PROCEEDINGS OF SCIENCE

Timing (Pulsating) Ultraluminous X-ray sources – lessons learned from M82

Matteo Bachetti[a,*]

[a] *INAF-Osservatorio Astronomico di Cagliari*
via della Scienza 5, I-09047 Selargius (CA), Italy

E-mail: matteo.bachetti@inaf.it

M82 X-2 is the archetypal pulsating ultraluminous X-ray sources – X-ray pulsars whose flux can be hundreds of times their Eddington limit. Since 2014, we have been conducting a thorough observation campaign of this pulsar, tracking the acceleration of its rotation over time, and now, tracking its orbital evolution. This work can in principle be applied to other ULXs as well, to try to understand their age, their mechanism of mass transfer and, ultimately, their origin and their fate.

Multifrequency Behaviour of High Energy Cosmic Sources XIV (MULTIF2023)
12-17 June 2023
Palermo, Italy

*Speaker

PoS(MULTIF2023)053

1. Introduction

Ultraluminous X-ray sources [1–3] are defined as point-like, off nuclear X-ray sources exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (StBH; $L_{\rm ULX} > 3x10^{39}$ ergs s^{-1}). The first evidence of these sources came from *Einstein* [4] observations, but it was not until the early 2000's that, in a very short time, the three currently leading models for ULX apparent luminosities were proposed: intermediate mass black holes (IMBH [5]), geometric beaming[6], proper super-Eddington fluxes (Begelman et al. 2002)[7].

Indeed, being the definition based just on the apparent luminosity, it is still very possible that all three ingredients are necessary to describe the whole ULX population, which is now known to comprise thousands of sources[8]. To what extent these physical processes contribute to the ULX population is very important for their implication on evolutionary models. The maximum accretion rate onto a compact object, and the relative populations of StBHs and IMBHs are important to understand the evolution of galaxies and the formation of super-massive black holes (SMBH; [9, 10], see also Rosin's contribution in these Proceedings).

The intermediate-mass black hole hypothesis received a significant boost when a soft excess, reminiscent of a cold accretion disk, was found around some ULXs[11]; however, the appearance in high quality *XMM-Newton* data of a cut-off slightly below 10 keV was interpreted by some as a sign of super-Eddington accretion[12]. A decisive boost towards the interpretation of ULXs as super-Eddington accretion came with the launch of *NuSTAR*: first, by showing that the cutoff was deep above 10 keV[13–15], and could not be explained as an artifact or a broadened iron line, and then with the first detection of a pulsating ULX[16], unequivocally identifying the accretor as a neutron star (NS). Since then, a number of pulsating ULXs (PULXs, also referred to as ultraluminous pulsars, ULPs) were found[17–21], some of them radiating at hundreds of times their Eddington limits. A few more Galactic super-Eddington NSs provide a possible link between high-luminosity X-ray binaries (XRBs) and ULXs (e.g. Swift J0243+6124[22], see Alfonso-Garzón's contribution in these proceedings).

To date, it is unclear what fraction of the transferred matter actually accretes on the compact object. Super Eddington accretion is known to produce features that are indeed observed around ULXs, like high-velocity winds [23] and outflows, like those producing the enormous (up to 400 pc) interstellar bubbles around some of these sources (e.g. [24]). Galactic sources like SS433 [25] and Cyg X-3 ([26], see also contribution by Rodriguez Cavero) show that strong outflows are able to screen the inner source, likely producing some geometrical beaming. However, NSs are known to be able to accrete well above their Eddington limits, due to the decrease of the Thomson cross section in high magnetic fields [27, 28], in particular in the presence of strong quadrupolar components of the magnetic field [29]. Roche Lobe overlow is generally assumed, because quasi-spherical accretion from a wind [e.g. 30] seems not able to produce the observed mass transfer rates. Some kinds of focused winds, like those proposed in the Wind Roche Lobe Overflow [31, 32], might be viable in the case of supergiant donors. Models of this kind of accretion, in any case, predict the formation of a disk.

