ULTRALUMINOUS X-RAY SOURCES

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Ç.Ü UZAYMER

Credit: X-ray: NASA/CXC/U. of Michigan
- \( L_x > 10^{39} \text{ erg/s} \) exceeding the Eddington limit for a stellar-mass (10 M\(_\odot\)) black hole

Eddington limit: \( L = 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ erg/s} \)
- ULXs are extragalactic off-nuclear point-like sources

- ULXs have not been found in our galaxy yet!

- The nature and formation mechanisms of ULXs remain unclear!
The most popular models

- **stellar-mass black holes** (~$10 \, M_\odot$) accreting at super Eddington rates (Shakura & Sunyaev 1973; Poutanen +2007).

- **intermediate-mass black holes** (IMBHs) of $10^2-10^4 \, M_\odot$ with standard accretion discs (Colbert & Mushotzky 1999, Miller & Colbert 2004)
the recent discoveries of three ULXs that exhibited pulsed X-ray emission as expected from neutron stars

- **M82 X-2** (Pulse period; \( P_s = 1.37 \)s), \((\text{Bachetti} + 2014)\)

- **NGC5907 ULX-1** (\( P_s = 1.1 \) s), \((\text{Israel} + 2017a)\)

- **NGC 7793 P13** (\( P_s = 0.4 \) s), \((\text{Furst} + 2016; \text{Israel} + 2017b)\)

make their nature highly controversial !!!!
The *Einstein* satellite (1978-1982) revealed for the first time a small number of ULXs in nearby galaxies (Long & van Speybroeck 1983; Fabbiano 1988, 1989; Stocke + 1991a,b).

The first systematic surveys of nearby galaxies for XRBs were done by *ROSAT* (1990-1999) (Colbert & Mushotzky 1999; Roberts & Warwick 2000).

The *XMM-Newton* and *Chandra* X-ray observatories (1999---) greatly increased the sensitivity and, critically, enabled accurate source localization. (Feng&Soria 2011, Kaaret,Feng&Robert, 2017)

yielding high-quality spectra and timing measurements: *ASCA*, *Suzaku*, *Swift*, *NuSTAR* ...
Catalogs

The largest samples of ULXs come from XMM-Newton due to its larger field of view and collecting area.

- Walton et al. (2011): 470 ULX candidates in 238 nearby galaxies (d<20 Mpc)

from Chandra

- Swartz et al. (2011): 107 ULX sources in 127 nearby galaxies (d < 14.5 Mpc)

The most luminous of ULXs, in late type, star-forming galaxies
Host Galaxies

- ULXs are found both in ellipticals and in spiral/irregular galaxies;

- 2/3 of ULXs, in ellipticals, ($L_X < 2 \times 10^{39}$ erg s$^{-1}$)

- in spirals, 1/3 of ULXs, ($L_X < 4-5 \times 10^{39}$ erg s$^{-1}$)

- about 10%, ($L_X > 10^{40}$ erg s$^{-1}$)

Feng & Soria, 2011
ULX Spectra

not like the canonical GBHB X-ray spectra

based on their spectral shape
and a multi-colour disc + power-law fit to
XMM-Newton EPIC data (Sutton + 2013)

- broadened disc (BD) states
- two-comp. hard ultraluminous (HUL)
- two-comp. soft ultraluminous (SUL)

BD: objects dominate $L_x = 3 \times 10^{39} \text{ erg s}^{-1}$, consistent population of stellar-mass BHs at mildly super-Eddington rates

HUL & SUL:
The contributions from MCD (blue dotted line) + PL (red dashed line) dominates $L_x = 3 \times 10^{39} \text{ erg s}^{-1}$
Figure 1: *(Left) XMM–Newton +NuSTAR* observation of NGC 1313 X-1 showing how NuSTAR data disentangle between the predictions of four models fitted in the XMM–Newton band; *(center-left)* the two observations of NGC 1313 X-2 in our sample (XMM–Newton only); *(center-right)* spectral variability shown by Holmberg IX X-1 in 2 weeks during our campaign and by *(right)* Circinus ULX5 in all available archival observations plus the NuSTAR +XMM–Newton pointings.
the X-ray spectral states and state transitions of ULXs

Three active states for Galactic BHBs: correspond to different accretion disc geometries

**Thermal**
- geometrically thin, optically thick accretion disk dominates the emission

**Hard**
- geometrically thick, optically thin Comptonizing region.
- non-thermal PL emission
  - $1.4 < \Gamma < 2.1$

**steep power law (PL)**
- defined by a softer spectrum having a photon index of $\Gamma > 2.4$
A similar correlation between luminosity and photon index has been found in ULXs X-1 in NGC 1313 (Feng & Kaaret 2006; Dewangan +2010).

