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Digging out the neutron stars extragalactic population – INAF-CINECA MoU report

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Abstract. Based on their X-ray luminosity exceeding the Eddington limit ($L_{\rm Edd}$) for a $\sim$10 $M_\odot$ object, ultraluminous X-ray sources (ULXs) have long been considered a very well suited population to look for and study BHs of stellar and intermediate mass (sMBH, IMBHs). The recent discovery of several ULXs showing fast ($\sim$ 1 s) and rapidly evolving pulsations (PULXs) unambiguously associated them to neutron stars (NSs) exceeding by orders of magnitude their $L_{\rm Edd}$. These discoveries challenge our understanding of accretion physics and pose a key question about the nature of the ULXs as a class: are ULXs a heterogeneous population hosting both accreting BHs and NSs, or is there a dominant new *Ultraluminous Neutron Star Extragalactic populatioN* (UNSeEN) with extreme properties? Our work was aimed at answering the question by tripling the number of ULXs over which sensitive searches for X-ray pulsations – which require the use of High Performance Computing (HPC) facilities – have been carried out. We expected to detect at least 1 new PULX. This was a joint project using the INAF-CINECA HPC MoU and the XMM-Newton Mission of the European Space Agency. Confirming our statistical expectations, a new PULX was discovered in the M51 galaxy, the first ever pulsar discovered in this galaxy.

Key words. Methods: Data mining – Stars: Neutron – Stars: Pulsating Ultraluminous X-rays sources

1. Introduction

Ultraluminous X-ray sources are off-nuclear objects detected in nearby galaxies with X-ray luminosities in excess of 10^{39} erg s^{-1}, which is the Eddington luminosity ($L_{\rm Edd}$) for a black hole (BH) of 10 $M_\odot$ (Kaaret & Roberts 2017).

$L_{\rm Edd}$ sets the upper limit to the accretion luminosity ($L_{\rm acc}$) that a compact object can steadily produce, since for $L_{\rm acc} > L_{\rm Edd}$, the accretion flow is halted by the radiation pressure. For spherical accretion of fully ionized hydrogen, the limit can be written as $L_{\rm Edd} = 4\pi cGMm_{\rm p}/\sigma_{\rm T} \simeq 1.3 \times 10^{38}(M/M_\odot)$ erg s^{-1}, where $\sigma_{\rm T}$ is the Thomson scattering cross section, $m_{\rm p}$ is the proton mass, and $M/M_\odot$ is the compact object mass in solar masses; for a 1.4 $M_\odot$ neutron star (NS), the maximum accreting luminosity is $\sim 2 \times 10^{38}$ erg s^{-1}.

Since their discovery in the '70s with the Einstein mission (Fabbiano, et al. 1992), the high luminosity of ULXs has thus been interpreted as accretion at or above the Eddington luminosity onto BHs of stellar origin (<80–

$100\,M_{\odot}$), or onto intermediate-mass (10^3–$10^5\,M_{\odot}$) BHs (Poutanen et al. 2007; Zampieri et al. 2009).

The recent discovery of coherent pulsations with periods in the order of a second in the X-ray light curves of a few ULXs with luminosities in the 10^{40} – 10^{41} erg s^{-1} range, unambiguously associate these ULXs with accreting NSs, therefore a compact object with mass of only $\sim 1.4 M_{\odot}$ or slightly larger (Bachetti et al 2014; Fürst et al 2016; Israel et al. 2017a,b), see Figure 1. More importantly, these X-ray pulsars demonstrates that accreting NSs can achieve extreme luminosities, above 500 times the $L_{\rm Edd}$, which is simply not conceivable in the current accretion models. A significantly super-Eddington luminosity can be achieved if the magnetic field of the NS is very high due to the reduction of the scattering cross sections: a luminosity of $\sim 500\,L_{\rm Edd}$ would require a field strength of $> 10^{15}$ G (Mushtukov et al 2015; Dall'Osso 2015). However, the ~ 1 s rotation of the NS and its magnetosphere would drag matter at the magnetospheric boundary so fast that the centrifugal force would exceed the gravitational force, inhibiting the accretion on the NS surface by the so-called propeller mechanism (Illarionov et al. 1975; Stella et al. 1986). This problem can be partially mitigated assuming that the emission is beamed (as expected in pulsars) though, in the most extreme case, an unrealistic beaming factor of 1/100 would be needed. Several new possible scenarios have been proposed to account for the PULX properties and the presence of a strong multipolar magnetic field ($\sim 10^{14}$ G) close to the surface of the NSs appears a reasonable way out of the problem (Israel et al. 2017a; Chashkina et al. 2017), though "standard" magnetic fields of $\sim 10^{12}$ G are not excluded by models (King et al. 2017).