2. Timing properties of M82 X-2 and the other PULXs

Spin up and down properties of accreting neutron stars can provide hints to the important physical quantities in these systems. From standard accretion theory, we know that around accreting NSs there should be a radius at which the influx of matter from the disk is interrupted, and matter is captured from the magnetic field lines and conveyed to the polar caps of the star. This is called the *magnetospheric*, or inner, radius[33, 34]:

$$R_{\rm M} \approx \xi 10^8\,{\rm cm} \left(\frac{B}{10^{12}{\rm G}}\right)^{4/7} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{-2/7} \tag{1}$$

where ξ is an efficiency parameter, B is the magnetic field, $\dot{M}$ the mass accretion rate. The radius at which the Keplerian orbital frequency equals the rotation frequency of the star is called the *corotation* radius:

$$R_{\rm co} = \left(\frac{GMp^2}{4\pi^2}\right)^{1/3} \tag{2}$$

when the magnetospheric radius is inside the corotation radius, the pulsar is slower than the matter in the inner orbits. This matter threads the magnetic field of the star, and applies a positive torque on the star itself, accelerating it (or spinning it up). This is also referred to as the slow-rotator configuration. When the two radii are equal, the torque on the star is close to zero and spin up and spin down alternate depending on small variations of the mass accretion rate. In this situation, it is common practice to equate Eqs. 1 and 2 to obtain, given an estimate of the mass accretion rate, an estimate of the magnetic field (or vice versa).

The best studied PULX, arguably, is the first that was found, M82 X-2. It resides in an intermediate or high-mass X-ray binary (HMXB), in a circular orbit ($e < 0.0015$) around a companion star $> 5M_\odot$, with an orbital period of 2.53 d, and an orbital separation of 22 light-sec[16, 35]. The source is also known to show a super-orbital modulation with a period of ~ 60 d[36], during which it seems to alternate high- and low-flux states. Pulsations are often undetected: in some cases, this can be due to the contamination of the nearby source M82 X-1, which is unresolved in all timing-capable instruments (except for *Chandra*/HRC, which however has a low count rate which leads to a low sensitivity to pulsations); however, strict upper limits in some observations show that pulsations change dramatically their significance as well [35]. At the moment, it is unclear whether this disappearance is correlated to the super-orbital modulation. The pulsar was observed to spin up and down over time (with $|\dot{\nu}_{\rm spin}| \sim 2 \cdot 10^{10}$ Hz/s), roughly described by a secular spin down and strong spin up during the brightest accretion phases. However, the source was also observed spinning down *while* accreting, which strongly suggests that the pulsar is close to *spin equilibrium* [33, 37].

Other PULXs show strong spin-up and spin-down as well, with different behaviors. NGC 5907 ULX-1 is arguably the most extreme, with a luminosity reaching 10^{41} ergs s^{-1} and values of spin up and spin down on the order of $(2 < |\dot{\nu}_{\rm spin}| < 6) \cdot 10^9$ Hz/s [38]. The orbital period of this source is not known precisely, but it has been hinted to be ~ 5 d [39]. This pulsar seems to, like M82 X-2, be close to spin equilibrium. In both cases, there is a positive correlation between spin change and luminosity, implying that the luminosity is roughly tracing the accretion rate on the compact object.

M51 ULX-7, a ULX with a ∼ 2 d orbital period, seems to also be close to spin equilibrium, but the uncertainty on the orbital ephemeris does not allow a definite answer at the moment [21].

NGC 300 ULX, a pulsar in a very wide binary with no detected orbital period, has been observed to dramatically spin up in archival observations, from a rotational period of ∼ 126 s in 2014 to almost ∼20 s in 2019 ($|\dot{\nu}_{\rm spin}| \sim 10^9$ Hz/s). In this case, the pulsar seems a typical case of *slow rotator*, where the pulsar is very far from spin equilibrium and matter reaches relatively close to the pulsar [40, 41]. NGC 7793 P13, another pulsar in a very wide binary ($P_{\rm orb} \sim 64$ d[42]) has also consistently spun up over time ($|\dot{\nu}_{\rm spin}| \sim 10^{10}$ Hz/s)[43]. A very interesting fact about these two sources is that they have low states where no pulsations are detected, but when pulsations come back they are faster than before, a sign that there was still accretion during the low states. This might imply that the low states are triggered by the occultation of the accreting compact object and not from a decrease of the accretion rate.

