ULTRA-LUMINOUS X-RAY SOURCES: AN OVERVIEW OF DISCUSSION ON THEIR ORIGINS AND NATURE

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ABSTRACT

The subject of the nature and origins of ultra-luminous X-ray sources (ULXs) remains at the frontier of modern research. Existing data allows to fit a wide range of interpretations, including those based on stellar-mass black holes (sMBHs) and intermediate-mass black holes (IMBHs), accretion-powered pulsars, microquasars, and so on. The research of the ULXs is of cosmological and astrophysical importance, as they may become evidence of the existence of IMBHs that may be intimately connected to the formation of first active galactic nuclei engines at $z \gtrsim 6.4$. Although more recent research favors ULX interpretation based on stellar origins, the presence of IMBHs cannot be ruled out completely. In particular, hyper-luminous X-ray sources (HLXs), which comprise the brightest subset of the ULXs with X-ray luminosities $L_X \gtrsim 10^{41}$ erg s^{-1}, are considered to be the strongest cases for harboring black holes of that type. This report will overview some of the observations and general properties of ULXs and will serve as an introduction to the discussion on the underlying physical models. In addition to ULX models based on black holes of both types, alternative interpretations will be reviewed. Within the sMBH framework, in particular, the importance of interpreting short timescale variations of ULXs is emphasized as a good diagnostic for revealing the underlying super-Eddington emission mechanisms.

Subject headings: stars: black holes — X-rays: binaries — X-rays: galaxies — X-rays: general

1. INTRODUCTION

Although the very first attempts in celestial X-ray detection date back to advances in electronics during the 1920s and 1930s, high-energy astrophysics, due to opacity of Earth's atmosphere at very short wavelengths, began to bloom only half a decade later with the launches of rocket-borne satellites. The evidence of X-rays coming from the outside of the solar system came with the discovery of the most powerful source in our sky, Scorpius X-1 (Giacconi et al. 1962). At that time, it had never been expected that individual stars could release such vast amounts of energy. With the advancement of the satellite age, the agreement was soon reached on that X-ray sources are associated with compact stellar systems with deep gravitational potential wells—white dwarfs, neutron stars or black holes—capable of producing high-energy radiation. It took precisely 40 years after its discovery to reveal the nature of Giacconi's object to be of a low-mass X-ray binary (XRB), in the work by Steeghs & Casares (2002). While the majority of X-ray sources are similar to Scorpius X-1 (Makishima et al. 2000), there is a class of ultraluminous X-ray sources (ULXs) for the explanation of the whole variety of which we are still yet to settle on a good unified model. First detected with *Einstein*, a small number of non-nuclear sources in nearby galaxies exhibited X-ray luminosities $L_X \gtrsim 10^{39}$ erg s^{-1} (Long & van Speybroeck 1983), however insufficient resolution and the lack of long-term monitoring prevented to differentiate them from transient events, such as young supernovae (SNe). In 1990s, repeated higher resolution observations using satellites, such as *ROSAT* and *ASCA*, allowed to reveal persistent characteristics of ULXs, which are now defined as extra-nuclear discrete (point) sources of X-rays with 0.3–10 keV band peak luminosities at or in excess of the Eddington luminosity[2] of a spherically accreting and emitting neutron star (NS), expressed as per Frank et al. (2002)

$$L_{Edd} = \frac{4\pi c G M m_p}{\sigma_T} \approx 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ erg s}^{-1}, \quad (1)$$

where σ_T is the Thomson scattering cross section, m_p is the proton mass, and M is the mass of accreting object in solar masses[3]. Thus, for a $\approx 1.4\ M_\odot$ NS, $L_{Edd} \approx 1.82 \times 10^{38}$ erg s^{-1}. Different names were used to identify this class of objects: extraluminous X-ray binaries, superluminous X-ray sources, and intermediate-luminosity X-ray objects, until community has settled on "ULXs," adopting terminology employed by Japanese teams (Feng & Soria 2011). Based on *ROSAT* HRI observations, Ptak & Colbert (2004) have shown that sources emitting at $L_X \gtrsim 10^{39}$ erg s^{-1}, which usually characterize the ULX category, are quite common and are present in ∼12% of all galaxies. A more recent research by Swartz et al. (2011) provides an estimate of ∼6.5% for the number of ULX-hosting galaxies in the local universe, accounting, however, for 71% of the total mass in their sample. Walton et al. (2011) have compiled one of the largest ULX catalogs published to date, with 470 ULX candidates identified in 238 nearby galaxies, based on the *XMM-Newton* data. In the same year, Liu (2011) has released a catalog of comparable extent[4],

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[2] Eddington luminosity, also referred to as the Eddington limit, is the maximum radiative luminosity a stellar body can achieve while remaining in hydrostatic equilibrium—a balance between outward radiation pressure and inward gravitational force.

[3] This is correct for ionized hydrogen, however accretion of helium or other heavier elements will raise this limit (Roberts 2007). It is also worth noting that some authors, e.g. Kaaret (2008), prefer to define ULX cut-off $L_X > 3 \times 10^{39}$ erg s^{-1}. Thus, the definition is somewhat ambiguous.

[4] Liu's catalog includes 300 ULXs within D_{25} galactic isophotes,

based on *Chandra* CCD imaging spectrometer (ACIS) observations.

