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The Ultraluminous X-ray Population

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Ultraluminous X-ray sources (ULX) are of great interest due to the possibility of harboring intermediate-mass black holes or, alternatively, to be super-Eddington accretors. Constraining the number of intermediate-mass black holes and the maximum rate of accretion is in fact very important to understand how black holes evolve - and in turn how Galaxies evolve.

In this short review, I will describe the advances done in the understanding of these sources in the last few years. This review is an extended and updated version of the one published in *Astronomy Notes* by the same author.

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1. Introduction

Black holes (BHs) come in different sizes through different formation paths (see Rees and Volonteri [2007] for a review): those believed to be produced through the explosion (*hyper*nova) of a very massive star are called stellar-mass BHs (StBH) and have masses $\lesssim 100 M_{\odot}$; the ones found in the core of galaxies are usually millions of times larger or more, and are called supermassive BHs (SMBH). The formation of SMBHs is not yet understood completely. An important role seems to be played by BHs of intermediate size (intermediate-mass BHs, IMBH, see Kormendy and Ho [2013] for a review), either via mergers (e.g. Madau and Rees [2001]) or as an intermediate step of the growth of StBHs at very high rates, due to super-Eddington accretion (e.g. Kawaguchi et al. [2004]). However, this intermediate population is very elusive.

One obvious way to look for large black holes is using the **Eddington limit**. Accreting matter emits a large part of its rest mass as radiation. Let us consider a toy model where matter is accreting spherically onto a compact object. The inner layers of this accreting matter heat up, and produce a strong radiation that interacts with the upcoming layers. The Eddington limit is the classical solution to an equation of hydrostatic equilibrium where the inward force is the gravitational attraction and the outward force is given by radiation pressure, under some stringent assumptions: matter is only composed of *fully ionized Hydrogen*, accreting *spherically and homogeneously*; magnetic fields are negligible. Under these assumptions, it can be shown that the luminosity at which the two forces equate, and thus accretion rate stops increasing, is only dependent on the mass of the compact object:

$$L_{Edd} \approx 1.38 \cdot 10^{38} \left(\frac{M}{M_{\odot}}\right) \mathrm{erg\,s^{-1}}. \tag{1.1}$$

This limit was created, and used extensively, to estimate the maximum mass of stars – how much can a star weight before its luminosity rises to the point of sweeping away its external layers? But for our purposes, it is particularly important because it allows to estimate a rough lower limit on the mass of a compact object given its maximum luminosity. In particular, observing sources above $10^{39}\,\mathrm{erg\,s^{-1}}$ suggests crude mass estimates exceeding the bulk of the small stellar-mass black hole population ($\sim 10 M_{\odot}$). Of course, the caveats above need to be properly accounted for. The non-sphericity or non-homogeneity of the accretion, non-zero metallicity or strong magnetic fields are all factors that can rise or lower the Eddington limit. Additional cooling processes such advection can lower the amount of output due to radiation (this is the case of the so-called *slim disk*, Abramowicz et al. [1988], see below); The luminosity can finally *appear* to be higher than the isotropic luminosity, due to beaming (e.g. King [2004]). All these issues are particularly relevant for the discussion on ultraluminous X-ray sources.

The *EINSTEIN* observatory first detected some sources exceeding $10^{39}\,\mathrm{erg\,s^{-1}}$ in the spiral arms of nearby galaxies [Long and van Speybroeck, L. P., 1983]. The fact of not being in the center of the galaxies is important, because we do expect very luminous sources in the Galactic centers: their central supermassive black holes. These supermassive black holes, even accreting at very low Eddington fractions, are able to radiate well above $10^{42}\,\mathrm{erg\,s^{-1}}$, the maximum luminosity observed in ULXs. But this off-nuclear, extragalactic population – with few exceptions [e.g. Fabbiano, 1989, Colbert et al., 1992] – remained far from the spotlight for almost twenty years. It was at the beginning of the new millennium that these sources, dubbed "ultra-luminous X-ray sources"

(ULX), gained momentum again [e.g. Okada et al., 1998, Makishima et al., 2000, La Parola et al., 2001, Mizuno et al., 2001, Körding et al., 2001].

In the last ∼15 years ULXs have attracted considerable attention. For the evolutionary reasons mentioned above, these sources might be harboring IMBHs, the elusive seeds to produce supermassive black holes, or – probably as interesting – be the clearest example of extreme accretion above the Eddington limit, again something important to understand in order to get better estimates of black hole growth timescales.

