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ULTRA LUMINOUS X-RAY SOURCES

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Abstract. Ultra Luminous X-ray sources (ULXs) are X-ray bright objects that are not coincident with the central nucleus of the host galaxy and which have luminosities that exceed the Eddington limit for a stellar mass black hole, typically L $> 3 \times 10^{39}$ erg s^{-1} for a black hole of 20 M$_\odot$. The nature of these objects is still unclear. However, it is possible that these sources do not form a single class of objects. Many ULXs may house stellar mass black holes accreting at super-Eddington rates, even if the physical mechanism for such high accretion rates is still not understood. Some ULXs may contain intermediate mass black holes ($\sim 1 \times 10^2 - \sim 1 \times 10^5$ M$_\odot$). These elusive black holes are thought to be the building blocks of the more massive supermassive black holes, observed at the centre of many galaxies. Other ULXs may not be accreting black holes at all. Recent evidence for the different types of ULXs is presented in this paper.

Keywords: Stars: black holes, X-rays: binaries, Galaxies: evolution, Accretion, accretion disks

1 Introduction

During the late seventies the X-ray observatory *Einstein* detected non nuclear X-ray sources that have luminosities exceeding the Eddington luminosity (L$_{\rm Edd}$) of a stellar mass black hole (BH, Fabbiano 1989), where L$_{\rm Edd} = 1.3 \times 10^{38}$(M/M$_\odot$) erg s^{-1}. These sources are now referred to as ultra-luminous X-ray sources (ULXs). Their nature as a population is still strongly debated, but given the fact that ULXs showed different spectral states, and some ULXs appeared to show spectral state transitions (Kubota et al. 2001), lent weight to the idea that most ULXs are stellar mass black holes accreting super-critically.

The physics describing super-critical accretion is still not clear (e.g. Walton et al. 2013b). Currently, different models are being proposed, e.g. Dotan & Shaviv (2011); Begelman (2002). It has been proposed that ULXs may only seem to exceed the Eddington limit. There are a variety of ways that an accreting source can appear to exceed the Eddington limit, e.g. via relativistic beaming (e.g. Freeland et al. 2006) or via geometric beaming (Paczyńsky & Wiita 1980), and thus appear to exhibit such high luminosities. However, it is generally accepted that many of the lower luminosity ULXs (L $< 1 \times 10^{41}$ erg s^{-1}) house stellar mass black holes (3-20 M$_\odot$, e.g. Walton et al. 2011), which are assumed to be accreting above the Eddington limit, as there is little evidence that the high luminosities are due to beaming, as most ULXs are seen to change state. In addition, two X-ray binaries in M 31 have been seen to transit into the ultra-luminous state and then return to their regular state, demonstrating that ULXs can be simply an ultra-luminous state of accreting compact objects (e.g. Middleton et al. 2012, 2013). None the less, there remains the possibility that these ULXs are simply higher mass stellar mass black holes ($20 <$ M$_{BH} \lesssim 100$ M$_\odot$) accreting below the Eddington limit e.g. Mapelli & Zampieri (2014); Zampieri & Roberts (2009). Determining the mass of the black hole in these objects is definitive in discerning between these two hypotheses. Also, studying the X-ray spectra (e.g. Gladstone et al. 2009) and X-ray timing properties (e.g. Middleton et al. 2015a), will reveal the physics behind the strong emission observed.

However, ULXs with L $> 1 \times 10^{41}$ erg s^{-1}, generally known as hyper luminous X-ray sources (HLXs, Gao et al. 2003) are difficult to explain without evoking more massive black holes, such as Intermediate Mass Black Holes (IMBHs) which have masses $\sim 1 \times 10^2 - \sim 1 \times 10^5$ M$_\odot$ (Gao et al. 2003; Farrell et al. 2009). This is because there is a limit to how much relativistic and geometric beaming is possible if the central object is a stellar mass black hole e.g. Freeland et al. (2006); King (2008). Whilst IMBH are evoked to explain the formation of

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supermassive black holes ($1 \times 10^6 - 1 \times 10^{10}$ M$_\odot$), either through mergers and/or through (super-) Eddington accretion, (see Greene 2012; Volonteri 2012, for reviews), they remain elusive observationally. If HLXs do contain IMBH, they then become interesting for constraining the formation mechanisms of supermassive black holes.

