Ultraluminous X-ray pulsars

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Plan:

• ULX - general properties (before 2014)
• Models (before 2014)
• ULX pulsars: P, Pdot, B?
• In spin equilibrium or not? Beamed or not? Winds or not?
Ultra- Luminous X-ray Sources

ULX are discovered with Einstein observatory in the 80s.

- Bolometric luminosity > Eddington limit for a $20 \, M_\odot$ black hole ($3 \times 10^{39}$ erg/s) - $M_{BH} < 20 \, M_\odot$
- Not at galaxy nucleus (not AGN)
- Unresolved (< 0.6” with Chandra)

HST and Chandra images of the star-forming galaxy NGC4038-the “Antennae”
Models for ULX (before 2014)

- Super-Eddington accretion onto a stellar-mass black hole (e.g. King 2001, Begelman et al. 2006, Poutanen et al. 2007)
- Sub-Eddington accretion onto intermediate mass black holes (Colbert & Mushotzky 2001)
- Young rotation-powered pulsar (Medvedev & Poutanen 2013)
- Accreting X-ray pulsars (discussed by us already in 2010).
Super-Eddington accretion

- **Slim disk models** Accretion rate is large, but most of the released energy is advected towards the BH.

\[ \dot{M}(r) = \dot{M}_0 \]

- **Super-disks with winds**

  Accretion rate is large, but most of the mass is blown away by radiation. Only the Eddington rate goes to the BH.

\[ \dot{M}(r) = \dot{M}_0 \frac{r}{R_{sph}} \]

\[ \dot{M}(r_{in}) = \dot{M}_{Edd} \]

\[ R_{sph} \approx R_{in} \frac{\dot{M}_0}{\dot{M}_{Edd}} \] - spherization radius

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Shakura & Sunyaev 1973
Super-Eddington accretion

• Slim disk models
  Accretion rate is large, but most of the released energy is advected towards the BH.

\[ \dot{M}(r) = \dot{M}_0 \]

• Super-disks with winds
  Accretion rate is large, but most of the mass is blown away by radiation. Only the Eddington rate goes to the BH.

\[ \dot{M}(r) = \dot{M}_0 \frac{r}{R_{sph}} \]

\[ \dot{M}(r_{in}) = \dot{M}_{Edd} \]

\[ R_{sph} \approx R_S \frac{\dot{M}_0}{\dot{M}_{Edd}} \]

-spherization radius

Ohsuga et al. 2005;
Super-Eddington accretion

Super-disks with winds and advection

Accretion rate is large, a lot of mass is blown away by radiation (using fraction $\varepsilon_W$ of available radiative flux), but still a significant fraction goes to the BH.

$$\dot{M}(r) = \dot{M}_0 + \left( \dot{M}_0 - \dot{M}_{in} \right) \frac{r}{R_{sph}}$$

$$\frac{\dot{M}_{in}}{\dot{M}_0} = \frac{1 - a}{1 - a(0.4\dot{m}_0)^{-1/2}}$$

$$a = \varepsilon_W(0.83 - 0.25\varepsilon_W)$$

Poutanen et al. (2007)
ULX pulsars

- M82 X-2 pulsar was discovered by Nustar (Bachetti et al. 2014)
- Pulsations were searched for before with XMM-Newton without much success.
- Two more sources were found later in XMM-Newton and Nustar data (Israel et al. 2017a,b; Fürst et al. 2017).
M82 X-2

Bachetti et al. 2014
M82 X-2

- Orbital period 2.518 days
- Mass function 2.1 solar mass =>
- For 1.4 solar mass neutron star, companion has $M_c > 5.2$ solar mass for $i < 60$ deg.
- Unstable accretion from a more massive companion on thermal timescale => huge Mdot (like SS433).
M82 X-2 spin up

<table>
<thead>
<tr>
<th>ObsId</th>
<th>MJD</th>
<th>Period (s)</th>
<th>Period derivative (s/s)</th>
<th>Period 2nd derivative (s/s²)</th>
<th>TOA Scatter (ms)</th>
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<tr>
<td>006</td>
<td>56685.5</td>
<td>1.3726001(4)</td>
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<td>011</td>
<td>56719.8</td>
<td>1.3722225(6)</td>
<td>-2.73(7)×10⁻¹⁰</td>
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<td>14</td>
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</table>
Spin equilibrium in M82 X-2

