Young X-ray pulsars and ULXs

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Thanks also to: Rosalba Perna (JILA-Boulder)
Luigi Stella (INAF-Rome)
Content

- What are the most luminous non-nuclear X-ray sources in galaxies? 
  (Ultraluminous X-ray sources = ULXs)

- Black hole X-ray binaries powered by accretion?

- Young neutron stars powered by spin-down?

- Search for luminous young X-ray pulsars in the Milky Way and nearby galaxies

- Constraints to the initial NS spin distribution
What are ultraluminous X-ray sources (ULXs)

Non-nuclear X-ray sources with apparent $L_x \sim 10^{39} - 10^{40}$ erg/s

NGC6946 (d ~ 6 Mpc)  Antennae (d ~ 20 Mpc)
What are ultraluminous X-ray sources (ULXs)

Non-nuclear X-ray sources 
with apparent $L_x \sim 10^{39}-10^{40}$ erg/s

Most luminous X-ray source in the Milky Way: 
GRS 1915+105: $L_x \sim 1 \times 10^{39}$ erg/s

Peak luminosity of MW X-ray binaries in outburst 
$L_x \sim 0.5 - 1 \times 10^{39}$ erg/s

Eddington luminosity for “typical” stellar-mass BHs: 
$L_x \sim 1 \times 10^{39}$ erg/s
What are ultraluminous X-ray sources (ULXs)

Non-nuclear X-ray sources with apparent \( L_x \sim 10^{39}-10^{40} \) erg/s

If ULXs are powered by **accretion**, they require either:

- Higher BH masses (100 \( M_{\text{sun}} \) ? 1000 \( M_{\text{sun}} \) ?)
- Moderately beamed emission
- Super-Eddington luminosity

But no such problem (no Eddington limit) if ULXs are not powered by accretion
Most luminous X-ray sources ($L_x \sim 10^{40}$ erg/s) found in starburst, starforming or colliding galaxies (not in massive ellipticals)

High-mass X-ray binaries?
Supernovae, young supernova remnants?
Young pulsars?

(Swartz et al 2004)
Supernovae produce (mostly) thermal emission from shocked gas after the *reverse shock* (shocked ejecta)

**Diagram:**
- **Undisturbed ISM/CSM**
- **Shocked ISM/CSM**
- **Hot (shocked) ejecta**
- **Cold ejecta**
Young SNe can have $L_x \sim 10^{39} - 10^{41}$ erg/s
But steady decline over $\sim 1000$ yr

(Immler & Kuntz 2005)
Young supernovae cannot explain ULXs (= power-law-dominated X-ray spectra)

SN1993J in M81 (Zimmermann & Aschenbach 2003)

Mekal spectrum

ULX in Holmberg II

Power-law + diskbb
SNe and SNR have softer X-ray colours than ULXs, X-ray pulsars and XRBs.

(Soria & Wu 2003)

(Swartz et al 2004)
Composite supernova remnants:
fast-spinning pulsar and pulsar wind nebula inside the expanding SN remnant

Gaensler BM, Slane PO. 2006.
Gallery of X-ray bright pulsar wind nebulae

3C58

B1509-58 / G320.4-1.2

Vela

Crab

G54.1+0.3

(Gaensler & Slane 2006)
Gallery of X-ray bright pulsar wind nebulae

(Kargaltsev & Pavlov 2008)
Pulsar J1846-0258 (Kes 75)

Age ~ 900 yr
P = 324 ms
B = 5E13 Gauss
D = 6 kpc
Edot ~ 1E37 erg/s
L_x ~ 2E36 erg/s

155ks Chandra observation from 2006, Ng et al (2008)
Magnetospheric emission + wind nebula powered by pulsar spin-down

\[ \dot{E}_{\text{rot}} = \frac{4\pi^2 \dot{P}}{P^3} = \frac{B^2 \sin^2 \theta \Omega^4 R^6}{6c^3} \sim B^2 P^{-4} \]

\[ B \approx 6.4 \times 10^{19} (P \dot{P})^{1/2} \text{ G} \]

From radio pulsar measurements and evolution models: magnetic field at birth

\[ \log B_0 (\text{G}) \approx 12.35 \pm 0.40 \quad \text{(Arzoumanian et al 2002)} \]
\[ \log B_0 (\text{G}) \approx 12.65 \pm 0.55 \quad \text{(Faucher-Giguere & Kaspi 2006)} \]

\[ L_X \approx a \dot{E}_{\text{rot}}^{1.34} \sim B^{2.7} P^{-5.4} \]
On-line pulsar catalog
from the Australia Telescope National Facility
\[ \dot{E}_{\text{rot}} = \frac{4\pi^2 \dot{P}}{P^3} = \frac{B^2 \sin^2 \theta \Omega^4 R^6}{6c^3} \sim B^2 P^{-4} \]
\[ L_X \approx a \dot{E}_{\text{rot}}^{1.34} \sim B^{2.7} P^{-5.4} \]

\[ L_X (psr) \approx a \dot{E}^{1.6}_{rot} \]

\[ L_X (pwn) \approx a \dot{E}^{1.3}_{rot} \]

\[ L_{X,obs} = L_X (psr) + L_X (pwn) \]

Kargaltsev & Pavlov (2008) based on Chandra data
Maximum luminosity limited only by initial NS spin and magnetic field *(no Eddington limit)*

Then $L_x$ declines with time, after a timescale $\sim 10^3$ yr

$$P(t) = \left[ P_0^2 + \left( \frac{16\pi^2 R^6 B^2}{3Ic^3} \right) t \right]^{1/2} \sim (a + bt)^{1/2}$$

$$\dot{E}_{rot} \sim B^2 (a + bt)^{-2}$$

$$L_X \sim B^{2.7} (a + bt)^{-2.7}$$
\[ \dot{E}_{\text{rot}} \sim B^2 t^{-2} \]
Different X-ray components