As luminosities of these sources exceed Eddington limits for accreting compact objects, such as NSs or stellar mass black holes (sMBHs) found in traditional XRB systems, it was of a natural consequence to diverge in our explanations that either some sort of super-Eddington emission mechanism is involved, that the accreting object is more massive (Komossa & Schulz 1998), the emission is beamed and the real luminosity is lower (Okada et al. 1998), or that these objects are of a completely different, non-accreting nature. Throughout the variety of the observed properties of ULX candidates, each of these statements could be backed by circumstantial evidence. The development of a ULX paradigm in the first decade of our century, however, was hindered by the fact that none of the individual models could explain all the data reliably. Furthermore, a peculiar subset began to emerge, with luminosities exceeding $\sim 10^{41}$ erg s^{-1}. Dubbed hyperluminous X-ray sources (HLXs), it is probably represented at best by the brightest source currently known—the HLX-1 in the edge-on S0a spiral galaxy ESO 243-49, with $L_{X,peak} \sim 10^{42}$ erg s^{-1}. Observations using novel wide bandpass CCD spectroscopy on *ASCA* supported the hypothesis that we are dealing with black holes, as the model of multicolor disk (MCD) blackbody emission from standard accretion disks fitted the spectra of seven ULXs in nearby spiral galaxies, albeit requiring that their black holes must be rapidly spinning (Kerr metric) in order to be able to explain excessive innermost disk temperatures[5] (Makishima et al. 2000). If sources as luminous as HLX-1 emit isotropically (no beaming) at or below the Eddington limit, for which there is also evidence, with X-ray spectra consistent with accreting black holes, then the energy outputs observed imply they harbor a new class of objects called intermediary mass black holes (IMBHs). These have masses of $\sim 10^2 - 10^4$ $M_\odot$ (Colbert & Mushotzky 1999) and are distinguished from sMBHs (~ 10 $M_\odot$) and supermassive black holes (SMBHs; $> 10^5$ $M_\odot$) that power active galactic nuclei (AGNs). Similarly to the case of HLX-1, where an IMBH in excess of 500 $M_\odot$, and by more recent estimates $\sim 3 \times 10^3$–10^5 $M_\odot$, would be required (Farrell et al. 2011; Servillat et al. 2011; Davis et al. 2011; Godet et al. 2012), it would have been tempting to explain the remainder of all less luminous ULXs (and HLXs) as powered by less massive IMBHs, if not a multitude of problems appearing with this, some fundamental. Among the difficulties, for example, is the requirement to explain their abundance—that is, galaxies would need to have exorbitant IMBH formation rates or host reservoirs of a yet unknown non-stellar mass to fuel accretion, as shown by King (2004b) in the case of the Cartwheel galaxy (ESO 350-40). This will be discussed in more detail in § 4.

Many of the characteristics some ULX sources exhibit, such as the association of large populations of them with regions of active star formation, allow the suggestion of hypotheses for their nature to be of a stellar origin (Gao et al. 2003). Using unprecedented quality spectra obtained with *XMM-Newton* observatory, Stobbart et al. (2006) were able to demonstrate that the most successful fit to the empirical description of spectra of their samples is provided by a physical model with two components: an accretion disk seeding photons to a Comptonized corona, referring to the earlier interpretation by Gierliński et al. (1999) of the spectrum of one of the best studied sMBHs in the Milky Way—Cygnus X-1. This shows that spectra of extragalactic ULX sources resemble that of the known Milky Way XRBs more than what is expected from lower temperature elements of IMBHs. While applicable to typically low luminosity ULXs, Gladstone et al. (2009) have proposed refined models to match the complex curvature exhibited by the spectra of the more luminous sources. In particular, they have identified three distinct types of ULXs that could be placed into a sequence with increasing accretion rate. Based on their results, Sutton et al. (2013), similar to the AGN paradigm (Antonucci 1993; Urry & Padovani 1995), have introduced the line-of-sight variable and made a step towards a unified ULX model, as it now became possible to explain most ULXs as sMBHs accreting at and above the Eddington limit, observed at different inclination angles. A similar direction has been taken earlier by Roberts (2007), although he has concluded that super-Eddington rates are not necessary because almost all ULXs "could trivially be explained" by more massive sMBHs of a few tens of $M_\odot$ accreting at or around the Eddington limit. As a foundation for this, he has employed model by Belczynski et al. (2006) that showed that black holes as massive as ~ 100 $M_\odot$ can be formed from binary mergers in young star clusters. Another option is the collapse of massive, low metallicity stars (Fryer & Kalogera 2001).

For sMBH models, however, the problem of the explanation of the most luminous of ULXs will stand if we will try to apply them to the whole set of sources, including those that are hyperluminous, especially with the record breaking output of HLX-1. Although the most recent catalogue of HLXs by Gong et al. (2015) includes 86 sources with $L_X \gtrsim 3 \times 10^{40}$ erg s^{-1}, the fact that many can be explained as sMBHs leaves a very small and rare group of candidates that would require IMBHs—perhaps only a handful of objects there. Among them the strongest cases are HLX-1, M82 X-1, Cartwheel N10, 2XMM J011942.7+032421 in NGC 470 and 2XMM J134404.1-271410 in IC 4320. The last in the list has recently been excluded from the category of ULXs by Sutton et al. (2015), identified as a background quasar (QSO). The same authors suggested that a gap between the properties of HLX-1 and other HLXs is apparent, and that the case for IMBHs in less luminous sources is not always strong. Certain evidence, such as the association of sources with star-forming regions (SFRs) and their certain spectral properties, points to that the whole HLX subset, if we exclude its luminosity leader, may represent the absolute luminosity peak of the ordinary ULX population, i.e. highly super-Eddington (hyper-Eddington) accretion onto the most massive of the sMBHs, leaving HLX-1 to be an outstanding IMBH candidate.

Lasota et al. (2015) and King & Lasota (2014) have recently shown that HLX-1 could be a strongly beamed,

and additional 179 ULXs between D_{25} and $2D_{25}$ isophotes, although Walton et al. (2011) cautions a large fraction (∼60%) of the latter sample are likely to be contaminants.

[5] Rotating Kerr black holes drag space around them allowing matter to orbit closer. This makes the inner edge of their accretion disks to be closer to them and, thus, to be hotter, if compared to non-rotating Schwarzschild cases.

hyper-Eddington stellar mass binary system similar to SS 433 (see § 5.1), seen along its X-ray jets. With the majority of the ULX population assigned to stellar mass systems and HLXs dissected, is there still a case for IMBHs? This report will overview some of the observations and general properties of the ULXs in § 2. This will be followed by an outline of modern discussion on the nature and origins of ULXs within the "traditional" frameworks of sMBHs (§ 3) and IMBHs (§ 4). Alternative, novel ULX models, among them those based on the SS 433 microquasar and accretion-powered pulsars, will be described in § 5. Arguments for and against these interpretations will be presented in § 6 and § 7, mostly in broad strokes, as well as the summary and possible ramifications for the evolution of galaxies.