3. What is the real mass transfer in ULXs?

As we have seen, when close to the spin equilibrium, in principle one could estimate the magnetic field of PULXs from their spin up/down properties. However, one open problem in ULXs is that it is not clear in what proportion their luminosity is driven by actual super-Eddington accretion or geometrical beaming. This uncertainty leads to mass transfer estimates spanning one or more orders of magnitude.

A possible independent avenue to measure of mass transfer is represented by the orbital evolution of the system. M82 X-2's orbital period is decreasing over time, by ∼ 2 seconds per year ($\dot{P}_{\rm orb}/P_{\rm orb} \sim 8 \cdot 10^{-6} yr^{-1}$) [44]. Assuming that the mass transfer is conservative, or non-conservative with mass loss from near one of the two orbiting objects[45], this leads to a lower limit on the mass transfer of $\dot{M} \approx 4.7 \cdot 10^{-6} M_{\odot}$ yr^{-1}. This inferred value of the mass transfer is just a factor ∼2 above that inferred from the isotropic luminosity (with the remaining matter possibly expelled from the system in winds), and a factor ∼ 10 above that inferred assuming geometrical beaming. If one trusts such measurement, the magnetic field of the neutron star should be $\sim 5 \cdot 10^{13}$ G. However, there are critics of this approach, mostly based on the fact that the timescales for mass transfer-driven orbital decay to become stable should be too long to be observable. [2]. Orbital decay is observed in some eclipsing HMXBs with lower inferred luminosities and mass transfer rates, [46], for reasons that might include the synchronization or circularization of elliptical orbits. M82 X-2, in principle, should be dominated by Roche Lobe overflow and these effects should be of secondary importance, but more work is needed.

In principle, there are other mechanisms that could produce some kind of orbital evolution. Gravitational wave emission and magnetic braking (see Pala's contribution to these proceedings) are very relevant in lower-mass systems, but should be negligible here. Circumbinary disks (see Alfonso-Garzón's contribution) could be an avenue for orbital decay, provided that significant mass loss happens from Lagrangian points.

I hope this paper gave an idea of the power of pulsar timing for investigating the Physics of PULXs. Future work should concentrate on searches for more PULXs and precise measurements of the spin and orbital properties of these systems. At the moment, we are limited by the small sample size and the technical difficulties afflicting this work: most sensitive instruments available

PoS(MULTIF2023)053

at the moment have long frame times which limit the sensitivity to relatively fast pulsations, or large point spread functions which are inadequate for these extragalactic sources, often found in crowded regions. Future missions might revive the field. For example, HEX-P ([47], see also Madsen et al. sub.), a mission concept recently submitted for the NASA Astrophysical Probe Explorer Announcement of Opportunity, the will be able to make much sharper images over the 0.3–30 keV, and allow for sensitive pulsar searches in crowded fields like those typical of ULXs. In particular, [48–50] show different examples of how the narrow PSF of the low-energy telescope (LET; 2.5″HEW) and the two high-energy telescopes (HET; ~ 18″HEW) carried by the mission, together with the large effective areas comparable to *XMM-Newton* and *NuSTAR* respectively, will lead to better sensitivity to pulsations than both *XMM-Newton* and *NuSTAR*.

References

[1] P. Kaaret, H. Feng and T.P. Roberts, *Ultraluminous X-Ray Sources*, *Annual Review of Astronomy and Astrophysics* **55** (2017) 303.

[2] A. King, J.-P. Lasota and M. Middleton, *Ultraluminous X-ray sources*, *New Astronomy Reviews* **96** (2023) 101672.