Off-nuclear sources are observed with luminosities up to $10^{42}\,\mathrm{erg\,s^{-1}}$. The highest limits of this population are very hard to reconcile with the emission from a small compact object, even with very fine-tuned beaming and extreme accretion. This is why *hyper*lumous X-ray sources (HLXs) are the best candidate IMBHs. The most famous, ESO 243-49 HLX-1 [Farrell et al., 2009] and it is located in the outskirts of the galaxy ESO 243-49, at a distance of 95 Mpc. Its apparent isotropic luminosity is indeed around $10^{42}\mathrm{erg\,s^{-1}}$.

$10^{39}\,\mathrm{erg\,s^{-1}}$ or less are easier to explain with mild super-Eddington accretion. Indeed, several sources in this luminosity range have been confidently found to harbor a StBH [Liu et al., 2013, Middleton et al., 2013, Motch et al., 2014] The investigation becomes particularly interesting above 10^{40} or more. It's in this range that either the masses implied are too high, or accretion is supposed to overcome the Eddington limit by a large amount. This review will mostly focus on the objects belonging to this range of luminosities.

The last four years have been particularly productive in the understanding of these sources, showing that ULXs are actually a very diverse population, including examples of both broad models above (super-Eddington BHs: Liu et al. [2013], Motch et al. [2014]; IMBH: Pasham et al. [2014]), plus a third possibility rarely mentioned before[1], that is the presence of an extremely bright neutron star Bachetti et al. [2014].

2. Models

Two main classes of models have naturally arisen from the observation of these very luminous sources.

The first class of models involves black holes of larger mass than stellar remnant BHs, accreting in the same sub-Eddington regime as the well-known Galactic BHs [Kaaret et al., 2001, Miller et al., 2003, etc.]. This means that ULXs would be rare examples of intermediate-mass black holes (IMBHs), with masses $\gtrsim 100\,M_\odot$. These objects are more massive than expected from a single star collapse [e.g. Belczynski et al., 2010], and possible mechanisms for their formation include the runaway collapse of a cluster of stars [Portegies Zwart and McMillan, 2002], and remnants of primordial stars [e.g. Madau and Rees, 2001, Bromm and Larson, 2004]. Evaluating the number of IMBHs has profound implications for the models of the evolution of supermassive black holes (SMBH). In fact, a possible path for the growth of SMBHs is through the merger of smaller, "seed" BHs, represented indeed by IMBHs [Kormendy and Ho, 2013]. This class of models is very likely to describe the most extreme of these sources, called hyperluminoux X-ray sources. The most famous of this kind is ESO 243-49 HLX-1 [Farrell et al., 2009], with a luminosity above $10^{42}\,\mathrm{erg\,s^{-1}}$,

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[1] E.g., Medvedev and Poutanen [2013] proposed young neutron stars as a model for ULXs. Their model, however, proposed rotation-powered emission and not accretion, as the source of their luminosity.

whose behavior is also consistent with part of the phenomenology of standard black holes. For example, it undergoes spectral transitions and outbursts, similar to those of Galactic black holes, with spectral states similar to this standard picture. Jets are also observed during spectral transitions. Only the time scale of these outbursts does not fit in this simple scenario (recurrence timescale: Lasota et al. 2011; irregularity of timescale: Godet et al. 2014).

The second class of models involves stellar black holes, with a super-Eddington apparent luminosity. Real super-Eddington accretion might be achieved up to $10\,L_{\rm Edd}$ through the so-called photon-bubble instability in standard "thin" disks [Begelman, 2002] or in inefficient regimes of accretion like the "slim" disk [e.g. Kawaguchi, 2003]. Mild beaming [e.g. King et al., 2001] might account for another factor and permit luminosities up to 10^{41} erg s^{-1}without requiring IMBHs. The hypothesis of extreme beaming, for example the fact of looking inside a jet [e.g. Körding et al., 2001], is mostly ruled out from the observation of fairly isotropic optical bubbles (see Section 8). This class of models, putting forward the hypothesis of extreme mass transfer, is also very interesting. In fact, it influences the timescales of the evolution of black holes from the initial seeds to the SMBHs we observe today [Kawaguchi et al., 2004, Rees and Volonteri, 2007, Volonteri, 2010].

Therefore, ULXs might be an important piece of the cosmological puzzle, permitting a test study of two phenomena relevant to black hole evolution: IMBHs and super-Eddington accretion.