2. OBSERVATIONS

2.1. *Distances, specific frequency and luminosity function*

Because of the limited spatial resolving power arising from the technical difficulty of building X-ray optics, instrumental sensitivity limits and that, by definition, ULXs are non-nuclear sources—not located in the nuclei of their hosting galaxies—present studies of them are exclusively concentrated in the local part of the universe, that is $z \lesssim 0.3$ (Hornschemeier 2003; Trinchieri & Wolter 2011). The most extensive of the ULX catalogs published to date (Walton et al. 2011), based on the cross-correlation of *XMM-Newton* data with the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991), reaches the most distant galaxy at $d \approx 188$ Mpc; although with the modal detection flux for the X-ray sources considered, detection of all ULXs within the field of view is expected out to only $d \sim 20$ Mpc. High signal to noise ratios are available only for bright ULXs in nearby ($d \lesssim 10$ Mpc) galaxies (Feng & Soria 2011). In a survey of galaxies at $d < 14.5$ Mpc spanning all Hubble types, Swartz et al. (2011) find one ULX per 57 Mpc^3 volume of space. This corresponds to one per 3.2×10^{10} $M_\odot$, or one per ~ 0.5 $M_\odot$ yr^{-1} star formation rate. They conclude that the ULX number density per unit mass and the star formation rate of their host galaxies are consistent with the extrapolation of the luminosity function of ordinary XRBs—high mass X-ray binaries (HMXBs), in particular—providing support to hypotheses of stellar origins of ULXs.

If we assume that majority of the ULXs are high-luminosity tails of XRBs, peculiarities of their luminosity functions[6] at $L_X \gtrsim 10^{40}$ erg s^{-1} provide support to that a subset of the brightest of them may be of a different nature (Feng & Soria 2011). It is reasonable to expect from populations of XRBs, at least as an approximation, that their luminosity functions (LFs) will have a break or a cut-off at the Eddington luminosity of their most massive members. It has been found that LFs of XRBs follow a power law, with HMXB-like sources dominating high-L end of their distributions in both young and old populations. This, however, does not always hold for ULXs, and Swartz et al. (2011) have found that while LF for their set is consistent with XRB-like power law curve for the majority of the population, the two of the brightest of HLXs are grossly inconsistent with it—see figures 1 and 2. There, an ULX LF is shown with two curves: a power law with an exponential cut-off, $CL_X^{-\alpha_1} \exp(-L_X/L_c)$, and a pure power-law model, $CL_X^{-\alpha_1}$. The fact that the latter is a poor fit to the data at the high luminosity end implies that those most brightest of HLXs may not share the same origin with the rest of the ULX population (King & Dehnen 2005). Walton et al. (2011) do not find similar cut-off in their

[6] Also known as $\log(N > S) - \log S$ curve, the number of sources as a function of flux allows to describe and investigate the properties of source populations.

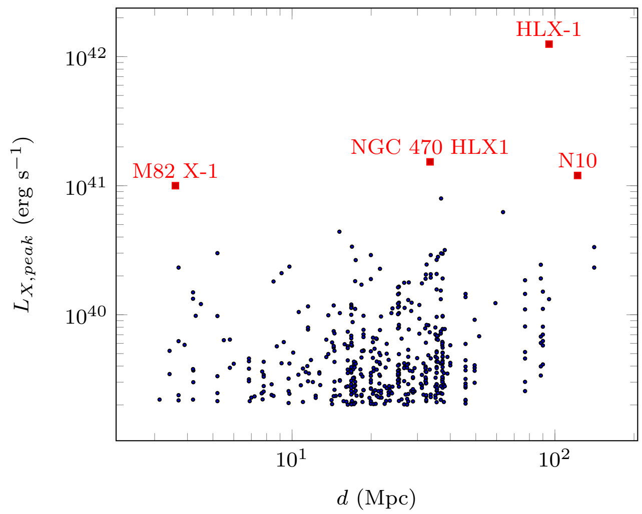

FIG. 1.— Distance-Luminosity plot, based on a synthetic set, composed of *Chandra* data for 479 ULXs from the survey by Liu (2011)—in black, and sources that are in the category of confirmed or best candidates to HLXs: ESO 243-49 HLX-1 (Servillat et al. 2011), M82 X-1 (Tsuru et al. 2004), Cartwheel N10 (Wolter et al. 2010), 2XMM J011942.7+032421 (also known as NGC 470 HLX1) (Gutiérrez & Moon 2014)—in red. Selection of HLXs as per Sutton et al. (2015). Clustering of ULXs is apparent due to that multiple sources were detected within the same galaxy. This is indicative of the survey limits, especially for increasing d.

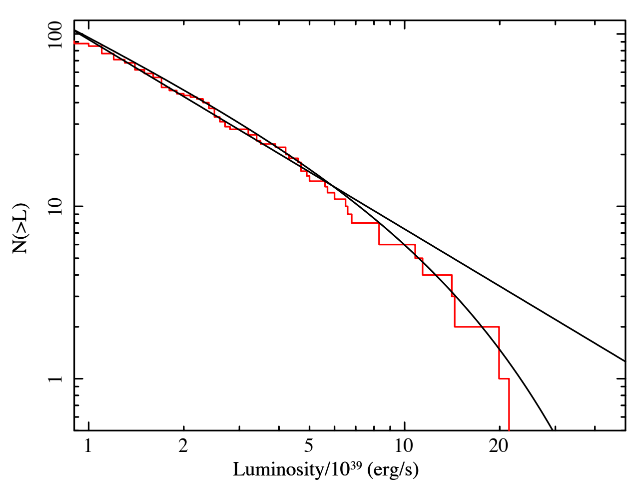

FIG. 2.— Luminosity function of 107 ULX candidates in 127 nearby galaxies, with two models applied: a power law with an exponential cutoff, and a pure power-law model (worse fit). Figure courtesy of Swartz et al. (2011).

data, however do not rule out its intrinsic presence due to possible biases.