[3] C. Pinto and D.J. Walton, *Ultra-luminous X-ray sources: Extreme accretion and feedback*, Jan., 2023. 10.48550/arXiv.2302.00006.

[4] G. Fabbiano, *The X-ray emission of M81 and its nucleus*, *ApJ* **325** (1988) 544.

[5] P. Kaaret, A.H. Prestwich, A. Zezas, S.S. Murray, D.W. Kim, R.E. Kilgard et al., *Chandra High-Resolution Camera observations of the luminous X-ray source in the starburst galaxy M82*, *MNRAS* **321** (2001) L29.

[6] A.R. King, M.B. Davies, M.J. Ward, G. Fabbiano and M. Elvis, *Ultraluminous X-Ray Sources in External Galaxies*, *ApJ* **552** (2001) L109.

[7] M.C. Begelman, *Super-Eddington Fluxes from Thin Accretion Disks?*, *ApJ* **568** (2002) L97.

[8] D.J. Walton, A.D.A. Mackenzie, H. Gully, N.R. Patel, T.P. Roberts, H.P. Earnshaw et al., *A multimission catalogue of ultraluminous X-ray source candidates*, *Monthly Notices of the Royal Astronomical Society* **509** (2022) 1587.

[9] P. Madau and M.J. Rees, *Massive Black Holes as Population III Remnants*, *ApJ* **551** (2001) L27.

[10] K.A. Postnov and L.R. Yungelson, *The Evolution of Compact Binary Star Systems*, *Living Rev. Relativ.* **17** (2014) 3.

[11] J.M. Miller, G. Fabbiano, M.C. Miller and A.C. Fabian, *X-Ray Spectroscopic Evidence for Intermediate-Mass Black Holes: Cool Accretion Disks in Two Ultraluminous X-Ray Sources*, *ApJ* **585** (2003) L37.

[12] A.-M. Stobbart, T.P. Roberts and J. Wilms, *XMM-Newton observations of the brightest ultraluminous X-ray sources*, *MNRAS* **368** (2006) 397.

[13] M. Bachetti, V. Rana, D.J. Walton, D. Barret, F.A. Harrison, S.E. Boggs et al., *The Ultraluminous X-Ray Sources NGC 1313 X-1 and X-2: A Broadband Study with NuSTAR and XMM-Newton*, *ApJ* **778** (2013) 163.

[14] D.J. Walton, F. Fuerst, F. Harrison, D. Stern, M. Bachetti, D. Barret et al., *An Extremely Luminous and Variable Ultraluminous X-Ray Source in the Outskirts of Circinus Observed with NuSTAR*, *ApJ* **779** (2013) 148.

[15] V. Rana, F.A. Harrison, M. Bachetti, D.J. Walton, F. Fürst, D. Barret et al., *The Broadband XMM-Newton and NuSTAR X-Ray Spectra of Two Ultraluminous X-Ray Sources in the Galaxy IC 342*, *ApJ* **799** (2015) 121.

[16] M. Bachetti, F.A. Harrison, D.J. Walton, B.W. Grefenstette, D. Chakrabarty, F. Fürst et al., *An ultraluminous X-ray source powered by an accreting neutron star*, *Nat.* **514** (2014) 202.

[17] F. Fürst, D.J. Walton, F.A. Harrison, D. Stern, D. Barret, M. Brightman et al., *Discovery of Coherent Pulsations from the Ultraluminous X-Ray Source NGC 7793 P13*, *ApJL* **831** (2016) L14.

[18] G.L. Israel, A. Papitto, P. Esposito, L. Stella, L. Zampieri, A. Belfiore et al., *Discovery of a 0.42-s pulsar in the ultraluminous X-ray source NGC 7793 P13*, *MNRAS Let.* **466** (2017) L48.

[19] S. Carpano, F. Haberl, C. Maitra and G. Vasilopoulos, *Discovery of pulsations from NGC 300 ULX1 and its fast period evolution*, *MNRAS Let.* **476** (2018) L45.