Another important consequence of the discovery of the PULXs is that the nature of many ULXs which have been classified in good faith as accreting black holes due to their high luminosity is now in doubt. An unknown but possibly large fraction of ULXs might host an accreting NS rather than a BH. The answer to this issue will have a strong impact on many topics beyond compact object studies and accretion models. For instance, the existence of IMBHs is a channel for the formation of $10^{4-5}\,M_{\odot}$ BHs, which are thought to be trelevant for the presence of supermassive BHs in quasars at $z > 6$–7 (Pacucci et al. 2017).

2. The jointed XMM-Mewton and INAF-CINECA UNSEeN Project

Assessing the nature of the compact objects hosted in ULXs is of paramount importance and the discovery of the PULXs demonstrate that we can tackle the problem. In general, the unambiguous identification of the nature of a NS in X-rays is achieved with: [1] the detection of rapid coherent signals reflecting the spin period of the NS ("BHs have no hairs" and no X-ray modulation related to its spin is detectable); [2] the detection of CRSFs (though less frequently seen) in their energy spectra. However, given the pulsed fractions (in the following we adopt the definition of semi-amplitude of the sinusoid divided by the source average count rate) observed in the PULXs and the intrinsically low intensity of CRSFs (we adopt the equivalent width, EW, measure to define their strength), both approaches need large count-statistics, order of or higher than $\sim 10{,}000$ counts (see below). This was available only for about ~ 13 ULXs (among which are the three PULXs) out of the sample of about 300 known (Earnshaw et al. 2017). We focused our work in [1].

The detection of pulsations does not depend on the brightness of the target as much as on the total number of source counts present in the data. In fact, we can detect at 3.5σ confidence level a pulsation in a fainter source by observing it for longer. The 3 PULXs known so far have all PFs between 10 and 20%. In order to detect a $\sim 10\%$ PF pulsation, at least 10.000 counts are needed. Counts collected in multiple, far apart observations, will not do the job, because of the orbital motion and the moderate-to-large $\dot{P}$ these sources have ($\dot{P} \sim 10^{-8} \div 10^{-11}$ s s^{-1}), which eventually washes out the signal too much to be corrected with reasonable searches. At the beginning of our project, there were only 13 ULXs in the XMM archive for which such pulsations

