Ultraluminous X-ray Sources forming in low metallicity natal environments

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Outline

► 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 $L \gg L_{\text{Edd}}$ for 1 Msun ($L > 1.0 \times 10^{39} \text{ erg/s}$)

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

ULXs are X-ray binaries with massive donors

- X-ray flux variability, Lx-spectral variability
- Modulation in the X-ray and optical light curve
- QPO in the PDS
- High luminosity end of the XLF of XRBs
- Detection of stellar optical counterparts
- Embedded in young stellar environ.

X-ray spectra: Similar to BHC spectra
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 → IMBHs (Colbert & Mushotzky 1999)
* Early X-ray spectroscopy estimates based on MCD+PL fits → IMBHs
* How big is the BH mass? $M_{bh} > 100-1000$ $M_{\text{sun}}$ (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
  → $T$ not good indicator of $M_{bh}$
  → From VHS to ultraluminous state
See talk by Tim Roberts

Gladstone et al. (2009)
Intermediate or stellar mass BHs?

Accretion flow in a different regime. Isotropy and/or the Eddington limit may be circumvented → **stellar mass BHs** ($M_{bh}=10-20$ $M_{\text{Sun}}$; 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)

$$L = \left[1 + \ln\left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}}\right)\right]L_{\text{Edd}}$$

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 $M_{\text{sun}}$ are not required for the majority of ULXs; might be present in a handful of objects (such as the hyper-luminous ULXs with $L \sim 10^{41}$ erg/s)

► Stellar mass BHs

Possible explanation up to $\sim 10^{40}$ 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 ~20Msun 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 ~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 ~30-40M\(_\odot\), 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).
Remnant mass

- 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:
  \[ \text{Mbh} > 30-40 \text{ Msun} \]

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
Testing this interpretation

- **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: \( Z \sim 0.05 \, Z_{\odot} \) (Fosbury & Hawarden 1977)
- Number of massive BHs (distribution of BHs \( \propto \) IMF above 40 Msun; Mapelli et al. 09):

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

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

\[ A = \frac{\text{SFR} \, t_{\text{burst}}}{M_{\text{tot}}} \]

\[ b = 0.54, \, c = 15.6 \, M_{\odot} \]

SFR \( \sim 20 \) Msun/yr (Mayya et al. 2005), \( t_{\text{burst}} \sim 10^7 \) yr

\[ \text{Nbh} = 1.2 \times 10^5 - 2.4 \times 10^5 \]

\[ \text{Mbh} = 6.2 \times 10^6 - 1.2 \times 10^7 \, M_{\odot} \]

- 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: \( N_{\text{ulxs}}/\text{Nbh} \sim 10^{-4} \)
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): $P=6.12\pm0.16$ d → not confirmed by Grise' et al. (09)

- Optical data modelled using colour-magnitude diagram, orbital period, age of the parent cluster (20+/−5 Myr; Grise' et al. 08), age of the surrounding emission nebula (≈1 Myr old; Pakull et al. 02)
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 ~$10^{40}$ 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)