All the same, a number of proposed ULXs have been shown to be supernova remnants e.g. Mezcua & Lobanov (2011), accreting white dwarfs e.g. Li et al. (2012), background AGN e.g. Dadina et al. (2013), amongst other things. It is clear that ULXs are therefore not a homogeneous sample of sources. Thanks to recent observations of ULXs with (hard) X-ray observatories, such as *XMM-Newton*, *Chandra* and more recently *NuSTAR* (Harrison et al. 2013), coupled with complimentary multi-wavelength observations, the nature of ULXs has been shown to be highly diverse. In this review article we discuss some of the more recent observational results concerning the nature of ULXs and discuss their implications.

2 Stellar mass black holes accreting above the Eddington limit

One of the best ways to unequivocally determine the mass of the accreting object is to determine it using a dynamical mass estimate, i.e. through the radial velocity motion of one or both the stars in the binary system and using Kepler's laws. This is actually difficult to do, as no object is observed to be a ULX in our own galaxy, and such observations are difficult to achieve for ULXs in other galaxies due to the large distances and hence relatively faint sources. Additionally, previous attempts to detect a spectral lines from the companion have revealed blue, almost featureless spectra (e.g. Zampieri et al. 2004; Kaaret & Corbel 2009; Grisé et al. 2012) which are probably dominated by the accretion disc and in some cases show evidence of the surrounding nebula. The companion star is therefore not detected.

Recently, however, Motch et al. (2014) observed a ∼64 day period from the ULX P13 in the galaxy NGC 7793 using optical photometry. They confirmed the period using optical spectroscopy of the companion star which they revealed to be a B9Ia star. The mass of the companion star was estimated to be 18-23 M$_\odot$. Using radial velocity measurements and thanks to Kepler's laws, the mass of the black hole was shown to be $\lesssim 15$ M$_\odot$. The binary has an eccentricity of 0.27-0.41. Given that the X-ray luminosity of the P13 is $\sim 4 \times 10^{39}$ erg s^{-1}, the black hole is accreting at at least twice Eddington, even if it is as massive as 15 M$_\odot$, confirming the stellar mass nature of the black hole, but also demonstrating that the black hole accretes super-critically. Further, this study shows that given the evolved nature of the donor star, the mass transfer must occur on a thermal timescale ($\sim 10^5$ yr) as the supergiant rapidly expands. This is more than an order of magnitude shorter than its main sequence life time. This then implies that supergiant ULXs are much more rare than systems with unevolved mass-donors.

The other major result from Motch et al. (2014) is that they show for the first time that the X-ray spectrum that they observe from P13 and which is typical of many ULXs, with both a medium energy break and a soft X-ray excess, is indeed the signature of an Eddington or super-Eddington regime. This supports the *NuSTAR* results (e.g. Bachetti et al. 2013; Walton et al. 2013a) that many of the lower luminosity ULXs ($L < 1 \times 10^{41}$ erg s^{-1}) are indeed stellar mass black holes accreting super-critically. Understanding the physical mechanism for this extreme accretion is not only useful for understanding the population of ULXs, but also the earliest and most massive super-massive black holes that may require super-critical accretion to achieve such masses at early times e.g. Willott et al. (2010).

3 Intermediate mass black hole candidates

Dozens of HLX sources proposed to house an intermediate mass black hole have been proposed in recent years. However, either these objects are observed only once e.g. Gao et al. (2003) and references therein or they are more often than not, shown to be either foreground or background objects e.g. Sutton et al. (2015). The serendipitous discovery of 2XMM J011028.1–460421 (hereafter Hyper Luminous X-ray source - HLX-1) with XMM-Newton on 23 November 2004 in the outskirts of the edge-on spiral galaxy ESO 243–49 at a distance of 95 Mpc marked a milestone with the most secure identification of a HLX (Farrell et al. 2009; Wiersema et al. 2010). With a 0.2-10 keV unabsorbed luminosity reaching 1.3×10^{42} erg s^{-1} at peak, HLX-1 is the brightest HLX detected so far. Spectral modelling of X-ray data with sophisticated accretion disk models (Davis et al. 2011; Godet et al. 2012b; Straub et al. 2014) and Eddington scaling of X-ray/radio data (Servillat et al. 2011; Webb et al. 2012) gave us a range of mass estimates from 9,000 to 90,000 M$_\odot$, placing it in the IMBH mass range. Multi-wavelength observations of HLX-1 over the past six years showed that HLX-1 displays several properties similar to those observed in stellar mass BH X-ray binaries (Remillard & McClintock 2006), contrary to other lower luminosity ULXs: i) regular outbursts with state transitions, but with X-ray luminosities orders of magnitude larger (Godet et al. 2009; Servillat et al. 2011; Godet et al. 2012b) ; ii) the detection of radio transient emission with ATCA interpreted as discrete jet ejection events following the hard-to-soft transitions (Webb et al. 2012; Cseh et al. 2015); iii) the possible detection of a radio compact jet when the source is in the hard state (Cseh et al. 2015). By modelling HST and *Swift*-XRT data, Farrell et al. (2012) showed that the HLX-1 host could be a globular cluster-like cluster or the stripped nucleus remnant of a dwarf galaxy formed following an interaction with ESO 243-49.