IC342 ULX-1 and X-2 (Kubato +2001)

NGC 1313 X-1 (Dewangan +2011)

A few more work: X37.8+54 in M82 (Jin + 2010)
NGC 2403 src 3, Isobe +2009; IC 342 X-1, Marlowe +2014).
Quasi-Periodic Oscillations (QPOs)

- QPOs in X-ray binaries provide information about the inner accretion disk structure around the compact object (Mucciarelli +2006).
- Up to now, QPOs have been detected from a few ULXs in nearby galaxies.

ULX (X-1) in M82 (Strohmayer & Mushotzky 2003).

- 30 ks XMM-Newton observation
- QPO peak at 54 mHz rms of 8.5% in the (2-10) keV.
- Mass of BH in X-1 $M_{\text{BH}}<1.87\times10^4 \, M_\odot$ (from Schwarzschild geometry)

More:
- NGC 6946 X-1 (Rao +2010)
- NGC 5408 X-1 (Pasham&Strohmayer 2012)
- NGC 47376 X-2 (Avdan +2014)
List of ULXs exhibit X-ray QPO frequencies or periodicities

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>ULX</th>
<th>R.A.</th>
<th>Dec.</th>
<th>$L_x$ (10^{39} \text{ erg s}^{-1})</th>
<th>QPO Frequency (mHz)</th>
<th>Period (hour)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>CXO J095550.2+694047</td>
<td>09:55:50</td>
<td>+69:40:47</td>
<td>40–50</td>
<td>50–166</td>
<td>1488</td>
<td>1</td>
</tr>
<tr>
<td>M74 (NGC 628)</td>
<td>CXOU J013651.1+154547</td>
<td>01:36:51</td>
<td>+15:45:47</td>
<td>0.5–1.3</td>
<td>0.1–0.4</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>Holmberg IX</td>
<td>X-1</td>
<td>09:57:54</td>
<td>+15:03:46</td>
<td>8.3–8.4</td>
<td>202.5</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>NGC 5408</td>
<td>X-1</td>
<td>14:03:20</td>
<td>-41:22:60</td>
<td>8.7</td>
<td>10–40</td>
<td>2760</td>
<td>5</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>X-1</td>
<td>20:35:01</td>
<td>+60:11:31</td>
<td>8.4–12</td>
<td>8.5</td>
<td>–</td>
<td>6</td>
</tr>
<tr>
<td>M51 (NGC 5194)</td>
<td>X-7</td>
<td>13:30:01</td>
<td>+47:13:44</td>
<td>0.1–2</td>
<td>–</td>
<td>1.7–2.1</td>
<td>7</td>
</tr>
<tr>
<td>NGC 3379</td>
<td>Source 6</td>
<td>10:47:50</td>
<td>+12:34:57</td>
<td>3.</td>
<td>–</td>
<td>8–10</td>
<td>8</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>X-2</td>
<td>03:18:20</td>
<td>-66:29:10</td>
<td>30</td>
<td>–</td>
<td>146.88</td>
<td>9</td>
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<tr>
<td>NGC 4490</td>
<td>CXOU J123030.3+413853</td>
<td>12:30:30</td>
<td>+41:38:53</td>
<td>0.2–1.1</td>
<td>–</td>
<td>6.4</td>
<td>10</td>
</tr>
</tbody>
</table>

Multiwavelength Observations of ULXs

Optical, infrared, radio observations of ULXs provide information on:

- the binary evolution history
- nature of the donor star
- disk geometry and mode of mass transfer
- help constrain the BH mass

The optical emission: the donor star and/or the accretion disk via X-ray photoionization (Feng & Soria 2011).
Optical Counterpart of ULXs

- > 20 optical counterpart of ULX (Tao + 2011; Gladstone + 2013)

- Optical magnitudes > 21 (faint sources)
  very good angular resolution of Chandra (0.6 arcsec) and HST (0.2-0.4 arcsec)