The definition of ULXs is based only on one observable (the apparent isotropic luminosity), so it is also likely that these objects are not truly a class, but more like a"zoo" with different animals. The findings of the last three years seem to confirm this, as we are going to see.

Since we know some hundred ULXs, it is not surprising that many subclasses have appeared in the literature, mostly based on luminosity ranges. Since there is some level of inconsistency between the definitions given to these subgroups of ULXs in different papers, in this work we will consider *weak* ULXs (wULX) those radiating below 10^{40}erg s^{-1}, *strong* ULXs (sULX) those above that and below 10^{41}erg s^{-1}, *extreme* ULXs (eULX) those below 10^{42}erg s^{-1}, and hyperluminous X-ray sources (HLX) those above 10^{42}erg s^{-1}. As anticipated, this review will cover mostly the range from wULXs up to eULX, where the overlap between the IMBH and the super-Eddington interpretations is larger.

For completeness, other reviews on the same subject were written by Fabbiano [2006], Feng and Soria [2011], Webb et al. [2014]. This review is itself an extension to the already published review by Bachetti [2016] In this review, I will concentrate on the discoveries and progress in the understanding of these objects gained in recent times (four/five years).

3. Weak ULXs - proofs of super-Eddington accretion

ULXs exceeding by less than an order of magnitude the Eddington limit were the easiest to explain with slightly larger black holes or slightly above-Eddington accretion. Nonetheless, these sources are numerous and they have produced some of the most important developments in the last few years.

One such example is the source XMMU J004243.6+412519 in M31. Discovered by Henze et al. [2012] at $L_{\rm X} \gtrsim 10 \cdot 10^{38}$ erg s^{-1}, it showed an increase in luminosity up to ULX levels in two subsequent detections. Middleton et al. [2013] performed a joint X-ray/radio monitoring with

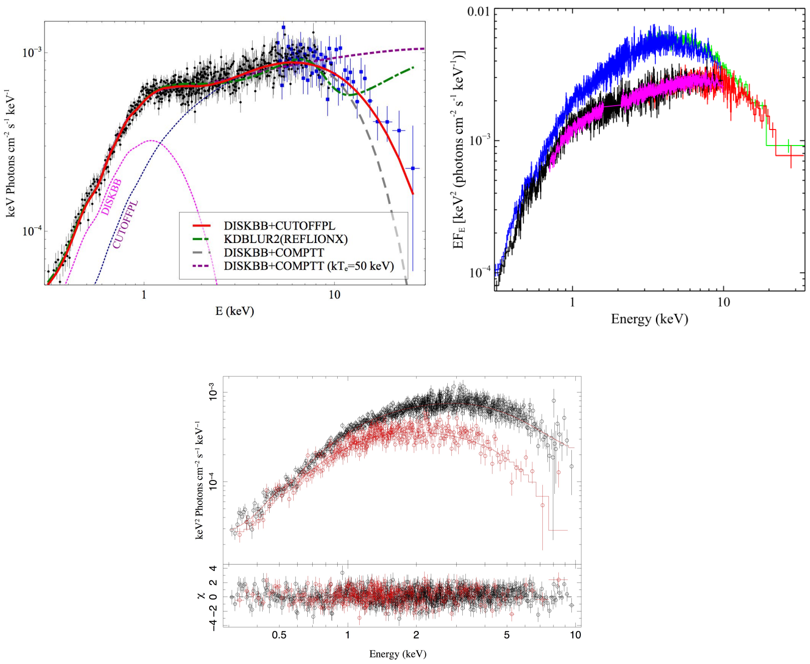

Figure 1: A sample of NuSTAR ULXs, showing the ubiquitous curved spectrum at high energy and the strong spectral variability observed in several sources of the sample (from Bachetti et al. 2013 and Walton et al. 2014). (Left) *XMM–Newton* and *NuSTAR* spectra of NGC 1313 X-1, showing the typical hard ultraluminous shape, the cutoff ruling out power law and reflection, and the excess with respect to single-T comptonization. (Middle and right) Holmberg IX X-1 and NGC 1313 X-2, showing the extreme variability observed in several sources on short time scales.

XMM–Newton and the VLA. They found highly variable radio emission on timescales of tens of minutes, implying a very compact source ($\lesssim 5$ AU). Also, whereas the spectrum could be fit with models implying either standard accretion disks or ULX broadened disks, the *behaviour* was not consistent with a standard $L \propto T^4$ relation expected from the standard disk. The comparison of these properties with known Galactic X-ray binaries such as GRS 1915+105, lead to the identification of this source as a StBH undergoing a transition to the super-Eddington regime.

