X-ray timing and spectral studies from Ultra-Luminous X-ray sources

M. D. Caballero-Garcia (INAF-OAB), T. Belloni (INAF-OAB), A. Wolter (INAF-OAB), L. Zampieri (INAF-OAPd)
Q (charge), M (mass), a (spin)
The X-ray emission: Timing
The X-ray emission: Timing

Light curve
(time domain)

Power Spectrum
(frequency domain)
What can timing tell us?

- Timing → characteristic time-scales = PHYSICS
- Timing measurements can be extremely precise!!
  - Binary orbits:
    - Orbital periods
    - Sizes of emission regions and occulting objects
    - Orbital evolution
  - Accretion phenomena (fast variability):
    - Broadband variability
    - “Quasi-Periodic Oscillations”
    - Bursts & “SuperBursts”
  - Energy Dependent Delays (Phase Lags)
Example: High-Frequency QPOs

- HFQPOs in stellar-mass BHs (BHBs) are signals at frequencies 35-450 Hz observed in a few systems.

Power Density Spectra of the seven good detections of High-Frequency QPOs for XTE J1550-564 (from Belloni, Sanna, Mendez et al. 2012)
What can timing tell us for accreting black holes?

- If this frequency coincides with the frequency of a particle moving in the ISCO around a (Schwarzschild) BH of mass $M$, we derive a mass for the BH.
- But this is only for the High-Frequency QPOs.
Example: Low-Frequency QPOs

- Come from the inner region of the compact object but NOT from the last stable orbit.
- Different types (A,B,C) depending on their characteristics plus broad band noise associated.
- Type-C LFQPO frequencies scale as $1/M_{BH}$ (McHardy et al. 2006). They might depend also on the accretion rate (Soria, 2007; Casella+08).

**Low-frequency QPO classification**
(Casella, Belloni & Stella, 2005)
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 ($L_X \sim 10^{38} \text{ erg/s}$).

→ either the emission is not isotropic or the black hole has a higher mass ($M_{BH} \geq 20 M_\odot$).
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 but only one case recently confirmed (ESO 243-49 HLX1; Farrell et al. 2011)

---

Stellar-mass Black Hole (BHB)  
Supermassive Black Hole (AGN)
The Ultra-Luminous X-ray sources

- X-ray spectroscopy is useful. From the Standard Disc Theory (applicable to sub-Eddington flows) the inner disk temperature scales with the mass of the BH as \( kT_{\text{in}} \sim M^{-1/4} \).

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

→ 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).
Quasi-Periodic Oscillations and energy spectra from M82 X-1

M. D. Caballero-Garcia, T. Belloni, L. Zampieri, (submitted to MNRAS)
The ULXs in M82

(Left) B,V and $H_{\alpha}$ combined image of the starburst galaxy M82. (Right) X-ray image of the nuclear region with Chandra.
The ULXs in M82

- M82 is a *starburst* galaxy located at a distance of $D=3.9\text{Mpc}$.
- It contains two ULXs (separated by 5” in the sky). M82 X-1 is the brightest, reaches a luminosity of $L_X \geq 10^{40} \text{erg/s}$ and is of persistent nature. The second is of transient nature (M82 X-2).
- M82 X-1 is at 1” from the super star cluster MCG11. Simulations have proved to be feasible the presence of IMBHs (Portegies Zwart+04).
- QPOs from M82 X-1 have been discovered at 50-100 mHz and confirmed to come from this ULX with *Chandra* (Feng & Kaaret, 2007).
- These frequencies are compatible with a BH of mass $100-10^3 \text{M}_\odot$.
- According to its transient nature and luminosity $L_{X,\text{max}} \approx 10^{40} \text{erg/s}$, Feng+2010 derived a mass of $10^4 \text{M}_\odot$ for M82 X-2.
The QPO in M82 X-1

Total power spectrum from the 2004 XMM-Newton observation (limited to the range 0.001-1 Hz). From Mucciarelli, Casella, Belloni, Zampieri & Ranalli (2006)
Observations and analysis

➢ We analyzed the data from 5 observations with XMM-Newton at the position of M82 X-1.

➢ M82 X-1 and M82 X-2 are unresolved sources with XMM-Newton (not with Chandra).