2.2. *Statistical properties of galaxies, host environment, connection with star-forming regions*

Ptak & Colbert (2004) have studied ULX hosting galaxies with the purpose to establish their fraction as a function of ULX luminosity. They have not found any significant statistical difference in the distributions of galaxy types of those hosting ULXs and all surveyed. The most luminous of ULXs, however, are found predominantly in late type, star-forming galaxies (Liu & Mirabel 2005). In particular, we find that more than two thirds of ULXs found in ellipticals are $L_X \lesssim 2 \times 10^{39}$ erg s^{-1}, and most of those that are more luminous could simply be dismissed as background or foreground sources (Irwin et al. 2003). On the other hand, in spirals, one third of ULXs have $L_X \gtrsim 4$–5×10^{39} erg s^{-1}, and about 10% have $L_X \gtrsim 10^{40}$ erg s^{-1}. This correlates with the traditional classification of galactic sources where HMXBs are mostly found in spiral and Irr galaxies, and LMXBs—in old spheroidals and globular clusters. That is, this particular property of the major proportion of the ULX population matches the traditional framework of galactic XRBs as explained by representing high-L tails of LMXB and HMXB distributions (Feng & Soria 2011). No trend between ULX frequency and host galaxy mass has been found (Plotkin et al. 2014). Liu & Bregman (2005) have identified a very strong connection between the ULX phenomenon and star formation, with majority of the ULXs in their survey found in dusty star-forming regions. The fact that we may find ULXs outside SFRs in spiral galaxies can be explained with a 10–20 Myr turn-on delay of the brightest of sources after star formation has ended (Swartz et al. 2009). In terms of the distribution within host galaxy environment, another evidence supporting hypotheses of stellar origin of ULXs comes from their surface distribution which is centrally peaked, implying relation with stellar population. Feng & Soria (2011) note that if ULXs were primarily IMBHs, they would appear less centrally located as primordial halo relics, spawned by Population III remnants or accreted satellite galaxies. Finally, Swartz et al. (2009) find the lack of the association of ULXs with young, massive star clusters. This poses a problem to IMBH hypotheses that rely on that these black holes could have appeared due to the runaway core collapse and mergers of O-type stars inside these clusters. The evaporation timescales such massive stellar clusters should have do not fit our observations.

2.3. *X-ray spectral properties*

2.3.1. *Transient behavior and spectral types*

There are two distinct spectral types of ULXs that can be identified: those exhibiting convex spectral curves, and those which curves can be, in general, described by a simple power law. Gladstone et al. (2009) have showed that, in fact, if the data quality is sufficiently high, single-component models, such as the power law, do not provide a good fit, thus, the difference in types must in this context be understood in terms of the general shape of the spectral curve. Typical complex curves, illustrated in Figure 3, have a mild curvature, a break or

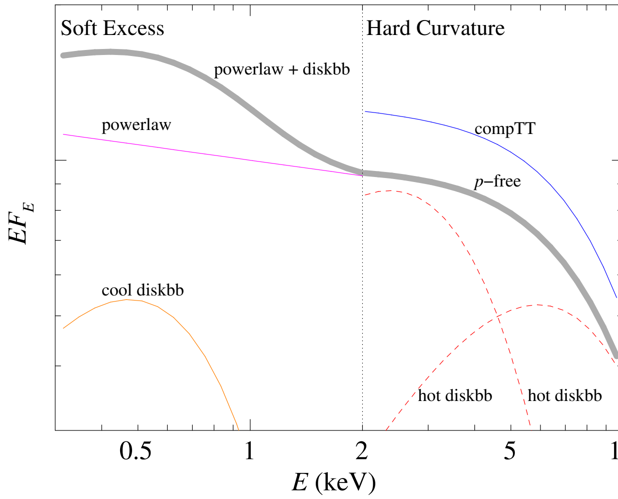

FIG. 3.— Typical complex X-ray spectrum of a ULX (grey), figure courtesy of Feng & Soria (2011). A power law curve alone is a poor fit to the data. Here, a DISKBB model is used in order to illustrate that complex spectrum curvature can be modeled with accretion disk consisting of multiple blackbody components. This is also known as multi-color disk (MCD) blackbody model. It provides a good fit to the soft excess, with a combination of the power law and a cool, thermal component. It does not provide a good fit to the hard curvature, however, and above 2 keV, a slim disk model (p-free) or a Comptonization model, COMPTT, would be more adequate.

steepening above $\sim$2 keV, or a soft excess below this level (Makishima 2007). As some ULXs transition between power law and convex (complex) types, they are understood as describing the objects of the same class having different states (Kubota et al. 2001). It would be tempting to classify these phenomena as black hole binaries (BHBs) occupying canonical high/soft and low/hard states[7]. The photon index[8] has a broad distribution, peaking at $\Gamma \approx 1.8$–2.0, although some sources exhibit both much harder (down to $\Gamma \approx 1$), and much softer (up to $\Gamma \approx 3$) spectra. Feng & Kaaret (2009) have analyzed spectral behavior of bright ULXs and identified two distinct behavioral types—one with constant hard Γ and strongly variable L_X, and another, with L_X and Γ correlated. The former is similar to BHB transients, however this does not support the sMBH hypotheses, as BHBs, in their canonical hard state, are known to radiate at only $\approx 0.05 L_{Edd}$; if we apply the same canonical state to ULXs, this would require IMBHs of up to 1500 $M_\odot$ (Winter et al. 2006). Additionally, most of the ULXs have persistent luminosities over multi-epoch observations, while galactic BHBs (sMBHs) are usually transients (Burke et al. 2013). A notable transient case is HLX-1, as its light curve shows variability with a recurrence time of a few hundred days, fast rise exponential

[7] Most BHBs are transient sources, having separate physical states: hard, dominated by thermal Comptonization, and usually associated with low luminosities, and a luminous ("high") soft state, dominated by an optically thick accretion disk with contribution from non-thermal component. For example, Cygnus X-1 transitioned in less than a month from high/soft to low/hard state, whereby its $L_{2-6\ \mathrm{keV}}$ decreased by a factor of 4, and $L_{10-20\ \mathrm{keV}}$ has increased by a factor of 2. Generally, five BHB states are acknowledged: quiescent, low/hard, intermediate, high/soft, and very high. For more information, consider Belloni (2010).