Liu et al. [2013] found an optical modulation due to orbital motion, with period 8.2 d, of M101 X-1, a ULX radiating at $\approx 3 \cdot 10^{39}\,\mathrm{erg\,s^{-1}}$. Together with the observation that the companion is a Wolf-Rayet star, the estimated mass range is $5 < M < 20 M_\odot$. The authors find signatures that accretion is happening from a stellar wind rather than Roche-Lobe overflow. Shen et al. [2015] find for this source signatures of a thick outflow.

Finally, Motch et al. [2014] found that the source P13 in NGC 7793, showing all typical spectral signatures of ULXs (curved spectrum, soft excess, $L_X \approx 4 \cdot 10^{39}\,\mathrm{erg\,s^{-1}}$), really is a black hole with mass $< 15 M_\odot$. This was done through the measurement from optical observations of the orbital period of 64 d, together with the identification of the companion star as a B9Ia star. This is considered some of the best evidence that the curved spectra of ULXs (see Section 5) are a signature of supercritical accretion.

4. Curved X-ray spectra?

In ULXs, the spectral and timing properties seem to be consistent with three main “states” [Sutton et al., 2013]: a broadened disk state, with a single thermal component at some keV, and two so-called ultraluminous states, containing a low-energy soft excess (0.1–0.3 keV) and a power law-like component with a slight downturn above 5 keV. These two ultraluminous states are named soft and hard ultraluminous, and they differ only on the slope of the power law. If the excess and the power law tail are to be interpreted as standard black hole spectra, the well known inverse proportionality between disk temperature and mass [Shakura and Sunyaev, 1973] would suggest that these spectra are indeed from a IMBH [e.g. Miller et al., 2003, 2004]. The observation of standard transitions from a disk-dominated to power-law dominated state would point towards this interpretation. However, even if strong luminosity variations are known in ULXs, transitions between dramatically different spectral *shapes* are very rare [e.g. Feng and Kaaret, 2010, unsurprisingly a strong IMBH candidate]. A few more have been shown to transition between states classified as ultraluminous [Sutton et al., 2013], but as the sampling of the ULX population gets better, more are found [Walton et al., 2013, 2014]. Also, the broadened disk is more likely to be observed in wULXs, and the two sources (NGC 1313 X-1 and Holmberg IX X-1) showing a transition between hard and soft ultraluminous, the soft was at higher fluxes than the hard. Fast variability is usually observed only in the soft ultraluminous and broadened disk states [Sutton et al., 2013].

In this super-critical accretion scenario, interpretations of the soft and hard components of the spectrum are very different from standard BH spectra: in the Gladstone et al. [2009] interpretation, the disk was invisible, the hard curved component was Comptonization of the underlying disk from an optically thick corona, while the soft component, more prominent at high luminosities, was produced by the far away truncated disk (outside the corona) and by winds arising at the extreme accretion rates (see Section 8). According to a more recent intepretation [Sutton et al., 2013], instead, the hard component is related to the temperature of the inner disk, while the soft component is arising from the wind, that reprocesses the disk emission and partially occultates it. See Section 8 for details.

5. NuSTAR: curved X-ray spectra!

One of the main questions about ULX spectra, before 2011, was whether the downturn above 5 keV [Stobbart et al., 2006] was a real cutoff, produced through Comptonization from a cold, optically thick corona [Gladstone et al., 2009] or the effect, for example, of a broadened iron line (e.g. Caballero-Garcia and Fabian 2010) over a power law continuum. The first hypothesis pointed strongly towards a new accretion regime, probably related to super-Eddington accretion, while the second was a possible way to justify the downturn in the IMBH scenario.