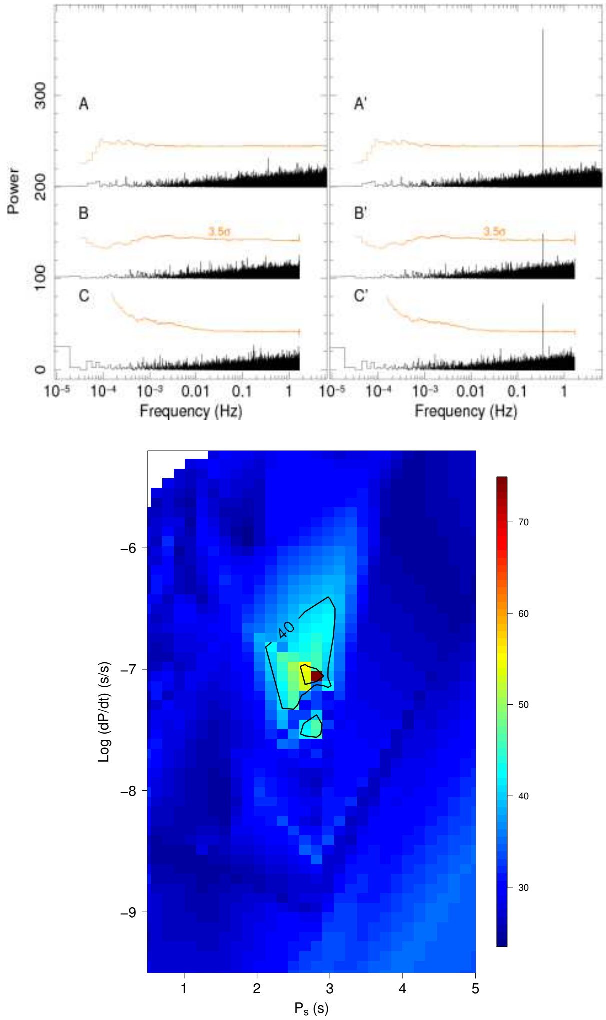

Fig. 1. Detection and study of the pulsations observed in the pulsar M51 ULX-7, discovered with CINECA HPC. Upper panel, left – Arbitrarily shifted (along the y-axis) power spectral density (PSD) of the 0.2-12 keV (XMM-Newton) M51 ULX-7 light curves of observations carried out on 2018 May 13 (A), June 13 (B), and June 15 (C), right – the same light curves after correcting their photon arrival-times for both a first period derivative and an orbital Doppler term (A',B' and C'). Orange curves mark the 3.5σ detection threshold for each PSD. Lower panel – PASTA@CINECA discovery plot for the 2.8 s-periodic signal in M51 ULX-7. Each point in the plane corresponds to the power of the highest peak found in different PSDs, obtained by correcting the photon arrival times for a first period derivative component with values in the $-11 < \mathrm{Log}\dot{P} < -5$ range. Colors mark the Leahy power estimates (for 2 degrees of freedom) in the corresponding PSD (see color scale on the right). For details see (Rodríguez Castillo et al 2020)

could have been detected, i.e. with more than 10,000 source counts in a single observation. For other ~10 ULXs, the number of counts (between 2,000 and 8,000 counts) would have allowed the detection of pulsations only for PFs larger than 20%-30%. However, for the large majority of the ULXs observed with XMM, the number of counts collected is by far too low to allow the detection of such pulsations.

The process of detecting a signal with respect to the statistical/instrumental noise(s) is carried out by using several different algorithms. Among others are the Fast Fourier Transform (Leahy et al. 1983), which we modified in order to take into account the possible presence of non-Possonian noise components in the power spectra (PSD Israel & Stella 1996), and the Z_N^2 periodogram (Buccheri 1988). These two methods are routinely applied since both methods have pro and cons and are somewhat complementary: FFTs are fast but less sensitive to non-sinusoidal signals and/or to time series with few counts (below 100 – 200), while Z_N^2 periodograms are more sensitive to faint and/or non-sinusoidal signals but much more CPU-consuming. Furthermore, we modified our searching strategies following the extreme timing properties of two out of the three new pulsators we discovered which possess $\dot{P}$ in the $10^{-(8\div9)}\,\mathrm{s\,s^{-1}}$ and orbital periods in the range of few days. Figure 1 clearly summarizes this issue: without a proper correction the signal of NGC 5907 ULX cannot be detected. Therefore, we developed new pipelines which systematically and automatically sample a multi dimensional grid of timing parameters (up to six: the spin period P, its first derivative $\dot{P}$, the orbital period $P_{\rm orb}$, the semi major axis projection $a_{\rm X}\sin i$, and the time of the ascendent node $T_{\rm node}$). Depending on the number of free parameters and grid step, up to 10^6 PSDs or periodograms are needed to complete the search analysis for each light curve. The only way to carry on these analysis is with the use of HPC, in particular, the CINECA-GALILEO cluster through the INAF-CINECA MoU, ensuring a deep and sensitive signal search over a large sample of corrections, maximizing the parameter resolution. Beside analysing the new obtained data, we also carried out a search (correcting only for the $\dot{P}$ component) of ULXs signals in the XMM-Newton archive and no new pulsar has been detected so far, while in almost all cases the 3σ upper limits to the PF are above the 10-15% observed in PULXs (Rodriguez et al. 2021, in prep.). In FFTs, the relation which links the number of counts to the minimum detectable signal PF is given by $PF = \left\{\left[\frac{P_j}{2M}\right]\frac{4}{0.773N_\gamma}\frac{(\pi j/N)^2}{sin^2(\pi j/N)}\right\}^{\frac{1}{2}}$, where P_j is the power in the jth Fourier frequency, N_γ and N the number of counts and bins in the time series, and M the number of averaged FFTs in the final PSD (Leahy et al. 1983). Before our XMM-Newton observations there were only 10 ULXs with statistics, within a single pointing, comparable or higher to that of the three PULXs known at the time. This number (10+3) is only ~6% of the total known ULX population. More importantly, the incidence of NS among this 6% of ULXs with good statistics is ~23%, implying that ULXs once thought BH population is instead dominated by NS.

3. Results

We observed 15 ULXs with the XMM-Newton mission long enough to get the needed statistics in order to be able to detect coherent puslations in the expected PF range. Using the HPC of CIENCA, we performed a search for signals, applying timing corrections for about two million different orbital parameters for each source. In this way we discovered the first pulsar in the M51 galaxy (Rodríguez Castillo et al 2020), confirming our statistical expectations and implying that the ULX population may be dominated by NS, instead of BH, a huge paradigm shift in our understanding of the ULXs.

4. Conclusions

Together with XMM-NEWTON, the HPC of CINECA, through the INAF-CINECA MoU, allowed us to discover the first pulsar in the Whirlpool Galaxy and enabled us to make an important step towards the understanding of the ULX population.

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