[8] Photon index Γ is a measure of the dependance of photon flux density on frequency, that is $\mathrm{d}N/\mathrm{d}E \propto \nu^{-\Gamma-1}$.

decay (FRED) shape, and a low/hard to high/soft transition reminiscent of BHBs (Lasota et al. 2011).

Figure 3 illustrates that complex spectral curves of ULXs can be modeled using a combination of power law and traditional models of spectral formation in X-ray sources, such as DISKBB (Mitsuda et al. 1984), COMPTT (Titarchuk 1994), and a slim disk (p-free) model (Mineshige et al. 1994), to name a few. This implies a range of competing physical models capable of describing ULX sources exists.

2.3.2. *Soft excess, multi-color accretion disk, outflows, ultraluminous state*

The soft X-ray excess can be, for example, interpreted as a cool accretion disk emission, or as a massive outflow. One of the traditional models used to describe accretion disks in BHBs is called DISKBB. It consists of two spectral components: a hard component—emission from the surface of the accretor, and a multi-color[9] soft component—emission from an optically-thick accretion disk. A statistically acceptable fit to the soft excess (< 2 keV) in typical ULX spectra can be obtained with a combination of a power law and a cool accretion disk component of this model, however, soft excess temperatures and ULX luminosities observed would require, according to DISKBB, black holes of 10^3–10^4 $M_{\odot}$.

Alternative interpretations of the soft excess observed exist. King (2004a) has suggested these are Eddington mass outflows from compact objects, which, he argued, is a very widespread phenomenon. A more recent outflow interpretation in M 101 X-1 is consistent with the recent kinematic measurements identifying this ULX as an sMBH (Shen et al. 2015). As many ULXs are observed to lie in the centers of unusually large, shock-excited nebulae, there is evidential support to explain these objects as bubbles in the ISM, blown up by such outflows. Others authors suggest that soft excesses are observed in less luminous X-ray sources that are not always candidates to hosting IMBHs (Berghea et al. 2008), or that they can be modeled well by sMBHs accreting at super-Eddington rates, in so called ultraluminous state (Stobbart et al. 2006; Gladstone et al. 2009).

2.3.3. *Hard curvature, hot and slim disks, coronal emission*

At high energies, complex ULX spectra curvatures can be described by a hot standard (DISKBB) disk, a slim disk, or by models that employ Compton up-scattering of soft disk photons by electrons in the corona (Steiner et al. 2009). Kubota et al. (2001), as a good fit to the spectra of one of the sources in IC 342, have proposed a model based on higher accretion disk temperature (1.8 keV). Their model covered the whole X-ray energy range, however required certain "salvations," such as rapid black hole rotation or the slim disk concept, in order to be self-consistent. Such hot disk models, in general, are problematic, as they are unable to fit most of the observations and have no simple physical interpretation (Winter et al. 2006). A much better candidate is a slim disk, as described by Abramowicz et al. (1988), that can radiate at $\gtrsim L_{Edd}$. In it, advective energy transport changes the typical MCD temperature dependance from $T \propto r^{-3/4}$, in DISKBB, to $T \propto r^{-p}$, where p is a free parameter—hence, the name p-free (Mineshige et al. 1994). Typically, $p = 1/2$ is used for a slim disk (Watarai et al. 2000), but Vierdayanti et al. (2006) have found their best fit with $p \approx 0.5$, working with four ULXs which were strong IMBH candidates, concluding they are, most probably, sMBHs. Being so flexible with fitting different complex spectra, the model has its limits. Gladstone et al. (2009), proponents of the ultraluminous mode, have found the disk inner temperature to be "unphysically" high (> 3 keV) for some of the sources. It is also incompatible with two-dimensional radiation-hydrodynamic simulations made by Ohsuga et al. (2005).

Several physical models describing radiation from accreting hot plasma that causes Comptonization of coronae have been developed, e.g. COMPTT by Titarchuk (1994), although widely used with ULX research is also a more physically self-consistent EQPAIR by Coppi (1999). In these models, corona emits at high energies due to being seeded by soft photons from the accretion disk. Thus, we are dealing with a two-component spectral curve, with the hard (2–10 keV) emission dependent on the soft disk temperature. In both EQPAIR and COMPTT models, best fits to the hard spectra curvatures observed are obtained with a cool, optically thick coronae. This is different from optically thin coronae typically found in BHBs. The fundamental problem with this approach, as Kubota & Done (2004) have demonstrated, is that an optically thick corona will obscure the accretion disk, or at least it will distort its emission, rendering previous disk spectra interpretations void. A good ULX paradigm would have to be based on a consistent spectral model.

2.3.4. *Supersoft sources*

Some ULXs, called supersoft sources (SSSs), unlike the majority of the population, have most of their emission output at below 2 keV. In our galaxy, SSSs are traditionally explained as nuclear-burning white dwarfs, which are progenitors of Type Ia SNe (Di Stefano 2010). Most of the ULX SSSs exhibit strong luminosity variability, with some of them displaying noise consistent with a thermal state, e.g. Jin et al. (2011), which rules out the AGN hypothesis. White dwarfs couldn't explain them as well, as luminosities and spectra temperatures observed are too high.

2.3.5. *Flux variability, quasi-periodic oscillations*

A systematic study of variability in *XMM-Newton* data of sixteen bright ULXs by Heil et al. (2009) has revealed two groups of sources—one with sources exhibiting significant intrinsic flux variability in the 10^{-4}–1 Hz range, with some of them exhibiting strong quasi-periodic oscillations (QPOs[10]), and another group with sources having weak or absent variability levels. Shaposhnikov & Titarchuk (2007, 2009) have proposed a

[9] The accretion disk can be considered as a collection of black-body emission rings of decreasing radius r, e.g. in DISKBB, $T \propto r^{-3/4}$. Hence, the whole accretion disk appears to be emitting simultaneously at different temperatures, i.e. appears to have a "multi-color" spectrum.