However, the spectral coverage granted by *XMM–Newton*, *Chandra*, *Swift*, limited to 10 keV, was not sufficient to disentangle between these very different models [Walton et al., 2011]. Non-imaging Hard X-ray satellites like *INTEGRAL* or *Suzaku* (as was done later by Yoshida et al. 2013, Dewangan et al. 2013, Sazonov et al. 2013), forced to rely on very heavy assumptions and very uncertain background subtraction procedures. For extragalactic sources like ULXs one can rarely assume that the target dominates the emission over the field of view (as one would do for most

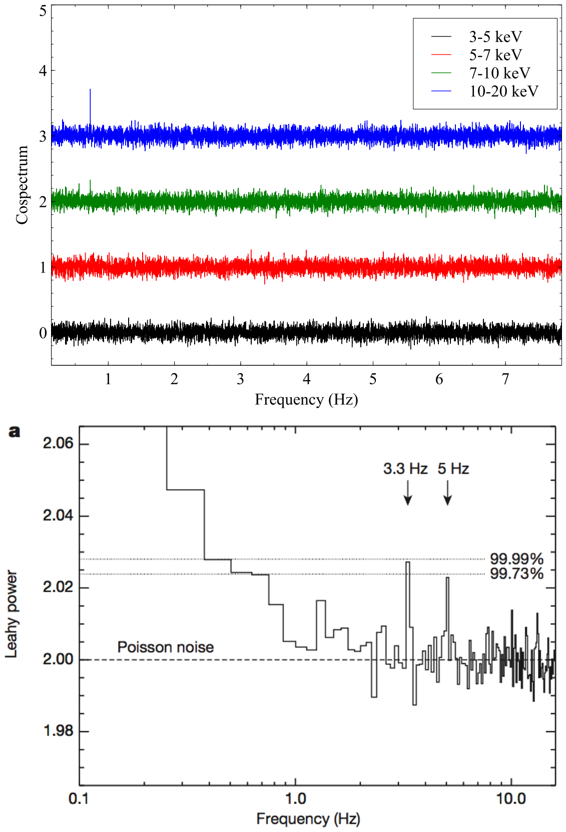

Figure 2: (Left) The cospectrum [á la Bachetti et al., 2015] of one of the long obsIDs of the *NuSTAR* campaign of M82, showing the peak at ~ 0.7 Hz corresponding to the pulsar, in different energy bands. (Right) *RXTE* power spectrum from Pasham et al. [2014] showing the pair of high-frequency QPOs from M82 X-1. The 5 Hz QPO is above detection level with a different binning.

Galactic sources outside some well-determined dense regions). From this point of view, the launch of *NuSTAR* was a breakthrough in ULX studies. Its imaging capabilities and spectral coverage up to 79 keV, with a comparable effective area to *XMM–Newton* in the 5–10 keV range, permitted to run a series of large programs of *NuSTAR* observations, aided by the soft X-ray coverage of *XMM–Newton*, *Swift* or *Suzaku*, obtaining the first broadband (from 0.3 to 40keV) X-ray spectra of these objects and measuring the spectral and timing variability when present. This program was able to clearly show that a real cutoff was present in all sULXs and eULXs of the program (e.g. Bachetti et al. 2013, Walton et al. 2013, Rana et al. 2015, Walton et al. 2014; this favored an interpretation of these ULXs as StBHs (probably in the high mass range for this class) accreting around or above the Eddington limit. Moreover, in most of these works the cutoff was found in excess of the prediction from Comptonization by a single-temperature corona, that was hypothesized in some papers [e.g. Gladstone et al., 2009].

6. M82 - a cradle of exceptions

In 2014, two remarkable discoveries came out of the Cigar Galaxy, M82, that harbors three known ULXs [Matsumoto et al., 2001, Kaaret et al., 2001, Feng and Kaaret, 2007, Kong et al., 2007, Jin et al., 2010]. The first was the observation of quasi-periodic oscillations from a known eULX, M82 X-1, also known as M82 X41.4+60[2]. The second was the discovery of pulsations from a sULX just $5''$ away from M82 X-1, M82 X-2 (or M82 X42.3+59).

M82 X-1 is a very well-known variable eULX, reaching above 10^{40} erg s^{-1}[Ptak and Griffiths, 1999, Kaaret et al., 2001]. It was observed to undergo spectral transitions reminiscent of standard BH spectral states (transition to "thermal-dominant": Feng and Kaaret 2010), and this pointed strongly towards the IMBH interpretation. It's one of the few ULXs known to show strong quasi-periodic oscillations, detected by *RXTE* and *XMM–Newton* in the range $50-100$ Hz [Mucciarelli et al., 2006]. In 2014, the IMBH hypothesis gained strong support when a timing analysis including all *RXTE* observations of M82 X-1 showed a new pair of quasi-periodic oscillations, at ~ 3 and ~ 5 Hz [Pasham et al., 2014, see Figure 2]. The frequencies of these oscillations were consistent with a 3:2 ratio observed in the high-frequency QPOs of two Galactic Black holes at hundreds of Hz [but whose identification is unclear, as is the scaling with the mass, see Belloni et al., 2012]. If this identification is correct, a simple scaling of the frequencies leads to a mass estimate of $\sim$400 $M_\odot$. This makes M82 X-1 one of the strongest IMBH candidate in the eULX range.