[20] R. Sathyaprakash, T.P. Roberts, D.J. Walton, F. Fuerst, M. Bachetti, C. Pinto et al., *The discovery of weak coherent pulsations in the ultraluminous X-ray source NGC 1313 X-2*, *Monthly Notices of the Royal Astronomical Society* (2019) L104.

[21] G.A. Rodríguez Castillo, G.L. Israel, A. Belfiore, F. Bernardini, P. Esposito, F. Pintore et al., *Discovery of a 2.8 s Pulsar in a 2 Day Orbit High-mass X-Ray Binary Powering the Ultraluminous X-Ray Source ULX-7 in M51*, *The Astrophysical Journal* **895** (2020) 60.

[22] C.A. Wilson-Hodge, C. Malacaria, P.A. Jenke, G.K. Jaisawal, M. Kerr, M.T. Wolff et al., *NICER and Fermi GBM Observations of the First Galactic Ultraluminous X-Ray Pulsar Swift J0243.6$\mathplus$6124*, *ApJ* **863** (2018) 9.

[23] C. Pinto, A. Fabian, M. Middleton and D. Walton, *Ultrafast outflows in ultraluminous X-ray sources*, *arXiv* (2016) arXiv:1611.00623 [1611.00623].

[24] A. Gúrpide, M. Parra, O. Godet, T. Contini and J.F. Olive, *MUSE spectroscopy of the ULX NGC 1313 X-1: A shock-ionised bubble, an X-ray photoionised nebula, and two supernova remnants*, *Astronomy and Astrophysics* **666** (2022) A100.

[25] M.J. Middleton, D.J. Walton, W. Alston, T. Dauser, S. Eikenberry, Y.F. Jiang et al., *NuSTAR reveals the hidden nature of SS433*, *Monthly Notices of the Royal Astronomical Society* **506** (2021) 1045.

[26] A. Veledina, F. Muleri, J. Poutanen, J. Podgorný, M. Dovčiak, F. Capitanio et al., *Astronomical puzzle Cyg X-3 is a hidden Galactic ultraluminous X-ray source*, Mar., 2023. 10.48550/arXiv.2303.01174.

[27] M.M. Basko and R.A. Sunyaev, *The limiting luminosity of accreting neutron stars with magnetic fields*, *MNRAS* **175** (1976) 395.

[28] A.A. Mushtukov, V.F. Suleimanov, S.S. Tsygankov and J. Poutanen, *On the maximum accretion luminosity of magnetized neutron stars: Connecting X-ray pulsars and ultraluminous X-ray sources*, *MNRAS* **454** (2015) 2539.

[29] N. Brice, S. Zane, R. Turolla and K. Wu, *Super-eddington emission from accreting, highly magnetized neutron stars with a multipolar magnetic field*, *Monthly Notices of the Royal Astronomical Society* **504** (2021) 701.

[30] N. Shakura, K. Postnov, A. Kochetkova and L. Hjalmarsdotter, *Theory of quasi-spherical accretion in X-ray pulsars*, *Monthly Notices of the Royal Astronomical Society* **420** (2012) 216.

[31] I.E. Mellah, J.O. Sundqvist and R. Keppens, *Wind Roche lobe overflow in high-mass X-ray binaries - A possible mass-transfer mechanism for ultraluminous X-ray sources*, *A&A* **622** (2019) L3.

[32] G. Wiktorowicz, J.-P. Lasota, K. Belczynski, Y. Lu, J. Liu and K. Iłkiewicz, *Wind-powered ultraluminous X-ray sources*, *arXiv e-prints* **2103** (2021) arXiv:2103.02026.

[33] P. Ghosh and F.K. Lamb, *Accretion by rotating magnetic neutron stars. III - Accretion torques and period changes in pulsating X-ray sources*, *ApJ* **234** (1979) 296.

[34] Y.-M. Wang, *Location of the Inner Radius of a Magnetically Threaded Accretion Disk*, *The Astrophysical Journal* **465** (1996) L111.