[10] The motions of matter in an accreting compact system will naturally result in a millisecond-scale flux variability of the source. For example, hot clumps of matter in an accretion disk around BHBs and NSs will cause QPOs on the time scales of ~ 1 ms. Various physical models were proposed to explain QPOs, and a good overview is available from van der Klis (2000).

novel technique to measure black hole masses using the correlation of QPO frequency and spectral index, the results of which were found to be in a good agreement with known Galactic BHB masses derived using traditional methods. Based on it, Casella et al. (2008) have found masses of the black holes in two ULXs with confirmed QPOs to be within the 100–1300 $M_{\odot}$ range, strongly supporting the IMBH hypothesis. This, however, is based on the assumption that the accretion rate in those ULXs is sub-Eddington, thus more observations are needed in order to test the validity of this method. The detection of strong, narrow QPOs can also be used as evidence against beamed emission. Strohmayer & Mushotzky (2003) have discovered 54 mHz QPO in a ULX and argued that this presents theoretical difficulties for its models based on either geometrically or relativistically beamed emission, hence favoring IMBH explanation. Abramowicz et al. (2004) have proposed a method to discriminate between black hole types based on twin-peak QPOs with 3:2 frequency ratio. Unlike other QPOs that are transient, vary with time and are poorly understood, the twin-peak 3:2 QPO is fixed in terms of the gravitational radius of the accreting compact object. As this type of QPOs has been found to scale as $1/M$ for Galactic black hole microquasars, it may be possible to apply this result to ULXs. That is, an IMBH should produce QPOs at ~ 1 Hz, while sMBHs should oscillate at $\sim$ 100 Hz. Based on this method, evidence for IMBH-like masses has recently been found for a number of ULXs (Pasham et al. 2014; Pasham et al. 2015).

2.4. *Optical counterparts, dynamical mass measurement*

As the X-ray emission of BHBs probes deep gravitational potential at regions close to the event horizon, optical observations enable to determine black hole masses and observe their evolution history and interaction with the environment. Using high-resolution data combined from both *HST* and *Chandra*, Tao et al. (2011) report photometric properties of more than a dozen ULXs that have a unique optical counterpart. X-ray to optical flux ratios and optical colors suggest that the dominant optical component in most of the ULXs appears to be produced via X-ray irradiation of the outer accretion disk, similar to LMXBs. This makes it impossible to determine the spectral type of the companion. Large optical emitting regions are required to explain the data, suggesting relatively large orbital separations and long orbital periods (or shorter periods with IMBHs). Within this set, it appears that many systems have unique peculiarities. With one of the ULXs, the optical spectral index is consistent with intrinsic emission of a standard MCD, while another's emission is dominated by a companion star, most probably F5 Ib or Iab. Another two ULXs exhibit flux ratios similar to HMXBs, with high X-ray variability that suggests uneven wind-fed accretion in elliptical orbits. As an example of an optical counterpart of ULX seen beyond reasonable doubt, NGC 7793 P13 can be used, which shows a late B type supergiant of 10–20 $M_{\odot}$, implying a similar most probable mass of the accreting black hole (Motch et al. 2011). The results of a more recent photometric survey by Gladstone et al. (2013) suggest the prevalence of OB type stars among the counterparts of 22 ULXs considered, excluding a single case, although the brightness of some cannot be explained even by the most brightest stars. This could be due to the enhanced emission from an irradiated star and/or accretion disk which could brighten the system up by $\sim 5^{\mathrm{m}}$. The masses of black holes in this survey obtained via X-ray irradiation models are mostly within the categories of sMBH and, slightly more massive but still stellar, massive stellar black hole (MsBH), although there are instances that would allow IMBHs. It is worth mentioning that in a study of a luminous ULX, a strong IMBH candidate, 2XMM J011942.7+032421, by Gutiérrez & Moon (2014), the authors have concluded that the high luminosity of the identified optical counterpart indicates it may be a stellar cluster.

Reliable identification of optical counterparts in ULXs and their periods potentially allows for dynamical mass measurements. In particular, the He II 4686 Å line that is known to be produced by strong X-ray photoionization may change its velocity (Gutiérrez & Moon 2014). Although emission lines were found to vary randomly instead of showing an ellipsoidal modulation (Roberts et al. 2011), an observation of M 101 ULX-1 by Liu et al. (2013) on *Gemini* and *Keck* resulted in the first successful dynamical measurement. They have been able to find 8-day period from the line shifts produced by a 19 $M_{\odot}$ Wolf-Rayet type WN8 star counterpart and obtain a limit of 5 $M_{\odot}$ for the black hole, although allowing for 60–80 $M_{\odot}$ estimate in a wind-fed system. It would be beneficial at this point to note that M 101 ULX-1 has been earlier considered a good candidate for a > 2800 $M_{\odot}$ IMBH (Kong et al. 2005), as its luminosity and soft spectrum suggested large emission radius of $\sim 10^9$ cm, versus $\sim 10^7$ cm expected from a typical sMBH. In the light of the recent kinematic measurements inclining the description towards sMBH models with super-Eddington accretion, the radius and temperature anomalies of this source can be explained with an optically thick outflow (Shen et al. 2015). A good overview on the current state of ULX black hole mass measurement techniques is available from Zhou (2015).

2.5. *X-ray ionized nebulae, ULX bubbles, radio emission*

Likewise ultraviolet sources, ULXs ionize the surrounding ISM with X-ray photons. The main difference to more conventional UV-ionized H II regions and X-ray ionized nebulae (XIN) is the lack of the Strömgen sphere in the latter, that is, there is no sharp transition between ionized and neutral plasma at the outer boundary, as X-rays are not absorbed very efficiently. This results in warm, weakly ionized zone with collisionally excited neutral atoms coexisting with ionized ones (Pakull & Mirioni 2002). The hallmarks of such XINe are the emission from highly ionized gas, such as the He II 4686 Å recombination line close to the source, and [O I] 6300 Å in the outer extended zones. Thus, the He II 4686 Å line may be considered as a photon counter for the emission and and can be used to estimate true X-ray luminosity of the source via photoionization and plasma simulation models, e.g. CLOUDY by Ferland et al. (2013). By analyzing nebula morphology and comparing apparent X-ray source flux to the one inferred from the He II line, it is possible to test whether the X-ray emission is isotropic or beamed (Pakull & Mirioni 2003; Kaaret et al. 2004). For a beamed source, the inferred flux will be lower than the one directly measured, with beaming factor proportional to the ratio of fluxes. For an isotropic source, both should be in agreement, which was found to be the case for multiple ULXs—see references above. That is, the number of ULX cases not favoring strong beaming is growing. The [Ne V] 3426 Å line can also be used for the same purpose (Kaaret & Corbel 2009).