But the most unexpected result was probably the discovery of the first ULX powered by an accreting neutron star [Bachetti et al., 2014, see Figure 2]. This source was a well-known ULX, showing very strong luminosity variations on timescales of $\sim$weeks and up to $3\cdot 10^{40}$erg s^{-1}[Kong et al., 2007, Feng and Kaaret, 2007]. The presence of mHz QPOs had been used to model it as an IMBH above $10000 M_\odot$ [Feng et al., 2010]. Pulsations, unequivocally, identified it as a NS. The possible explanations for the extreme luminosity of this object, 100 times the Eddington limit for a neutron star and $\sim$10 times higher than the limiting luminosity for a NS [Basko and Sunyaev, 1976], include the changes in the Thomson scattering coming from a strong magnetic field (e.g. Ekşi et al. 2015, Dall'Osso et al. 2015, Tsygankov et al. 2015, Mushtukov et al. 2015), and beaming (e.g. Christodoulou et al. 2014). This source has also been proposed as an alternative path for the formation of millisecond pulsars [Kluźniak and Lasota, 2015].

7. Host environments

One way to understand what are ULXs is by looking at their counterparts in other bands and the association with specific environments.

Population studies of bright extragalactic X-ray binaries highlight a strong correlation between the number of high-mass X-ray binaries above 10^{39}erg s^{-1}and the star formation rate [Grimm et al., 2003, Mineo et al., 2012]. The same studies do not find a significant cutoff of the X-ray luminosity function at the Eddington limit for neutron stars and stellar-mass black holes, while they do find a cutoff at about 10^{40}erg s^{-1}. The lower-end of the ULX population seems to be composed of the bright end of the HMXB population.

ULXs are associated with regions where the formation of more massive stars is possible due to low metallicity (e.g. Prestwich et al. [2013], Zampieri and Roberts [2009]).

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[2] Sources in M82 are often named by their offset from $\alpha = 09^h51^m00^s$, $\delta = +69\,\mathrm{deg}\,54'00''$ (B1950.0)

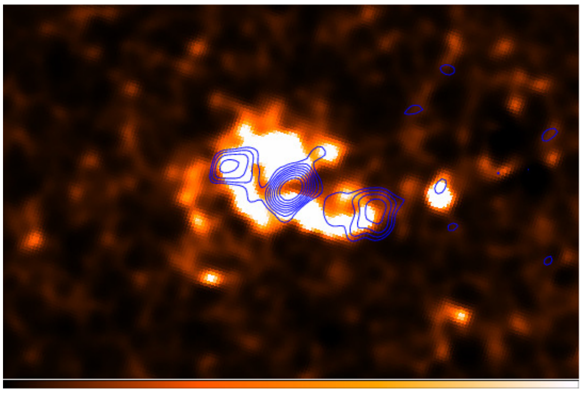

Figure 3: HST image using the FR462N narrow-band filter of the optical bubble around Holmberg II X-1, with contours showing the radio structure associated with a jet [Cseh et al., 2014].

8. Jets and Outflows

Collimated jets are usually observed in hard and intermediate states of sub-Eddington Galactic BHs, but not in the high/soft states [Fender et al., 2004]. In the microquasar GRS 1915+105, often compared to ULXs for its peak luminosity, steady jets are present during the hard so-called "plateau" state and ejection events during state changes [Mirabel and Rodríguez, 1994, Fender and Belloni, 2004].

To date, radio emission has only been detected in a few ULXs. In most ULXs the upper limit on radio emission goes down to $L_R \lesssim 10^{34}\,\mathrm{erg\,s^{-1}}$. They cannot be radio supernovae or IMBHs with steady radio jets because these objects have typical radio luminosities order of magnitudes larger (Mezcua [2014] and references therein).

In the few ULX with detected and resolved radio emission, it has been possible to distinguish the physical mechanism at work and to associate the radio counterpart with i) extended emission from jets Mezcua et al. [2015], Cseh et al. [2015], ii) radio nebulae powered by StBHs Cseh et al. [2015], Soria et al. [2014], and iii) supernova renmants Mezcua et al. [2013b]. [Middleton et al., 2013] report on a ultraluminous stellar-mass microquasar from a wULX.

