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)
The Ultra-Luminous X-ray sources

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 ($L_X \sim 10^{38}$ 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.

\[ \sigma_p \frac{L}{4 \pi c r^2} \leq \frac{G M m_p}{r^2} \]

\[ L \leq \frac{4 \pi G m_p c}{\sigma_T} M = L_{\text{EDD}} \]

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

➢ It depends on the mass of the star.

➢ When the source emits isotropically. If not, this limit can be exceeded.

*Eta Carinae (Eddington limit exceeded)*
The Ultra-Luminous X-ray sources

➢ This opens a real possibility to the existence of the InterMediate-Mass Black Holes (IMBHs; $M_{BH} \geq 10^2 - 10^4 \, M_\odot$; 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 $M_{BH} \geq 10^3 - 10^4 \, M_\odot$. 

Stellar-mass Black Hole (BH); $M_{BH} \leq 10 \, M_\odot$

Supermassive Black Hole (AGN); $M_{BH} \geq 10^6 \, M_\odot$

IMBHs (Madau & Rees, 2001)
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)

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

→ Inner disc temperatures found imply IMBHs for some ULXs (Miller et al. 2004).
The need of slim-disc models

INNER DISC TEMPERATURE IS APPROX. “CONSTANT” (0.1-0.2 keV)

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).
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 $L_X=2\times10^{40}$ erg/s (Strohmayer, 2009).
- Strohmayer & Mushotzky (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).

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)
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 $\approx 100$ and X-ray luminosity is higher by a factor of a few $\times 10$, when compared to BHBs $\rightarrow M_{\text{BH}} \geq 10^3-10^4 M_\odot$. 

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) $\rightarrow$ $M=2\times10^3 M_\odot$; $\eta=10^{-1}$.

XMM-Newton fitted-spectra from the 6 observations (from Caballero-Garcia et al., 2013)
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 SLIMULX 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 \( \gg 1 \) → Reduces inferred BH mass !!!!!!

➢ General Relativistic effects are fully consistently taken into account.
The SLIMULX model

Analytical solutions

Sadowski+2009
We fitted the spectrum of NGC 5408 X–1 with the model $TBabs (apec + apec + slimulx + powerlaw)$ in XSPEC.  

Obtained parameters:

- $M_{BH} = 5.7 \pm 0.2 \, M_{\odot}$
- $a = 0.99$
- $L = 3.2 \pm 0.3 \, L_{EDD}$
- $i \leq 30 \, \text{deg.}$
- $h \, (\text{disc thickness}) = 1$
The SLIMULX model

Accretion disc as seen from an observer located at infinity (credits: M. Bursa)
Gravitational Waves: a new window to the Universe

Black Holes of Known Mass

"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 $M_{BH} \geq 30 - 10^2 \, M_\odot$ has never been detected so far.
- These invisible/ “elusive” BHs ($M_{BH} \geq 30 - 10^2 \, M_\odot$) are now systematically being observed by GW-detectors (LIGO, VIRGO,...).
- The discovery of BHs in the mass-range of $M_{BH} \geq 30 - 10^2 \, M_\odot$ 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”.
Summary and Conclusions

- 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!
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