- $P/P_{\text{dot}} = 300$ yr
- Object has to be close to spin equilibrium.
- $P_{\text{dot}}$ (which even changes the sign) does not really tell anything about $M_{\text{dot}}$ or B-field, because the accretion and magnetic torques are in balance.
- Maximum $P_{\text{dot}}$ gives a lower limit on the accretion rate.
Minimum Mdot

- Maximum spin up torque is

\[ -\frac{2\pi I \dot{P}}{P^2} \leq \dot{M} (G M r_c)^{1/2} \]

\[ \dot{M} \geq 3.55 \times 10^{18} \dot{P}_{-10} P^{-7/3} \text{ gs}^{-1} \]

- M82 X-2

\[ \dot{P} \simeq -2.7 \times 10^{-10} \text{ ss}^{-1} \]

\[ \dot{M} \geq 4.6 \times 10^{18} \text{ gs}^{-1} \]
Possible propeller effect in M 82 X-2
Tsygankov et al. 2016

Transitions due to propeller effect at $R_m = R_{CO}$?
NGC5907 ULX1

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission</td>
<td>XMM–Newton</td>
<td>NuSTAR</td>
<td>XMM–Newton</td>
<td>NuSTAR</td>
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<tr>
<td>Epoch (MJD)</td>
<td>52690.9</td>
<td>56848.0</td>
<td>56848.2</td>
<td>56851.5</td>
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<tr>
<td>$P$ (s)</td>
<td>1.427579(3)</td>
<td>1.137403(1)</td>
<td>1.137316(2)</td>
<td>1.136041(1)</td>
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<tr>
<td>$\dot{P}$ (s s$^{-1}$)$^a \times 10^{-9}$</td>
<td>-9.6(7)</td>
<td>-5.2(1)</td>
<td>-5.0(4)</td>
<td>-4.7(1)</td>
</tr>
</tbody>
</table>

Secular $\dot{P} = -8.1 \times 10^{-10}$ s s$^{-1}$

Israel et al. (2017)
Minimum Mdot

- Maximum spin up torque is

\[ -2\pi I \dot{P}/P^2 \leq \dot{M}(GMr_c)^{1/2} \]

\[ \dot{M} \geq 3.55 \times 10^{18} \dot{P}_{-10} P^{-7/3} \text{ gs}^{-1} \]

- M82 X-2

\[ \dot{P} \simeq -2.7 \times 10^{-10} \text{ ss}^{-1} \]

\[ \dot{M} \geq 4.6 \times 10^{18} \text{ gs}^{-1} \]

- NGC 5907

\[ -9.6 \times 10^{-9} \text{ ss}^{-1} \]

\[ \dot{M} \geq 1.5 \times 10^{20} \text{ gs}^{-1} \]
NGC5907 ULX1

(superorbital?) period 78 days (Walton et al. 2016)
NGC5907 ULX1

Israel et al. (2017)
Spectra cutoff at 10 keV

Fürst et al. (2017)
Israel et al. (2017)
Secular
\[ \dot{P} = -3 \times 10^{-11} \text{s s}^{-1} \]
Fürst et al. (2017); Israel et al. (2017)
NGC7793 P13

Israel et al. (2017)

Hu et al. (2017)

$P = 65 \text{ d}$

Superorbital?