Extreme ULXs and *hyper*luminous X-ray sources are the most natural targets to look for off-nuclear IMBHs. For example, ESO 243-49 HLX-1 is, up to now, the strongest candidate IMBH with a luminosity exceeding $10^{42}\mathrm{erg\,s^{-1}}$Farrell et al. [2009]. In this source, transient radio-jet emission was detected in association with X-ray state transitions, yielding to an estimate between $9\times10^3\,M_\odot$ and $9\times10^4\,M_\odot$ for the BH mass Webb et al. [2012]. A powerful radio jet with size 1.8 pc has been also discovered in the extreme ULX NGC2276-c3, providing evidence for the existence of a $\sim5\times10^4\,M_\odot$ BH in the spiral arm of NGC 2276 Mezcua et al. [2015]. Furthermore, hints for the possible presence of an IMBH in the ULX NGC5457-X1 comes from the detection of a radio counterpart of $\sim1\times10^{34}\,\mathrm{erg\,s^{-1}}$. However, the estimate is very uncertain due to the absence of simultaneous X-ray and radio flux density measurements Mezcua et al. [2013a].

Strong outflows are instead generally expected to arise from super-critical accretion (e.g., Dotan and Shaviv 2011; in simulations: RHD, Ohsuga and Mineshige 2011, Hashizume et al. 2015; GRMHD, McKinney et al. 2014), and the presence of these outflows, cold and/or optically thick, have been proposed alternatively as the origin for the soft excess in ULX spectra while the hard cutoff has been associated with the high accretion rate [e.g. King et al., 2001, Begelman, 2002, King and Pounds, 2003, Kubota et al., 2004, Gladstone et al., 2009, Kajava et al., 2012, Feng and Soria, 2011].

As we have seen, in the Sutton et al. [2013] framework it is expected that these outflows play an important role both in the spectral and timing behavior of ULXs (see Section 4).

However, direct observations of outflows have proven, up to last year, elusive. Before, most of the evidence of outflows came from shock-ionized and X-ray ionized nebulae, seen in optical and radio observations and ruling out anisotropic accretion for most ULXs [Pakull and Mirioni, 2002, Kaaret et al., 2003, Lehmann et al., 2005, Kaaret and Corbel, 2009, e.g.].

Signatures in the Fe K complex often observed in ultra-fast outflows from SMBHs [e.g. Tombesi et al., 2010] and BH and NS binaries [e.g. Ponti et al., 2012, and references therein] were not found in ULXs [Walton et al., 2012]. Excesses often seen in X-ray spectra [e.g. Strohmayer and Mushotzky, 2009, Miller et al., 2013, Bachetti et al., 2013, , Walton et al. in prep.] were interpreted as possible signatures of outflows.

Fabrika et al. [2015] report on optical observations of ULXs, where they show that the spectra of ULXs, very similar to each other, originate from very hot winds from the accretion disks. The optical spectra are indeed similar to that of the Galactic source SS 433 but with a higher wind temperature. This points towards the supercritical stellar black holes interpretation.

Finally, Pinto et al. [2016] reported on signatures of fast outflows from high-resolution X-ray spectra from the RGS camera onboard *XMM–Newton*, strenghtening this interpretation further.

9. Conclusions

Feng and Soria [2011]'s famous review on ULXs in 2011 more or less predicted correctly the landscape we now know of ULXs:

> *ULXs are a diverse population; MsBHs with moder- ate super-Eddington accretion seem to be the easiest solution to account for most sources up to luminosi- ties ∼a few* $10^{40}\,\mathrm{erg\,s^{-1}}$*; strong beaming* $(1/b > 10)$ *can be ruled out for the majority of ULXs; IMBHs are preferred in a few exceptional cases*

Nonetheless, reading in detail that review there are observing properties that changed, several open questions that have been addressed, and interpretations that evolved:

- ULX spectra *do* vary significantly with flux increases. More and more ULXs were found to change their spectral shape considerably and some of them even to undergo dramatic luminosity increases on timescales of ∼weeks [Bachetti et al., 2013, Walton et al., 2014, 2015].

- Neutron stars were only mentioned twice, in the same phrase, and not as possible ULX-powering compact objects. The discovery of M82 X-2 was completely unpredicted.

- The toy model about ULX emission gave the soft emission coming from the outer disk and the hard emission from the inner disk and the wind. Today's leading interpretation interprets the soft component as coming from the wind.