➢ The exposure time of each observation is ≈ 30 ks

➢ The goals were to find relationships between the timing and spectral properties from M82 X-1.
Fast variability from M82 X-1

XMM-Newton EPIC/pn+MOS PDS in the energy and frequency range 1-10 keV and 0.0004-0.19Hz from M82 X-1 (from Caballero-Garcia et al., MNRAS submitted)
All the PDS show flat-topped noise.

QPOs are seen in the PDS of three observations at \( v_{\text{QPO}} \approx (50, 8, 40) \) mHz with single-trial significances of \( (3.6, 3.8, 4.5)\sigma \), respectively.

Questions to be addressed:

- What QPOs come from M82 X-1(2)? Interpretation of the QPOs in the framework of possible scenarios (LFQPOs, HFQPOs,...)?
- Possible further constraints on the mass of the BH?
- \( \rightarrow \)stellar-mass BHs (< 100 M_\odot) or IMBHs (100-10^4 M_\odot)?
Spectra from M82 X-1

(0.3-10 keV) XMM-Newton energy spectra from M82 X-1 and best-fit model during observations 1-5.
Spectra from M82 X-1

The best-fit model is one composed by:

1) Emission from two diffuse emission components (one *hot* and one *cold*), as typically seen in the X-ray spectra from the nucleus of *starburst galaxies*, as common for NGC5408 X-1.

2) Emission from the *inner* accretion disc, with a temperature of $kT \approx 0.2$ keV, common for ULXs. *This has historically been interpreted as evidence from the existence of IMBHs (Miller+04)*.

3) Comptonized emission from a *cold* ($kT_e \approx 2$ keV) *and optically thick* ($\tau \geq 10$) corona, common for ULXs. The origin of this component is unclear (wind,corona?)

→ *Basic property of these highly accreting sources*
Spectra vs QPO frequency

Unabsorbed (1-10 keV) flux from the high-energy component versus the frequency of the QPOs from our work.
Spectra vs QPO frequency

- A hardening of the spectra occurs when the frequency of the QPO is the lowest ($\nu_{\text{QPO}} \approx 8 \text{ mHz}$).
- Because XMM-Newton is unable to resolve M82 X-1 from M82 X-2 great caution is needed to infer spectral-timing relationships.
  
  **Possible contribution from M82 X-2?**

- The hardening has been seen to occur when the flux was the highest.
- M82 X-2 has been seen to show a very hard spectrum with Chandra ($\Gamma \approx 0.6-1.1$).
- This QPO is compatible with previous detections of sub-millihertz QPOs (2-7 mHz) from M82 X-2 with Chandra (Feng+10).
- **This QPO might be an analog to the LFQPOs observed in BHBs. In such a case, a mass for the BH in M82 X-2 of $100-10^4 M_\odot$ is derived.**
History of QPO detections from M82

Time history of the centroid frequencies of the QPOs from M82 from the sample of Mucciarelli+06; Strohmayer & Mushotzky (2003) and Kaaret+ (2006). In red QPOs likely from M82 X-2. In blue the detections from our work plus one from Kaaret+06.
History of QPO detections from M82 X-1

Histogram of the frequencies of the QPOs from the total sample and only the QPOs from M82 X-1 with significant (considering all the trials) detections (dotted and solid bars, respectively).
First HFQPOs detected from a ULX?

- Comparing the QPO at $\nu \approx 50$ mHz with previous findings (Mucciarelli+06; Strohmayer & Mushotzky, 2003, Kaaret+06) we see that all the detections are distributed in the 1:2:3 ratio.

- The QPO at $\nu \approx 50$ mHz is compatible with the fundamental and the QPOs at $\nu \approx 100, 150$ mHz as the harmonics. This is compatible with previous suggestions from Fiorito & Titarchuk (2004).

- If really distributed harmonically, the QPOs found from M82 X-1 could be interpreted as the first indication of HFQPOs in ULXs.
Conclusions

➢ A unified characterization of the spectral evolution in BHBs has been done in the last 30 yrs. The study of their spectral and aperiodic variability is a very useful tool to understand the mass of the BH and the physics of accretion onto these sources.

➢ ULXs are accreting sources that might represent strong evidence of IMBH. Nevertheless, their X-ray properties have been seen to be different from the case of BHBs.

➢ In this talk I have presented the results we have obtained from two outstanding ULXs (2 ULXs in M82) and discussed the properties that can be derived from their X-ray emission.