Ultraluminous X-ray Sources forming in low metallicity natal environments

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Intermediate or stellar mass black holes interpretation

ULXs forming in low metallicity natal environments?
→ 30-80 Msun BHs

Massive BHs in the Cartwheel galaxy

Independent evidence from NGC 1313 X-2?

Conclusions
ULXs are pointlike, off-nuclear X-ray sources in nearby galaxies with L >> Ledd for 1 Msun (L>1.0e39 erg/s)

• Super-Eddington sources, later called UltraLuminous X-ray sources (ULXs) first noticed in Einstein data (Long & Van Speybroeck 1983; Helfand 1984; Fabbiano 1989)

• More than 200 sources observed by ROSAT (Roberts & Warwick 2000; Colbert & Ptak 2002; Liu & Bregman 2005; Liu & Mirabel 2005), ASCA (Makishima et al. 2000), XMM-Newton (Foschini et al. 2002; Feng & Kaaret 2005), Chandra (Swartz et al. 2005)
What are Ultraluminous X-ray Sources

X-ray flux variability, Lx-spectral variability

Modulation in the X-ray and optical light curve

QPO in the PDS

Detection of stellar optical counterparts

Embedded in young stellar environ.

ULXs are X-ray binaries with massive donors

X-ray spectra: Similar to BHC spectra

High luminosity end of the XLF of XRBs
Intermediate or stellar mass BHs?

ULX models differ in the assumptions on the physical state of the disc

- Accretion disk in a standard regime
  - Isotropic X-ray emission $\rightarrow$ IMBHs (Colbert & Mushotzky 1999)
  - Early X-ray spectroscopy estimates based on MCD+PL fits $\rightarrow$ IMBHs
  - How big is the BH mass? $M_{bh}>100-1000$ $M_{\odot}$ (e.g. Miller et al. 03)
  - Recently spectroscopic estimates of $M_{bh}$ partly revised (e.g. Lorenzin & Zampieri 09; Hui & Krolik 08) or questioned (e.g. Goncalves & Soria 06; Stobbart et al. 06; Soria & Kuncic 2007)
  - Other, physical X-ray spectral models: disc+Comptonized, thick corona
    $\rightarrow$ T not good indicator of $M_{bh}$
    $\rightarrow$ From VHS to ultraluminous state

See talk by Tim Roberts
Intermediate or stellar mass BHs?

- Accretion flow in a different regime. Isotropy and/or the Eddington limit may be circumvented → **stellar mass BHs** \((M_{\text{bh}}=10-20 \text{ Msun}; \text{ King et al. 01})\)
  - *Slim disk* (Ebisawa et al. 03)
  - *Photon-bubble disks* (Begelman 02, 06)
  - *Radiatively efficient, two-phase super-Eddington discs* (Socrates & Davis 06)
  - *Thick disks with beaming* (King 02)
  - *Thick disks with beaming and super-Eddington L* (Poutanen et al. 07; King 09)

\[ L = [1 + \ln(M_{\text{dot}}/M_{\text{dot Edd}})]L_{\text{edd}} \]

Consistent with disc+Comptonized, thick corona X-ray spectral models
Intermediate or stellar mass BHs?

► IMBHs

Current observational evidence (in particular from X-ray spectra) indicates that BHs of several hundreds to thousands Msun are not required for the majority of ULXs; might be present in a handful of objects (such as the hyper-luminous ULXs with L~10^{41} erg/s)

► Stellar mass BHs

Possible explanation up to ~10^{40} erg/s, but rather extreme conditions needed to account for ULXs above this (isotropic) L

► Different interpretation?
Possible connection between ULXs and star formation in low metallicity environments (Pakull & Mirioni 02; Cropper et al. 04; Zampieri et al. 04)

At sub-solar metallicities, line-driven winds become progressively less efficient and stars with masses above \( \sim 20 \text{Msun} \) may retain rather massive envelopes at the time of explosion.

What is the final mass of the star?