- The V-band absolute magnitudes, $M_V = -3$ to $-8$, (bright)
  the colors, with $B - V$ in the range $-0.6$ to $+0.4$ (tend to be blue)

- spectroscopic observations is important!!
  possible to trace the radial velocity curve of the donor and
  measure the mass function

NGC 54744
ULX-X1

M66 X1

Avdan +2016
if ULX donor stars are indeed massive young stars,

- some will be Wolf–Rayet stars (like the counterpart to M 101 ULX-1, Liu + 2013)
- or red supergiants (RSGs; Copperwheat + 2005)

- >4m telescopes systematic search for NIR counterparts to nearby ULXs Heida + (2014,2016)
- discovered 11 candidate counterparts that could be RSG donor stars
- RSG stars are bright in NIR
  - \( M_V \sim -6, V - H \sim 4, H - K \sim 0 \)
  - in contrast with the blue supergiants
    - \( M_V \sim -6, V - H \sim 0, H - K \sim 0 \); (Drilling & Landolt 2000)

**Figure 1.** WHT/LIRIS H-band image of ULX1 in NGC 925, with the MOSFIRE slit positions indicated by red (2013 Dec /2014 Jan obs) and blue (2014 Nov. Obs.) The black circle indicates the Chandra X-ray localization of the ULX. The white circles indicate the sources visible in our 2014 November MOSFIRE observation.
Optical Spectra of ULXs with Subaru telescope ~ 8.2 m

spectra of ULXs are very similar to SS 433 and LBV stars in their hot state or WNLh stars

Figure 2: Spectra of the ULX optical counterparts from top to bottom, Holmberg II, Holmberg IX, NGC 4559, and NGC 5204 in blue (a) and red (b) spectral regions. The spectra are normalized for better inspection. The most strong are the He II \( \lambda 4686 \) line and the hydrogen lines H\( \alpha \) \( \lambda 6563 \) and H\( \beta \) \( \lambda 4861 \). The broad He I \( \lambda 6678 \) line is also detected. Narrow nebular emission in H\( \beta \) and [O III] \( \lambda \lambda 4959, 5007 \) lines is oversubstacted. Although the hydrogen lines are contaminated with the nebular emission, their broad wings are clearly seen.

Fabrika +(2015), Nature
Stellar environments
ULX belongs to a stellar cluster or association

- Star cluster ~200 pc
- Cluster age > $10^{7.5}$ Myr
- if ULX donor a member of cluster $M \sim 10M_{\odot}$

NGC 1313 X-1 Yang+2011
The X-ray to optical flux ratio

\[ \xi = B_0 + 2.5 \log F_X \]

(Paradijs & McClintock 1995)

For high mass X-ray binaries (HMXB) outbursts, \( \xi \sim (12-18) \);
for LMXBs, \( \xi \sim (21-22) \)

\( F_X \), 2-10 keV flux in \( \mu \)Jy

optical emission from ULXs is likely dominated by light from the accretion flow.

\[ \log(f_X/f_V) = \log f_X + m_v/2.5 + 5.37 \]

\[ \log(f_X/f_V) = 3.1-3.7. \]

NGC 1313 X1

AGN \((-1 - (1.7)) \) \( (0.3-3.5 \text{ keV} : \text{Maccacaro et al 1988}) \)
Fig. 4.—: Identification of HoIX X-1 ULX on an HST/ACS image in the F435W filter (left) and in the F330W filter (right). The counterpart is designated by a blue cross (left). Slits from the SUBARU (position angle of 180°) and GEMINI observations (position angle of 90°) are overlaid on the right image. The Chandra (green circle) and XMM-Newton (red circle) positions are also overlaid with error circles of 0′.67 and 0′.80 radius, respectively (90% confidence, including the error on the calibration of the optical image). We also note the association of stars to the east of the ULX.
Table C: Observed and Dereddened Magnitudes and Colors of the ULA Counterpart, from the HST/ACS Observations

<table>
<thead>
<tr>
<th>Filter/Magnitude</th>
<th>Observed Magnitude/Color</th>
<th>Dereddened Magnitude/Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>22.604 ± 0.015</td>
<td>21.536 ± 0.015</td>
</tr>
<tr>
<td>V</td>
<td>22.609 ± 0.024</td>
<td>21.780 ± 0.024</td>
</tr>
<tr>
<td>I</td>
<td>22.328 ± 0.034</td>
<td>21.844 ± 0.034</td>
</tr>
<tr>
<td>B−V</td>
<td>-0.005 ± 0.028</td>
<td>-0.247 ± 0.049</td>
</tr>
<tr>
<td>V−I</td>
<td>0.281 ± 0.042</td>
<td>-0.064 ± 0.058</td>
</tr>
</tbody>
</table>

Note. Values are expressed in the Johnson-Cousins (UBVRI) system.