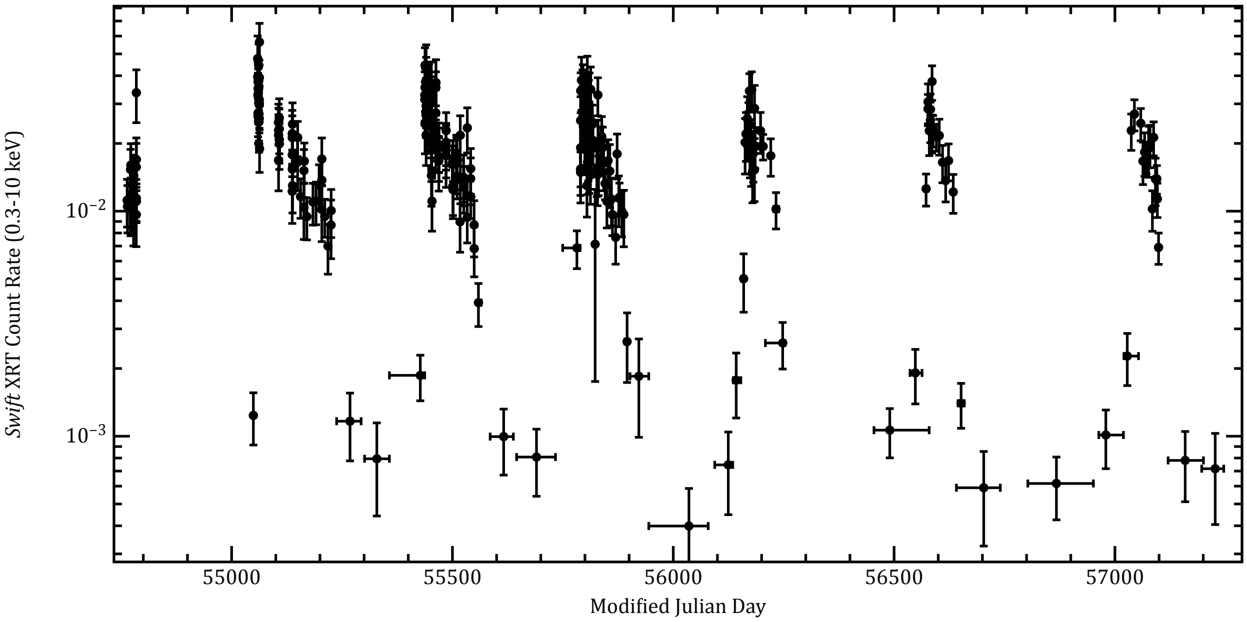

Fig. 1. The Swift X-ray lightcurve of ESO 243-49 HLX-1 from 2008-2015.

The *Swift*-XRT light-curve from 2009 to 2012 shows FRED-like outbursts separated by an apparent recurrence time of nearly a year, see Fig. 1. Since 2013, the time interval between the outbursts has increased by more than a month for the outburst starting in October 2013 (56570 MJD) and around three months for the one starting in January 2015 (57030 MJD). The spectral properties of these two last outbursts are consistent with those seen in previous outbursts, but with a possible moderate spectral softening for the 2015 outburst. Lasota et al. (2011) proposed that the X-ray light-curve is the result of enhanced mass transfer from an Asymptotic Giant Branch star in an eccentric orbit occurring when the star passing at periapsis is tidally stripped. Using contemporary optical (VLT) and X-ray (*Swift*-XRT) observations over the rise of the outburst, Webb et al. (2014) showed that a fraction of the optical emission comes from the accretion disk and that the optical might start just before the X-rays indicating an outside-in outburst and a distance from the delivery-mass radius to the inner edges of the disk to be less than $\sim 10^{11}$ cm. This implies a highly eccentric orbit ($e \rightarrow 1$) and therefore a possibly unstable and potentially short-lived system. From Fig 1, it is also clear that the duration of the outbursts decreases over time until the 2015 outburst. Indeed, the duration of the outbursts decreased from ~ 170 days in 2009 to $\sim 65 - 72$ days in 2013. The duration of the 2015 outburst was slightly longer than that measured in 2013. This might indicate a change in the supply of matter to the IMBH or in the accretion flow.