* According to the adopted mass loss history, it may differ up to a factor of \( \sim 2 \) (more for clumpy winds; e.g. Moffat & Carmelle 1994; Fullerton et al. 06)

* Scaling law \( \propto Z^{0.5} \) often adopted for the mass loss in hot stars (e.g. Kudritzki et al. 1989; Nugis & Lamers 2000)
If the envelope is \( \sim 30-40 \text{Msun} \), the supernova shock wave loses too much energy in trying to unbind the envelope until it stalls and most of the star collapses (Fryer 1999; Zampieri 02).
A low metallicity (Z ~ 0.1-0.2 Zsun) star may retain a ~30-40Msun envelope and then collapse directly to form a BH (Heger et al. 2003; Belczynski et al. 2009)

These may be the BHs hosted in some ULXs

If the core is not rapidly rotating, BH mass comparable to final mass:

\[ \text{M}_{\text{BH}} > 30-40 \text{ Msun} \]

Pros

* Does not require new mechanism but is referable to stellar evolution
* Continuum distribution of masses above 10-20Msun up to ~80 Msun consistent with the power-law slope of the XLF of the X-ray binary population of galaxies
* Only modest beaming (bf ~ 0.5) or slight violations of the Eddington limit (a factor of a few) needed for bright (> 10^40 erg/s) ULXs
* Consistent with isotropic irradiation of X-ray photoionised nebulae
Metallicity of the environment. Discrepancies between optical and X-ray data (e.g. Winter et al. 07): Optical spectrum of the nebula of Ho II X-1 → Z~0.1 Zsun (Pakull & Mirioni 02), but XMM-Newton RGS spectrum → Z~0.6 Zsun (Goad et al. 06)

Specific ULX frequency decreases with increasing host galaxy mass indicating that smaller, lower metallicity systems have more ULXs per unit mass (Swartz et al. 2008)

Dynamical mass measurement of the WR optical counterpart of IC 10 X-1 → 23-33 Msun (Prestwich et al. 2007; Silverman & Filippenko 08)
Massive BHs in the Cartwheel galaxy

- Metallicity of the Cartwheel: $Z \sim 0.05 \ Z_{\text{sun}}$ (Fosbury & Hawarden 1977)
- Number of massive BHs (distribution of BHs $\propto$ IMF above 40 Msun; Mapelli et al. 09):

\[ N_{\text{BH}} = A \int_{40 \ M_{\odot}}^{m_{\text{max}}} m^{-\alpha} \, dm \]

\[ M_{\text{BH}} = A \int_{40 \ M_{\odot}}^{m_{\text{max}}} m^{-\alpha} (m b + c) \, dm \]

- $A = \frac{\text{SFR} \ t_{\text{burst}}}{M_{\text{tot}}}$
- $b = 0.54$, $c = 15.6 \text{Msun}$

- SFR $\sim 20 \ M_{\odot}/\text{yr}$ (Mayya et al. 2005), $t_{\text{burst}} \sim 10^{7} \ \text{yr}$
  - $N_{\text{bh}} = 1.2 \times 10^{5} - 2.4 \times 10^{5}$
  - $M_{\text{bh}} = 6.2 \times 10^{6} - 1.2 \times 10^{7} \ M_{\odot}$

- 3-6% of the total stellar mass in the ring

- *No difficulty with the fraction of star-forming mass ending up in BHs*
  (large mass in BH-forming clusters major problem for the IMBH interpretation; e.g. King 2004; Mapelli et al. 08)

- Reasonable production efficiency: $N_{\text{ulxs}}/N_{\text{bh}} \sim 10^{-4}$
NGC 1313 X-2: orbital period and Mbh

- Tentative identification of the orbital period in the HST optical lightcurve (3 cycles in the B band; Liu et al. 09): \( P = 6.12 \pm 0.16 \) d → not confirmed by Grise' et al. (09)
- Optical data modelled using colour-magnitude diagram, orbital period, age of the parent cluster (20\(\pm\)5 Myr; Grise' et al. 08), age of the surrounding emission nebula (~1 Myr old; Pakull et al. 02)

\[ \text{Mbh} = 50-100 \]

\[ \text{RLOF during MS} \]

\[ \text{Patruno & Zampieri (2009)} \]

\[ \text{Mbh} = 20 \]
Conclusions

- **100-1000 Msun BHs not required for the majority of ULXs;** might be present in a handful of objects

- **Stellar mass (≈10-20 Msun) BHs possible explanation for ULXs below ≈10^{40} \text{ erg/s},** but they need extreme conditions above this (isotropic) L

- **Bright ULXs may contain BHs with masses above 30–40 Msun and up to 80–90 Msun,** produced by low metallicity stars with initial mass above 40–50 Msun \(\rightarrow\) **(very) massive BHs or (V)MBHs**
  - * Formation referable to ordinary stellar evolution
  - * Only modest violations of the Eddington limit
  - * No difficulty with the fraction of star-forming mass in BHs
  - * BH in NGC 1313 X-2 (Mbh=50-100 Msun)

- **Future tests:** \(\rightarrow\) metallicity measurements (Ripamonti et al. 09)
  \(\rightarrow\) surveys of ULX locations looking for a statistically meaningful relationship between position, average L and local Z (Mapelli et al. 09b)