Also, some of the bullet points of possible evolution of ULX studies have been addressed, in particular (letters are referred to the original article points, and italic is used for the original text):

(a) *(...) search for possible high frequency fea- tures (breaks and QPOs) that are found in Galactic BHs at frequencies* $\sim 10^2$ *Hz*: M82 X-1 was indeed interpreted as an IMBH thanks to the discovery of QPOs in a 3:2 ratio

(b) *Determining the relative contribution of thermal emission and Comptonization component is a key test (...) X-ray telescopes with good sensitivity up to a few tens of keV are needed*: *NuSTAR* proved to be capable of doing this, clearly finding an excess of the cutoff from the predictions of single-T comptonization.

(i) *searching for compact radio jets (...)*: compact radio jets were indeed found in a eULX [Cseh et al., 2014, 2015] and in a HLX [Mezcua et al., 2015].

For the remaining questions in the Feng and Soria [2011] review, the landscape of the next few years looks encouraging. The surveys by *e-Rosita* [Merloni et al., 2012] approaching, SKA [Wolter et al., 2014] in the works, and the next big X-ray observatory, *Athena* [Nandra et al., 2013] to come in the 2028, will surely fill most of the instrumental gaps that slowed down the progress until now[3].

As it often happens, the discoveries have opened the path to new questions and new important fields of investigation. Super-Eddington accretion is now accepted as a relatively frequent phenomenon. There is much to be learned about it yet: how frequent it is, how it changes the accretion geometry, if it changes considerably the evolution time scales of black holes and galaxies.

Timing techniques will be likely to gain importance. Besides being key for the two major discoveries in M82, they represent an independent and complementary approach to spectral studies. Spectral timing studies of ULXs, for example based on time lags [De Marco et al., 2013, e.g.] and covariance spectra [Middleton et al., 2015, e.g.] are very promising. A thorough search of pulsations in ULXs is already ongoing from several groups [e.g. Doroshenko et al., 2015]. This is not an easy task; ULXs are distant sources, their flux is relatively low, their signal often contaminated, and detection limits are heavily dependent on flux and rms [Lewin et al., 1988]. Nonetheless, it's probable that other neutron stars will be found in ULXs, thanks to the upcoming focusing telescopes and the awareness that this is an option.

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[3] *Astro-H*, launched on 2016 February 17th, with its high spectral resolution and good imaging capabilities [Miller et al., 2014], was regarded as another possible step forward in this direction. Sadly, due to a series of technical problems the attitude control failed and all communication with the satellite was lost on March 27th.

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DISCUSSION

BIDZKINA KAPANADZE: What are the timescales of short-term variability in these objects? Is it periodic or erratic?

MATTEO BACHETTI: Some of these sources show a wide range of variability features, from red noise to quasi-periodic oscillations. Characteristic frequencies are usually lower than Galactic black hole binaries. M82 X-1, for example, showed historically a QPO from 50 to 100 mHz, and lately it has been shown that two QPOs at 3 and 5Hz are detectable in archival RXTE data of this source. This source also shows a standard red noise component at lower frequencies.

JIM BEALL: Can the variability be modeled by transient accretion from the disk?

MATTEO BACHETTI: Short term variability can be described by “patchy” accretion. However, the leading model is that the variability is extrinsic, i.e. it is inprinted on the harder X-ray emission from the inner disk by inhomogeneities in an optically thick outflow.

WOLFGANG KUNDT: Are you aware that during the past decade BHs have lost their property of being expected as the final state of gravitational collapse, through work by Pankaj Farhi, Hernando Quevedo, Bahram Mashhoon? They have turned out to be of measure zero in the set of all collapse situations: Realistic collapse does not remove all higher multipoles so that we deal with naked singularities.

MATTEO BACHETTI: I am aware that there are alternative theories about the nature, formation and evolution of black holes. However, as far as I know, much of the theoretical work predicting the properties of black holes is testable and actively been tested through observations with good results. Thanks for pointing this out, I will read with interest the works you mention.

SHUANG-NAN ZHANG: What is the physical or real accretion rate for this Super-Eddington X-ray pulsar?

MATTEO BACHETTI: The estimates of accretion rate in our paper and in the other theoretical papers that came out after the discovery are wildly different, ranging from sub-Eddington to far above that. So, a better estimate can only come from follow-up observations. We will try, for example, to constrain the total mass transfer through the timing of the orbital evolution and by looking for outflowes. More to come in the future!