Godet et al. (2014) investigated through a series of smoothed particle hydrodynamical simulations the origin of the delay in the framework of the mass transfer model and the consequences for the IMBH-star system (e.g. the evolution of the orbital period over time, the system lifetime, the constraints on the donor type). Godet et al. (2014) followed a large number of dynamical timescales (from 6000 to 70000) in order to study the evolution of such a system. Once the system is formed with an eccentricity always close to 1, the orbital period (P) decreases until reaching a minimum. Then, the period tends to increase over several periapsis passages due to tidal effects and increasing mass transfer, leading ultimately to the star ejection. The development of stochastic fluctuations inside the donor could lead to sudden changes in P from orbit to orbit with the appropriate order of magnitude of what has been observed for HLX-1 so far. They also showed that if the HLX-1 orbital period is currently near a minimum ($P \sim 1$ yr) and provided that $M_{BH} > 10^4\ M_\odot$, the donor has to be a white dwarf (WD) or a stripped giant core. If $P_{\rm min} \sim 1$ yr and $M_{BH} < 10^4\ M_\odot$, then there is no viable solution for the donor star. Recently, MacLeod et al. (2015) used N-body simulations to investigate the close stellar companions of IMBHs located in globular clusters. They found that most bound companion stars (including white dwarfs) could suffer grazing tidal interactions with the hole.

HLX-1 is clearly very different from regular ULXs and all the observations support the IMBH hypothesis for accreting compact object. Recently, a similar object has been proposed (Heida et al. 2015; Jonker et al. 2010). CXO J122518.6+144545 has shown a maximum luminosity of 2.2 × 10^{41} erg s^{-1}, with X-ray variability with a factor >60 and repeated outbursts. This will be an interesting object to follow up to confirm its nature. Using radio and X-ray observations and the black hole fundamental (e.g. Falcke et al. 2004), Mezcua et al. (2015) have identified another IMBH candidate of ∼5 × $10^4\ M_\odot$, so it appears that at least some types of ULXs may host the much sought after IMBH. It would then be instructive to determine their number and distribution, so as to assess their role in the formation of supermassive black holes (e.g. Volonteri 2012; Greene 2012). Other searches for similar sources are therefore underway e.g. Zolotukhin et al. (accepted).

4 Other types of ULXs

As outlined in Sec. 1, ULXs have been shown to be a heterogeneous set of objects. The most extreme and surprising result in recent years is the identification of a neutron star in the ULX M 82 X-2 (Bachetti et al. 2014). M 82 X-2 reaches maximum X-ray luminosities of 1.8 × 10^{40} erg s^{-1}, is highly variable, and has an X-ray spectrum similar to other ULXs of a similar luminosity. These characteristics would therefore lead us to expect a stellar mass black hole accreting super-critically or a more massive stellar mass black hole accreting at or close to the Eddington limit (see Sec. 2). M 82 was pointed by the hard X-ray observatory *NuSTAR* at the beginning of 2014, for almost 2 Ms to observe the type 1a supernova, SN 2014J. M 82 X-2 was also in the field of view and the long exposure revealed a highly periodic signal (pulse period 1.37 s, 30 σ significance) from this ULX. Not only was a pulse detected, a strong spin up of the period of 2.2 × 10^{-10} s s^{-1} was discovered and a longer period of 2.53 d was also identified. Only a very compact object (neutron star or black hole) can have such a short period, but to have such a rapid spin up, the object requires a surface, demonstrating that the accreting object is a neutron star and thus emits at 100 times the Eddington limit.

This result implies that ULXs may not only host black holes as their compact object, but also host neutron stars. It also shows that an object can (appear to) emit at highly super-Eddington luminosities for extended periods. This surprising result has triggered a lot of work in understanding how this could occur. Bachetti et al. (2014) suggest that the neutron star may have a fan beam geometry and if viewed at a favourable angle, the observed pulse profile could be produced and the accretion stream could become sufficiently collimated to generate the observed luminosities. Shao & Li (2015) show that just after the onset of Roche lobe overflow in a system like M 82 X-1 with a companion star of mass > 5.2 $M_\odot$, the mass ratio of the stars is such that the mass transfer rate can not be stable and increases rapidly to become super-Eddington, allowing the binary to transition to a ULX for ∼10^5 years. Thus it would be possible to have a population of neutron star X-ray binaries contributing significantly to the ULX population. Shao & Li (2015) show that high-mass and intermediate-mass X-ray binaries dominate the neutron star ULX population in M 82- and Milky Way-like Galaxies, respectively. Wiktorowicz et al. (2015) support this by showing that several binary evolutionary channels lead to phases of very high mass transfer rate in close Roche lobe overflow binaries, so that any ULX, including the most luminous ones, may potentially be a short-lived phase in the life of a binary star.