Fig. 7.—. 4600–5100 Å part of the GEMINI/GMOS-N one-dimensional spectrum of HαX-1 optical counterpart, confirming the presence of the He II line at 4686 Å. The other annotated line in emission is from the nebula in which the counterpart is located and which could be probably from one such subtraction considering the highly variable profile of the

He II 4686
Recombination line
>310^{39} erg/s
Beaming olamaz!

Age < 20 Myr
M > 25 Msun

(Grise +2011)
X-RAY SPECTRAL AND OPTICAL PROPERTIES OF A ULX IN NGC 4258 (M106)

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ULX X-6

![Graph showing hardness ratio vs. time with energy ranges for H and S](image)

- H: 2.0 – 8.0 keV
- S: 0.3 – 2.0 keV

![Images of F435W, F555W, F814W](images)
PL and MCDBB model parameters

### X-Ray Spectral Fitting Parameters for X-6

<table>
<thead>
<tr>
<th>No.</th>
<th>$N_{\text{H}}$ ,$(10^{22}$ cm$^{-2})$</th>
<th>$\Gamma$</th>
<th>$T_\text{e}$ ,(keV)</th>
<th>$\chi^2$/dof</th>
<th>$N_{\text{PL}}$ ,$(10^{-3})$</th>
<th>$N_{\text{diskbb}}$ ,$(10^{-3})$</th>
<th>$L_X$ ,$(10^{39}$ erg s$^{-1}$)</th>
<th>$L_{\text{bol}}$ ,$(10^{39}$ erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XM1</td>
<td>0.10$^{+0.02}_{-0.03}$</td>
<td>1.77$^{+0.10}_{-0.10}$</td>
<td>...</td>
<td>40.11/33</td>
<td>2.59$^{+0.11}_{-0.11}$</td>
<td>...</td>
<td>1.21$^{+0.09}_{-0.09}$</td>
<td>...</td>
</tr>
<tr>
<td>XM2</td>
<td>0.21$^{+0.04}_{-0.04}$</td>
<td>2.13$^{+0.10}_{-0.10}$</td>
<td>16.76/17</td>
<td>...</td>
<td>3.66$^{+0.33}_{-0.33}$</td>
<td>1.37$^{+0.11}_{-0.11}$</td>
<td>1.57$^{+0.11}_{-0.11}$</td>
<td>...</td>
</tr>
<tr>
<td>C1</td>
<td>0.22$^{+0.04}_{-0.04}$</td>
<td>1.91$^{+0.15}_{-0.15}$</td>
<td>10.39/15</td>
<td>...</td>
<td>3.74$^{+0.43}_{-0.43}$</td>
<td>1.57$^{+0.11}_{-0.11}$</td>
<td>1.57$^{+0.11}_{-0.11}$</td>
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<tr>
<td>XM3</td>
<td>0.34$^{+0.06}_{-0.06}$</td>
<td>2.47$^{+0.13}_{-0.13}$</td>
<td>15.67/22</td>
<td>...</td>
<td>5.49$^{+0.48}_{-0.48}$</td>
<td>1.80$^{+0.11}_{-0.11}$</td>
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<td>...</td>
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<tr>
<td>XM4</td>
<td>0.21$^{+0.06}_{-0.06}$</td>
<td>1.96$^{+0.12}_{-0.12}$</td>
<td>35.13/28</td>
<td>...</td>
<td>5.05$^{+0.53}_{-0.53}$</td>
<td>...</td>
<td>2.06$^{+0.21}_{-0.21}$</td>
<td>...</td>
</tr>
<tr>
<td>XM5</td>
<td>0.19$^{+0.03}_{-0.03}$</td>
<td>2.40$^{+0.20}_{-0.20}$</td>
<td>30.49/28</td>
<td>...</td>
<td>3.32$^{+0.29}_{-0.29}$</td>
<td>...</td>
<td>1.11$^{+0.10}_{-0.10}$</td>
<td>...</td>
</tr>
<tr>
<td>XM6</td>
<td>0.25$^{+0.05}_{-0.05}$</td>
<td>2.11$^{+0.11}_{-0.11}$</td>
<td>101.26/79</td>
<td>...</td>
<td>5.84$^{+0.32}_{-0.32}$</td>
<td>...</td>
<td>2.20$^{+0.12}_{-0.12}$</td>
<td>...</td>
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<tr>
<td>XM7</td>
<td>0.20$^{+0.02}_{-0.02}$</td>
<td>1.90$^{+0.06}_{-0.06}$</td>
<td>160.34/150</td>
<td>...</td>
<td>3.87$^{+0.10}_{-0.10}$</td>
<td>1.65$^{+0.07}_{-0.07}$</td>
<td>...</td>
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</table>

