On the search of the elusive Intermediate Mass Black Holes

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Ultra-Luminous X-ray sources

Chandra X-ray image of the Antennae galaxies (from Fabbiano et al. 2004)
Ultra-Luminous X-ray (ULX) sources are point-like, off-nuclear sources observed in other galaxies, with total observed luminosities greater than the Eddington luminosity for a stellar-mass black hole ($L_X \sim 10^{38} \text{ erg/s}$).

→ either the emission is not isotropic or the black hole has a higher mass ($M_{BH} \geq 20 M_\odot$).
The Eddington limit

➢ Probably the maximum luminosity of a star.

\[ \sigma_p \frac{L}{4\pi cr^2} \leq \frac{GMm_p}{r^2} \]

\[ L \leq \frac{4\pi Gm_p c}{\sigma_T} M \equiv L_{\text{EDD}} \]

\[ L_{\text{EDD}} = 1.2 \times 10^{38} \left( \frac{M}{M_\odot} \right) \]

➢ It depends on the mass of the star.

➢ When the source emits isotropically. If not, this limit can be exceeded.
The Ultra-Luminous X-ray sources

➢ This opens a real possibility to the existence of the InterMediate-Mass Black Holes (IMBHs; $M_{\text{BH}} \geq 10^2 - 10^4 \ M_{\odot}$; Colbert & Mushotzky, 1999).

➢ The existence of these ULXs-IMBHs is controversial only few cases recently confirmed (ESO 243-49 HLX1, Farrell et al. 2011; see Sutton et al. 2012 for a few more candidates). See Mezcua+17 for many IMBH candidates with $M_{\text{BH}} \geq 10^3 - 10^4 \ M_{\odot}$.
The Ultra-Luminous X-ray sources – the Standard (thin) Disc Theory

- X-ray spectroscopy is useful. From the Standard (Thin) Disc Theory (applicable to sub-Eddington flows) the inner disk temperature scales with the mass of the BH as (Makishima et al. 2000)

\[ kT_{\text{in}} \sim M^{-1/4} \]

→ Inner disc temperatures found imply IMBHs for some ULXs (Miller et al. 2004).

The XMM-Newton/EPIC-pn X-ray spectrum of NGC 1313 X-1 is shown (Miller, Fabian, & Miller 2004).
The need of slim-disc models

X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Miller, Fabian & Miller (2004).

INNER DISC TEMPERATURE IS APPROX. “CONSTANT” (0.1-0.2 keV)
The need of slim-disc models

X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Poutanen et al. (2007).

IS THE ACCRETION DISC REALLY “STANDARD” IN ULXs?
The need of slim-disc models

L-T plot in near-Eddington case

➢ Standard (thin) disc follows $L \sim T^4$ relation.

➢ Advection and obscuration effects cause significant deviations from that relation in super-Eddington regime.

➢ The effect is strong inclination dependent.

➢ Observed luminosity can stay around Eddington if mass accretion rate is high.

X-ray luminosity versus inner disc temperature for the standard (red) and the slim accretion disc (blue). Figure taken from Bursa (2016).
**NGC 5408 X-1**

- Nearby (D=4.8 Mpc)

- Peak (RXTE, 0.3-10 keV, 2008-2009) X-ray luminosity of $L_X=2 \times 10^{40}$ erg/s (Strohmayer, 2009).

- Strohmayer & Mushoztky (2009) estimated a BH mass of $M=10^3-10^4 M_\odot$.

- 6-Long 100 ks observations with XMM-Newton performed in 5 years (2006-2011).

- X-ray timing and spectral analysis reported in Strohmayer et al. (2007), Strohmayer & Mushotzky (2009), Dheeraj & Strohmayer (2012), Caballero-Garcia et al. (2013).

*HST image (blue - F225W, green - F502N, red - F845M) of ULX NGC 5408 X-1 (circled), the surrounding field and a nearby stellar association (box) (from Grise et al. 2012)*
NGC 5408 X-1 – X-ray timing

- BH masses scale with the break frequency of their Power Density Spectrum (PDS; McHardy et al. 2006; Kording et al. 2007). This relation holds over six orders of magnitude in mass, i.e., from Black Hole Binaries (BHBs) to Super-Massive Black Holes (SMBHs).