5 Discussion

As discussed above, the term ULX denotes a highly inhomogeneous group of objects, some which appear to be accreting super-critically, whilst others below the Eddington limit. Not only that, the accreting compact object ranges from neutron stars and stellar mass black holes and quite probably all the way to intermediate mass black holes. As the number of ULXs grows, it is quite likely that sub-groups of these objects will be formed, above and beyond the standard ULX and HLX division. Indeed, some authors have already attempted to make this sub-division. Gladstone (2013) propose a third class, the 'Extreme Ultra Luminous X-ray Sources' composed of objects with X-ray luminosity of 2 × 10^{40} erg s^{-1} - 1 × 10^{41} erg s^{-1}. This luminosity range includes the break in the X-ray luminosity function in our local Universe and the luminosity due to accretion onto extreme massive stellar remnant black hole accretors. Sutton et al. (2013) defined an empirical classification scheme based on spectral morphology and timing properties. Below $\sim 3 \times 10^{39}$ erg s^{-1} the disc X-ray spectra are broad, consistent with a population of stellar mass black holes (M $\lesssim 20$ M$_{\odot}$), accreting at, or just above, the Eddington limit. ULXs with luminosities above this value and up to $\sim 2 \times 10^{40}$ erg s^{-1} with broad X-ray spectra may be powered by accretion onto larger black hole primaries, although higher beaming factors remain a possibility. Brighter sources show either hard ultraluminous spectra with fractional variability much less than 10% or soft ultraluminous spectra with 10-30% fractional variability. This is thought to be due to the large winds created at these high luminosities and the spectral and timing differences are due to viewing angle, where looking down the opening angle of the wind, the geometrically-beamed hard emission from the central source dominates, and at higher inclinations to our line-of-sight a wind-dominated soft ultraluminous spectrum is seen. This creates a unified model for the majority of ULXs, but does not allow us to distinguish between neutron star or intermediate mass black hole accretors, for example, see e.g. Middleton et al. (2015a).

Obviously more work remains to be done to validate this model and understand where the outliers to this generalisation fit in. Continued observations to monitor the variability of all types of ULXs with *Swift* and in the future with *SVOM* (e.g. Godet et al. 2012a), will allow us to understand the transitions between ULX spectral states, that are for the most part, quite different to those observed for sub-Eddington X-ray binaries. Using the high resolution gratings on *XMM-Newton* and *Chandra* should also give us some insight into the nature and importance of the wind in ULXs (e.g. Middleton et al. 2015b). These winds may also be investigated by studying the optical emission-line nebulae that are sometimes seen around ULXs, and are thought to be due to shock-ionised driven jets, outflows or disc winds and/or because of photo-ionisation from the X-ray and UV emission around the black hole. In the future, sensitive radio observatories such as the *SKA* will be able to look for emission emanating from (possible) jets and nebulae in ULXs, extending recent work carried out with the VLBI (Mezcua et al. 2013). This will enable us to constrain whether the source is in a low hard state, as oppose to the hard ultra-luminous state, for example, giving us the nature of the compact accretor. The nebulae can also serve as a calorimeter, implying the total intrinsic power of the ULX, (e.g. Pakull & Mirioni 2002, 2003). They can be used to understand how outflows and photo-ionisation can play a role in the behaviour of the ULX and on its surrounding environment (e.g. Pakull & Mirioni 2002, 2003). In the optical, future surveys such as the *Large Synoptic Survey Telescope* (*LSST*)[*] from 2022, will observe the sky using an 8.4 m telescope. This will allow us to identify new and monitor known transient ULXs in order to identify ULXs under-going state transition. Observations with the proposed *Extremely Large Telescopes* which should be able to achieve excellent signal to noise for good resolution spectra of ULX companion stars, will allow us to make dynamical mass measurements of many of the known (and still to be found) ULXs in a similar way to Motch et al. (2014), thus allowing us to unequivocally determine the nature and mass of the compact accretor. Future X-ray observations with the X-ray observatory *Athena* (Nandra et al. 2013) will be able to probe the accretion regime, allowing us to finally understand these diverse and extreme objects.

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