[35] M. Bachetti, T.J. Maccarone, M. Brightman, M.C. Brumback, F. Fürst, F.A. Harrison et al., *All at Once: Transient Pulsations, Spin-down, and a Glitch from the Pulsating Ultraluminous X-Ray Source M82 X-2*, *ApJ* **891** (2020) 44.

[36] M. Brightman, F.A. Harrison, M. Bachetti, Y. Xu, F. Fürst, D.J. Walton et al., *A ~60 day Super-orbital Period Originating from the Ultraluminous X-Ray Pulsar in M82*, *The Astrophysical Journal* **873** (2019) 115.

[37] C.R. D'Angelo and H.C. Spruit, *Accretion discs trapped near corotation*, *Monthly Notices of the Royal Astronomical Society* **420** (2012) 416.

[38] F. Fürst, D.J. Walton, G.L. Israel, M. Bachetti, D. Barret, M. Brightman et al., *Probing the nature of the low state in the extreme ultraluminous X-ray pulsar NGC 5907 ULX1*, *Astronomy and Astrophysics* **672** (2023) A140.

[39] G.L. Israel, A. Belfiore, L. Stella, P. Esposito, P. Casella, A. De Luca et al., *An accreting pulsar with extreme properties drives an ultraluminous x-ray source in NGC 5907*, *Science* **355** (2017) 817.

[40] G. Vasilopoulos, F. Haberl, S. Carpano and C. Maitra, *NGC 300 ULX1: A test case for accretion torque theory*, *Astronomy and Astrophysics* **620** (2018) L12.

[41] G. Vasilopoulos, M. Petropoulou, F. Koliopanos, P.S. Ray, C.B. Bailyn, F. Haberl et al., *NGC 300 ULX1: Spin evolution, super-Eddington accretion, and outflows*, *Monthly Notices of the Royal Astronomical Society* **488** (2019) 5225.

[42] F. Fürst, D.J. Walton, M. Heida, F.A. Harrison, D. Barret, M. Brightman et al., *A tale of two periods: Determination of the orbital ephemeris of the super-Eddington pulsar NGC 7793 P13*, *Astronomy and Astrophysics* **616** (2018) A186.

[43] F. Fürst, D.J. Walton, M. Heida, M. Bachetti, C. Pinto, M.J. Middleton et al., *Long-term pulse period evolution of the ultra-luminous X-ray pulsar NGC 7793 P13*, *A&A* **651** (2021) A75.

[44] M. Bachetti, M. Heida, T. Maccarone, D. Huppenkothen, G.L. Israel, D. Barret et al., *Orbital Decay in M82 X-2*, *ApJ* **937** (2022) 125.

[45] T.M. Tauris and E.P.J. van den Heuvel, *Formation and evolution of compact stellar X-ray sources*, *Compact stellar X-ray sources* (2006) 623.

[46] M. Falanga, E. Bozzo, A. Lutovinov, J.M. Bonnet-Bidaud, Y. Fetisova and J. Puls, *Ephemeris, orbital decay, and masses of ten eclipsing high-mass X-ray binaries*, *Astronomy and Astrophysics* **577** (2015) A130.

[47] K. Madsen, R. Hickox, M. Bachetti, D. Stern, N.C. Gellert, J. García et al., *HEX-P: The High-Energy X-ray Probe*, .

[48] M. Bachetti, M.J. Middleton, C. Pinto, A. Gúrpide, D.J. Walton, M. Brightman et al., *The High Energy X-ray Probe (HEX-P): Studying Extreme Accretion with Ultraluminous X-ray Sources*, Nov., 2023.

[49] J.A.J. Alford, G.A. Younes, Z. Wadiasingh, M. Abdelmaguid, H. An, M. Bachetti et al., *The High Energy X-ray Probe (HEX-P): Magnetars and Other Isolated Neutron Stars*, Nov., 2023.

[50] K. Mori, G. Ponti, M. Bachetti, A. Bodaghee, J. Grindlay, J. Hong et al., *The High Energy X-ray Probe (HEX-P): Resolving the nature of Sgr A* flares, compact object binaries and diffuse X-ray emission in the Galactic Center and beyond*, Nov., 2023.