A significant fraction of ULXs is found surrounded by large quasi-spherical interstellar bubbles (see § 2.3.2) which are produced via shock excitation from ULX outflow winds or continuous jets rather than photoionization. These ionized nebulae extend to several hundreds of pcs in diameter, have expansion velocity of $\sim$ 100–200 km s^{-1} and characteristic age of $\sim$ 0.5–1 Myr. These ULX bubbles (ULXBs) appear in a variety of filamentary and shell morphologies and, in general, resemble SNRs with the exception that they are an order of magnitude larger and are more luminous. Shock-ionized plasma of ULXB is generally distinguished by a specific spectrum it produces, with high ratios of low-excitation lines, such as [O I], [S II] and [N II], over Hα. A probable origin of a black hole—hypernova (HN) explosion—has recently been proposed as an explanation of a radio bubble in IC 10 (Lozinskaya & Moiseev 2007); although evidence generally supports the wind/jet inflation hypothesis, as, in some cases, ULXBs were found surrounding old stellar populations. Additionally, it is unlikely that a HN-surviving companion would start feeding the ULX so quickly after the explosion (Pakull & Grisé 2008; Feng & Soria 2011). Most ULXBs discovered so far have no direct signature of relativistic collimated jets, however Pakull et al. (2010) report on a source in NGC 7793—a black hole with a pair of collimated jets inflating a bubble, similar to the SS 433 microquasar. In it, the mechanical power of jets is $\sim$ a few 10^{40} erg s^{-1} which is 10^4 more energetic than the X-ray emission from the core. Such an ultrapowerful (rather than ultraluminous) system is the local universe analog of a recently discovered class of quasars, dominated by mechanical power (Feng & Soria 2011; Punsly 2011).

Some of the ULXBs are also associated with radio emission which can help in determining certain properties of the X-ray source. For example, the analysis of its morphology allows to determine whether the emission is beamed. Unresolved, compact radio emission would be consistent with beaming while isotropic source would result in an extended radio bubble (Miller et al. 2005), although the extent of the surveys in this regard is currently limited. Some radio bubbles, such as that of Holmberg II X-1, exhibit complex multi-layered morphology (Cseh et al. 2014). Radio emission from a black hole would also signify presence of relativistic jets, with the radio luminosity being a function of both X-ray luminosity and black hole mass (Körding et al. 2006). Deep radio observations of black holes allow, thus, to place constraints on their masses, e.g. non-detection of radio emission at $\sim$ 45 μJy would be consistent with an IMBH of $\leqslant 10^5$ $M_\odot$, and, alternatively, detection at $\sim$ 185 μJy would signify presence of a SMBH of $\geqslant 10^6$ $M_\odot$ (Farrell et al. 2011; Webb et al. 2012).

3. STELLAR MASS BLACK HOLE INTERPRETATION

3.1. *Cool accretion disk, Comptonized corona and energetic disk–corona coupling*

With the influx of high-resolution data from instruments like *Chandra*, *XMM-Newton*, *HST* and others, the signal that many sources in the ULX population have stellar origins was growing stronger. Luminosity functions, association with SFRs, centrally peaked distribution, successful identification of stellar mass optical counterparts and dynamical measurements of some—all pointed to that. Even of more importance was the possibility to obtain statistically acceptable fits to their spectra using existing X-ray binary models. By analyzing the highest quality *XMM-Newton* datasets available to date, Stobbart et al. (2006) have shown that the model that provided the best overall fit was DISKPN+EQPAIR, that is, accretion disk seeding cool photons to an optically-thick ($\tau \sim 8$, and well in excess of 30 for some sources) corona. The cool DISKPN accretion disk, based on the extension of the DISKBB model, explained the soft excess well, while Comptonized EQPAIR corona—an improvement of COMPTT mentioned earlier—was responsible for the hard curvature. Recent calculations have shown that coronae might reach $\tau \sim 20$ if strong magnetic fields are present (Różańska et al. 2015). This physical interpretation, by the way, was reminiscent of a three-layered atmosphere model proposed for Galactic BHBs half a decade earlier by Zhang et al. (2000). In it, however, the component responsible for the hard curvature was not an optically-thick corona—which was incompatible with thin coronae expected from typical BHBs—but an additional warm layer with a temperature of $\sim$100 keV. Structurally, the BHB system with an accretion disk engulfed in a warm layer is, to some extent, similar to the solar atmosphere that has a transition layer sandwiched between its chromosphere and the outmost hot corona.

Earlier, Kubota & Done (2004) have shown that the interpretation of the two-component spectrum based on thick coronae and simple summation, such as DISKPN+EQPAIR discussed above, has a fundamental flaw: it requires that the corona does not intercept our line of sight towards the accretion disk, as otherwise, it changes its apparent emission and renders the disk part of the fit void. If we consider geometries of the source then it is reasonable to expect that optically thick coronae will mask the innermost portions of the disks, making their temperatures to appear lower. Thus, black hole mass estimates using direct disk temperature measurements can be flawed. Additionally, both disk and corona should be energetically coupled, as they are both powered by a common gravitational energy release. For example, a powerful corona should imply that less energy is available to heat the disk, and this is not accounted for in the DISKPN+EQPAIR summation (Gladstone et al. 2009). The DKBBFTH model that incorporates the Svensson & Zdziarski coupling[11], proposed by Done & Kubota (2006), was employed by Gladstone et al. (2009) to fit high quality ULX data, however, about a third of sources in their set required accretion disks with large radii and low disk temperatures ($kT < 0.5$ keV) and, thus, massive black holes of 80–430 $M_\odot$ accreting at sub-Eddington

[11] Oversimplified, corona takes a fraction f of the gravitational energy available, and only the remainder $(1 - f)$ is available to power the disk emission.

rates. Additionally, optically thick coronae should show deep Fe K absorption edges, not detected in the data (Feng & Kaaret 2005).