#### Additional plots

**XM7 – PL**

Energy spectra of X-6

**XM7 – DISKBB**

Energy spectra of X-6
NGC 4258 X-6 HST ACS/WFC

F555W Spectrum of cluster from RTT150

For 3 counterpart candidates

Abst. Mag : −7 < M_V < −3

Mass ~ (9-25 M_{sun})

Ages ~ 12-25 Myr
Colliding Galaxies NGC4485/4490

Chandra (0.3-8keV)  Optik (DSS)  XMM-Newton (0.3-10 keV)
Table 28: Comparison of XMM-Newton with other X-ray satellites

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Mirror PSF FWHM [&quot;]</th>
<th>Mirror PSF HEW [&quot;]</th>
<th>E range [keV]</th>
<th>A at 1 keV [cm]</th>
<th>Orbital target visibility [hr]</th>
<th>Energy resolution at 1 keV [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XMM-Newton</td>
<td>6</td>
<td>15</td>
<td>0.15 - 12</td>
<td>4650</td>
<td>36.7</td>
<td>4 (RGS)</td>
</tr>
<tr>
<td>Chandra</td>
<td>0.2</td>
<td>0.5</td>
<td>0.1 - 10</td>
<td>555 (ACIS-S)</td>
<td>44.4</td>
<td>1 (HETG)</td>
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<td>ROSAT</td>
<td>3.5</td>
<td>7</td>
<td>0.1 - 2.4</td>
<td>400</td>
<td>1.3</td>
<td>500</td>
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<td>ASCA</td>
<td>73</td>
<td>174</td>
<td>0.5 - 10</td>
<td>350</td>
<td>0.9</td>
<td>100</td>
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<tr>
<td>Suzaku</td>
<td>96 - 120</td>
<td>108 - 138</td>
<td>0.2 - 600</td>
<td>1760 (XIS)</td>
<td>0.72</td>
<td>50</td>
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<td>RXTE</td>
<td>n.a.</td>
<td>n.a.</td>
<td>2-250</td>
<td>n.a.</td>
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<td>n.a.</td>
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<tr>
<td>Swift</td>
<td>8.8</td>
<td>18</td>
<td>0.2-10 (XRT)</td>
<td>133.5</td>
<td>0.8</td>
<td>70</td>
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<td>NuSTAR</td>
<td>18</td>
<td>58</td>
<td>3-79</td>
<td>n.a.</td>
<td>0.8</td>
<td>n.a.</td>
</tr>
<tr>
<td>Parameter</td>
<td>ART-XC</td>
<td>eROSITA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------</td>
<td>------------------</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Energy range</td>
<td>5-30 keV</td>
<td>0.2-12 keV</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Effective area</td>
<td>455 cm$^2$ at 8 keV</td>
<td>2500 cm$^2$ at 1 keV</td>
<td></td>
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<tr>
<td>FOV (Filed of View)</td>
<td>34 arcmin</td>
<td>1°</td>
<td></td>
<td></td>
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<tr>
<td>System angular resolution (on axis)</td>
<td>≤1 arcmin</td>
<td>15 arcsec</td>
<td></td>
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<tr>
<td>Energy resolution</td>
<td>1.4 keV at 14 keV</td>
<td>130 eV at 6 keV</td>
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Teşekkürler   !!!!!!!
Figure 2. Decision tree showing the procedure by which observations were assigned into the three spectral types based on the resulting parameters from the doubly absorbed MCD plus power-law spectral model.