- P-L synchrotron emission from pulsar magnetosphere
- BB emission from polar cap (heated by polar-gap current)
- BB emission from polar cap (heated by outer-gap current)
- P-L synchrotron emission from wind nebula (jet, torus, termination shock)

Spatially unresolved in other galaxies

$L_x$
Expected spectral appearance:
Power-law (photon index ~ 2)
+ soft bb component (T ~ 0.2 keV)

(possibly in addition to optically-thin thermal-plasma emission from the surrounding SNR)
Pulsar+PWN X-ray spectra may look similar to the X-ray spectra of ULXs. Just a coincidence?
Young X-ray pulsars
$P_0, B_0$

Old radio pulsars
$P(t), B(t)$

Infer $P_0, B_0$
for young pulsars

Determine $P(t), B(t)$
from old pulsars

[Evolution models]
Young X-ray pulsars
\[ P_0, B_0 \]  

**VERY FEW OF THEM**

Old radio pulsars
\[ P(t), B(t) \]  

**LOTS OF THEM**

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Infer \( P_0, B_0 \) for young pulsars

**Calculate X-ray luminosity expected for those \( P_0, B_0 \)**

Measure X-ray luminosity of young pulsars in nearby galaxies

**Direct way to constrain \( P_0, B_0 \)**
Observed distribution of old radio pulsars

Evolution models by Arzoumanian et al. (2002)

Predicted X-ray luminosity of pulsars at birth

\[
\log B_0 \approx 12.5 \pm 0.5 \\
\log P_0 \approx -2.0 \pm \sigma_P
\]

\(f_{\text{birth}}(>L_x)\)

\(L_x \text{ (erg/sec)}\)

\(\sigma_{P_0} = 0.5\)

\(\sigma_{P_0} = 0.4\)

\(\sigma_{P_0} = 0.3\)

(Stella & Perna 2004)
Predicted number of X-ray pulsars and high-mass X-ray binaries as a function of star-formation-rate

\[ N(>L_x) / \text{(SFR)} \]

- young pulsars
- HMXBs

(Stella & Perna 2004)
We measured or constrained the X-ray luminosity of ~ 100 historical SNe with ages ~ 10-100 yrs (Chandra, XMM, Swift data).

We found fewer (fainter) X-ray pulsars than predicted (Perna et al 2008).
Assuming we know birth rate and magnetic field

Constraints on birth period

For a log-normal distribution,

\[ \langle P_0 \rangle > 50 \text{ ms} \]

(Perna et al 2008)
X-ray luminosity associated with every core-collapse SN from 1900-1970 in galaxies at distances <= 15 Mpc

<table>
<thead>
<tr>
<th>SN ID</th>
<th>Type</th>
<th>Galaxy</th>
<th>Distance (Mpc)</th>
<th>Chandra time available (ks)</th>
<th>Chandra time requested (ks)</th>
<th>X-ray SN?</th>
<th>$L_{0.3-8}$ (erg s$^{-1}$)</th>
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<td>II</td>
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<td>-</td>
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<td>-</td>
<td>30</td>
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<td>(5)$^c$</td>
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<td>?</td>
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<tr>
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<td>Ib</td>
<td>N3198</td>
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<td>(62)$^c$</td>
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<td>?</td>
<td>?</td>
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<td>1969L</td>
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<td>1970G</td>
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<td>7.4</td>
<td>140</td>
<td>-</td>
<td>Y$^d$</td>
<td>$\approx 10^{37}$</td>
</tr>
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</table>
One of the very few Crab-like young pulsar candidates, at the location of SN 1968D in NGC 6946 ($L_x \sim 10^{37}$ erg/s) (Soria & Perna 2008)
Our X-ray survey result agrees with the pioneering study of Srinivasan et al (1984), based on X-ray and radio luminosity of young Galactic SNRs.
Low angular parameter at birth:

\[ \frac{\alpha}{M} \approx 0.015 \left( \frac{50 \text{ ms}}{P} \right) \]

consistent with Spruit & Phinney’s (1998) model, initial spin ~ kick velocity

Not enough energy at birth to power a hypernova

\[ E_{\text{rot}} \approx 10^{49} \text{ erg for } P = 50 \text{ ms} \]
\[ E_{\text{rot}} \approx 3 \times 10^{52} \text{ erg for } P = 1 \text{ ms} \]

Consistent with Vink & Kuiper’s (2006) study of magnetar/SNR associations

Implies pre-collapse Fe core \( P \sim 50-100 \text{ s} \)

(Revised 2006)
Almost all NS pulsars born with P > 40 ms

Why? Is it true also for stellar BHs? Are BHs born with angular parameter a ~ 0.01?

High-energy pulsars are a small fraction of X-ray population (Crab-like systems are rare)

Alternative possibility:

Is the NS birth rate overestimated?

Perhaps a larger fraction of core-collapse SNe forms BHs or leaves no remnant?

Do many SNe produce quark stars (expected to be X-ray fainter) instead of neutron stars?
Ultraluminous X-ray sources (ULXs) cannot be high-energy pulsars.

ULXs = accreting X-ray binaries with BH + donor star

- $L_x \approx 10^{37}$: Young pulsars
- $L_x \approx 3 \times 10^{38}$: NS XRBs
- $L_x \approx 10^{39}$: Stellar BH XRBs
- $L_x \approx 10^{40}$: ULXs

Higher BH masses ($100 \ M_{\text{sun}}$? $1000 \ M_{\text{sun}}$?)

ULXs

Beamed emission

Super-Eddington emission