet theory is robust** - provides close description/prediction for Crab or Vela-like jets

- external pressure should **bend** these multi-pc structures, **not observed**

- alternative scenarios: **diffusion of high-energy particles** accelerated at the PWN shock interface, leaking then into surrounding B-field lines

- 3D MHD simulations **can explain/confirm** such diffusion model, predicting also **jet/counter-jet asymmetry**

- several open questions: bending signatures in some instances, why large-scale jets appear (mainly) in super-fast runaway PSRs? Radio counterparts to the jets?

Thanks for your attention!
BACKUP
open questions: jet precession

- free pulsar precession through ISM
  - pulsar oblateness constraints: $\epsilon \sim 10^{-10}$ (~ Crab, Vela)
- MHD Kink instabilities (no periodicity)
  - counter-jet disappearance: destroyed?
  - $L_{\text{kink}} \sim 10$ jet radii (~ abrupt bending)
  - main-jet destroyed after ~ one precession period

IGR J11014-6103, Pavan et al. (2014)

Vela PWN, Durant et al. (2013)
PWNe - kick velocity, pulsar spin

- jets are in most systems ejected **along the pulsar spin axis**
- **velocity - spin correlation** in most models (Spruit & Phinney 1998, Lai et al. 2001)
- several SN explosion “**kick models**” and mechanisms have been suggested
  - hydrodynamical kicks
  - asymmetric neutrino emission (Lai & Qian 1998)
  - electromagnetic rocket postnatal kick (Harrison & Tademaru 1975)
  - binary proto-NS + disruption (Colpi & Wasserman 2002)
open questions: kick velocity, spin axes, SN mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Time scale</th>
<th>$V_{\text{max}}$, km s$^{-1}$</th>
<th>Alignment (spin and V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrodynamical</td>
<td>0.1 s</td>
<td>$(100-200)$</td>
<td>random</td>
</tr>
<tr>
<td>$v$-driven</td>
<td>~few s</td>
<td>$\sim 50 R_\odot$</td>
<td>parallel</td>
</tr>
<tr>
<td>Electromagnetic rocket</td>
<td>long</td>
<td>$1400 R_\odot^2 P_{\text{ms}}^2$</td>
<td>parallel</td>
</tr>
<tr>
<td>Binary disruption (without add. kick)</td>
<td>$\ll P_{\text{orb}}$</td>
<td>$\sim 1000$</td>
<td>perpendicular</td>
</tr>
<tr>
<td>NS instability</td>
<td>few ms</td>
<td>$\sim 1000$</td>
<td>perpendicular</td>
</tr>
<tr>
<td>Magnetorotational</td>
<td>0.2 s – min</td>
<td>(up to 1000)</td>
<td>quasirandom</td>
</tr>
</tbody>
</table>

- **kick velocities** and **spin mis/alignment**:  
  - depend on SNe explosion mechanisms + post-natal kicks  
  - ultra-fast ($\geq 1000$-2000 km/s) + misalignment are **very rare**  
  - **binary disruption models** can explain it, but a large angular momentum of collapsing iron core is required.  
    *Imshennik & Popov (1998), Colpi & Wasserman 2002*  
- MSH 11-61A ears: "echoes from a past core-collapse SN"?  
  - asymmetry from as **massive star wind anisotropy**  
  - (highly speculative): **roughly aligned** with IGRJ11014’s jets…


García et al. (2012)
new Chandra observations in 2015 (250 ksec)
IGR J11014-6103: echoes from a core-collapse supernova

MSH 11-61A

García et al. (2012)