$P_{\text{orb}} = 3 - 7 \text{ d}$
Large pulsed fraction

Fürst et al. (2017)
ULX-pulsars in a nutshell

- Large pulsed fraction, 20-30%, in all objects
- Huge variations in luminosity

<table>
<thead>
<tr>
<th>Name</th>
<th>M82 ULX2(^1)</th>
<th>NGC 7793 P13(^2)</th>
<th>NGC5907 ULX1(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_X(\text{max})) \ [\text{ergs}^{-1}]</td>
<td>(1.8 \times 10^{40})</td>
<td>(5 \times 10^{39})</td>
<td>(~10^{41})</td>
</tr>
<tr>
<td>(P_s) \ [s]</td>
<td>1.37</td>
<td>0.42</td>
<td>1.13</td>
</tr>
<tr>
<td>(\dot{\nu}) \ [s^{-2}]</td>
<td>(10^{-10})</td>
<td>(4 \times 10^{-11})</td>
<td>(4 \times 10^{-9})</td>
</tr>
<tr>
<td>(P_{\text{orb}}) \ [d]</td>
<td>2.51 (?)</td>
<td>64</td>
<td>5.3 (?)</td>
</tr>
<tr>
<td>(M_2) \ [M_\odot]</td>
<td>(\gtrsim 5.2)</td>
<td>18–23</td>
<td></td>
</tr>
</tbody>
</table>

or 3-7?
Characteristic radii

\[ R_c = \left( \frac{G M P^2}{4 \pi^2} \right)^{1/3} \]

=10^8 \text{ cm} \quad \text{Corotation radius}

\[ R_{\text{sph}} = R_* \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \]

\[ R_m = k \dot{M}^{-2/7} \mu^{4/7} (2GM)^{-1/7} \]

- \( k \) - depends on the disc structure
  (e.g. Chashkina, Abolmasov, JP 2017)

For M82 X-2 all radii are close to each other
(if no beaming is involved)
Accretion in ULX-pulsars

\[ R_c = \left( \frac{GM P^2}{4\pi^2} \right)^{1/3} \]

\[ R_{sph} = R_s \frac{\dot{M}}{\dot{M}_{Edd}} \]

\[ R_m = k \dot{M}^{-2/7} \mu^{4/7} (2GM)^{-1/7} \]

Kulkarni & Romanova 2013
Beaming?

- For example, King & Lasota (2016); King, Lasota, Kluzniak (2017) assume strong beaming (by accretion disc wind), by a factor 10-20.
- This also means that the orbital inclination has to be very small.
- The accretion rate is 40 Eddington ones and wind removes 90% of Mdot
- $B=10^{11}$ G, $R_m=20\ R_*$, Mdot to the star = 3 Mdot\_Edd.

- How to explain huge variations in the luminosity?
- How to explain $>30\%$ pulsed fraction?

- No strong beaming => large Mdot and large B.
Possible propeller effect in M 82 X-2

\[ R_m = R_c \rightarrow B \propto L_{ir} P_{sp}^{7/3} \]

\[ R_c = \left( \frac{G M P^2}{4\pi^2} \right)^{1/3} \]

\[ R_m = k \dot{M}^{-2/7} \mu^{4/7} (2GM)^{-1/7} \]
How to exceed the Eddington limit?

Geometrical effect
(accretion disc, accretion column; photons escape sideways)

Basko & Sunyaev 1976
Wang & Frank 1981
Lyubarskij & Sunyaev 1988
Mushtukov et al. 2015
Postnov et al. 2015
Kawashima et al. 2016

• Photon bubbles (Klein+1996; Begelman 2006)
• Strong B-field reduction of the scattering cross-section; for X-mode

\[ \sigma_\perp(E) \simeq \sigma_T \left( \frac{E}{E_{\text{cycl}}} \right)^2 \]
Spectrum formation in ULX-pulsars

1. Accretion disc – soft
2. Accretion column – hard
3. Optically thick envelope – anything in between
How to force the gas to accrete?

Lyutikov (2014)
ULX-pulsars: luminosity, B-field

Theoretical curve for maximum luminosity of an Eddington supported column (apparent can be larger due to beaming)

Propeller effect

Supercritical accretion disc

Column

Hot spot

7793

5907

M82X2
Conclusions

• ULX-pulsars clearly show that neutron stars can exceed Eddington limit by a factor of >100
• There is probably no strong beaming involved
• If the sources are close to the equilibrium (as supported by huge luminosity variations), the B-field has to be $10^{13}$-$10^{14}$ G.
• Highly super-Eddington luminosities can be reached due to geometric effects, reduced opacity and photon bubbles.