- PDS and the energy spectrum of NGC 5408 X-1 are very similar to that of BHBs in the Steep Power-law (SPL) state. BUT the characteristic timescales within the PDS are lower by a factor of ≈100 and X-ray luminosity is higher by a factor of a few ×10, when compared to BHBs → $M_{\text{BH}} \geq 10^3$-$10^4 M_\odot$. 

Average PDS of NGC5408 X-1 (from Strohmayer & Mushotzky, 2009)
NGC5408 X-1 X – X-ray spectroscopy

- Little spectral evolution (slight spectral hardening), in spite of the observations spread in 5 yr.
- Fit with several phenomenological models (diskbb or diskpn for the soft X-rays and powerlaw or compTT for the high-energies; 2 apec for the diffuse emission).
- Steep spectra ($\Gamma \approx 3$) and cold (and constant) inner disc temperature ($kT_{in} \approx 0.17$ keV) $\rightarrow M = 2 \times 10^3 M_\odot; \eta = 10^{-1}$
Does it mean that we have found one of the IMBHs proposed to exist as cosmological seeds of current galaxies by Madau & Rees (2001)?

Very likely not
The SLIMULUX model

- It is a thermal disc model (effects from the corona not taken into account).

- Thin disc model is inaccurate for $L > 0.3 \, L_{\text{edd}}$.

- Such models tend to give incorrect values for BH masses and for accretion rate (luminosity).

- Standard (thin) discs follow $L \sim T^4$ relation.

- Advection and obscuration effects cause significant deviations from that relation in super-Eddington regime.

- The effect is strongly inclination dependent.

- Observed luminosity can stay around Eddington even if mass accretion rate $>> 1 \rightarrow \text{Reduces inferred BH mass} !!!!!$

- General Relativistic effects are fully consistently taken into account.
The SLIMULUX model

Analytical solutions

Sadowski+2009
NGC 5408 X-1 spectrum fitted with SLIMULX

We fitted the spectrum of NGC 5408 X–1 with the model \( TBabs(apec + apec + slimulx + powerlaw) \) in XSPEC.

Obtained parameters

- \( M_{\text{BH}} = 5.7 \pm 0.2 \, M_\odot \)
- \( a = 0.99 \)
- \( L = 3.2 \pm 0.3 \, L_{\text{edd}} \)
- \( i \leq 30 \, \text{deg.} \)
- \( h (\text{disc thickness}) = 1 \)
Accretion disc as seen from an observer located at infinity (credits: M. Bursa)
Gravitational Waves: a new window to the Universe

“Elusive” IMBHs
\( (M_{BH} \geq 30-10^2 \, M_\odot) \)
Gravitational Waves: a new window to the Universe

Known Stellar-mass Black Holes

- Gravitational Wave Candidate
- Gravitational Wave Detection
- X-ray Measurement
Gravitational Waves: a new window to the Universe

- BHs do not necessarily have EM counterpart (i.e. they are “black”).
- Only BHs interacting with another star and/or clouds of gas can have EM counterpart.
- The EM counterpart of BHs with masses of $M_{BH} \geq 30 \times 10^2 M_\odot$ has never been detected so far.
- These invisible/ “elusive” BHs ( $M_{BH} \geq 30 \times 10^2 M_\odot$ ) are now systematically being observed by GW-detectors (LIGO, VIRGO,...).
- The discovery of BHs in the mass-range of $M_{BH} \geq 30 \times 10^2 M_\odot$ is unexpected (they are “black” and they have been detected in this mass-range with GWs).
- They might constitute a significant part of the enigmatic “dark matter”.
Standard (thin) disc model is inaccurate for $L_{\text{disc}} > 0.3 L_{\text{EDD}}$.

Such models tend to give incorrect values for BH masses and for accretion rate (luminosity).

Standard (thin) accretion disc theory is not enough → need to move on to *slim-discs*.

For the case of NGC 5408 X-1 *a maximally rotating, of 5 M_{\odot} BH* is inferred.

No need of IMBH for NGC 5408 X-1 (prototype of the ULX classification).

Many ULXs previously understood as IMBHs are instead super-Eddington accreting stellar-mass compact objects (NS/BH).

Gravitational waves are finding the “elusive” IMBHs.

BH binaries in dense plasmas may produce EM counterparts → Look for them! → Robotic and automatic systems are absolutely mandatory!
Acknowledgements

Financial support provided by the European "Seventh Frame-work Programme (FP7/2007-2013) under grant agreement # 312789".

Period of the project's realization 1.1.2013 – 31.12.2017