3.2. *The ultraluminous state, funnel wind geometry and the importance of inclination*

In their paper, Gladstone et al. (2009) have instead proposed that very cool accretion disks are not associated with the direct emission, but rather appear during super-Eddington accretion that causes disk outflows. Due to the powerful winds, the outflows engulf the innermost regions of the accretion disk, which are the most hot, along with the corona, producing apparently soft spectrum for a high-temperature object. The authors have attempted, using DISKPN+EQPAIR as the basis, to recover the intrinsic spectrum of the disk by modeling energetically-coupled corona that Comptonizes its inner regions. That the intrinsic disk temperature is actually higher than it appears would allow to explain most of the ULXs with black holes of stellar masses instead of IMBHs. Luminosities are explained due to geometric beaming, as per Poutanen et al. (2007). Three spectral types of ULXs that could be placed into a sequence with increasing accretion rate have been identified: (i) broadened disk (BD) spectrum single component emission, potentially from moderately massive black holes accreting at sub-Eddington rates, (ii) hard ultraluminous (H–UL) state, arising from higher, super-Eddington rate accretion, with peak at high energies due to coronal emission, and (iii) soft ultraluminous (S–UL) state arising from the highest accretion rates, with peak at lower energies due to emission from the disk. It was assumed that BD-type ULXs represent more extreme versions of Galactic BHBs. According to this concept, as black hole accretes with an increasing rate, winds intensify and spectrally soft outflows begin to envelop the inner regions of the disk and hard corona out to an increasing photospheric radius, thus decreasing the apparent temperature of the source in line with the Stefan–Boltzmann law. The combination of spectral features observed in H–UL and S–UL ULXs is not commonly present in any known sub-Eddington Galactic BHBs, thus authors identify it with a new *ultraluminous* state based on super-Eddington accretion. The fact that BD-type sub-Eddington ULXs are usually low-luminosity ($L_X < 3\times10^{39}$ erg s^{-1}) sources, while ultraluminous super-Eddington states are seen almost exclusively at higher luminosities suggests a distinction between these accretion modes.

A few years later, Middleton et al. (2011) suggest, while refuting IMBH interpretations, a model geometry to explain variability in NGC 5408 X-1. Their super-Eddington sMBH interpretation is based on the clumpy material at the edge of the wind intermittently obscuring Comptonized emission—see Figure 4. Sutton et al. (2013), combining this concept with the spectral classification scheme proposed earlier by Gladstone et al. (2009), suggest a unified model of ULX accretion. They find that high levels of variability in their sample of *XMM-Newton* data are mostly associated with S-UL sources. Moreover, the fact that the variability is strongest at high energies is suggestive of its origin being the harder of the components. This is similar to the NGC 5408 X-1 explanation, with strong radiatively-driven winds forming a funnel-like geometry around the central regions of the accretion flow. The variability, then, can be explained with clumpy material at the edge of the wind obscuring the hard component coming from the corona or the hot part of the accretion disk. The type of the ULX spectrum and the level of variability observed would then, obviously, depend on the line of sight. As such, it became possible to explain most of the ULXs as sMBHs with two characteristic variables: accretion rate and inclination. As a physical model for super-Eddington sMBHs one may, for example, refer to Dotan & Shaviv (2011) or Kawashima et al. (2012). The spectrum computed from radiation hydrodynamic simulation of the latter group of authors has been found consistent with NGC 1313 X-2. They also demonstrate that the luminosity of a supercritically accreting 10 $M_{\odot}$ sMBH can significantly exceed 10^{40} erg s^{-1}.

3.3. *Reflection-based and slim disk models and variability*

The super-Eddington emission model discussed above is still not universally accepted. A reflection-based model proposed by Caballero-García & Fabian (2010) should be mentioned as an example of available alternatives, as it provides a remarkable fit to the *XMM-Newton* data. In it, high-energy spectral break and soft excess originate from relativistically blurred ionized reflection from the metal-rich accretion disk around a highly spinning black hole. The Eddington limit in this model is circumvented, as the energy is magnetically extracted from the accretion flow and released outside the disk region. Sutton et al. (2013) argue that variability provides a good diagnostic here, as it would be difficult to explain, in terms of reflection, why variability is stronger in only one part of the spectrum. Slim disk models (see § 2.3.2) also have problems explaining variability.

3.4. *Difficulties explaining HLXs*

Despite the success of sMBH models in fitting empirical spectral and timing data, a peculiar subset of ULXs could still not be explained well. Among them, HLX-1 is probably the most puzzling case, as sub-Eddington solutions for it result in IMBH-like black hole masses (Godet et al. 2012). It has a steep spectrum ($\Gamma = 3.4$) which rules out relativistic beaming[12]. Even with it, an IMBH would still be required (Farrell et al. 2009). Super-Eddington, most massive sMBHs with geometric beaming (collimation) could explain ULXs with $L_X \lesssim 10^{41}$ erg s^{-1}, and a ≈ 10 $M_{\odot}$ black hole solution for HLX-1, due to the extreme luminosity of the source, would require accretion with Eddington factor of ≈ 110—an order of magnitude above the majority of the ULX population (King & Lasota 2014). Assuming we limit super-Eddington accretion mode to $10 \times L_{Edd}$, HLX-1 would still imply a black hole with a mass in excess of 500 $M_{\odot}$. It is located ~ 0.8 kpc above the ESO 243-49 galaxy plane, at a distance of ~ 3.3 kpc from its center. Early sources indicate it is far removed from SFRs, thus assume that either it has experienced a natal kick, perhaps due to anisotropic

[12] Increase in apparent luminosity of the source due to relativistic “headlight” effect in which all of the light emitted into the forward hemisphere is concentrated into a narrow cone in the direction of the light source’s motion (Carroll & Ostlie 2006).

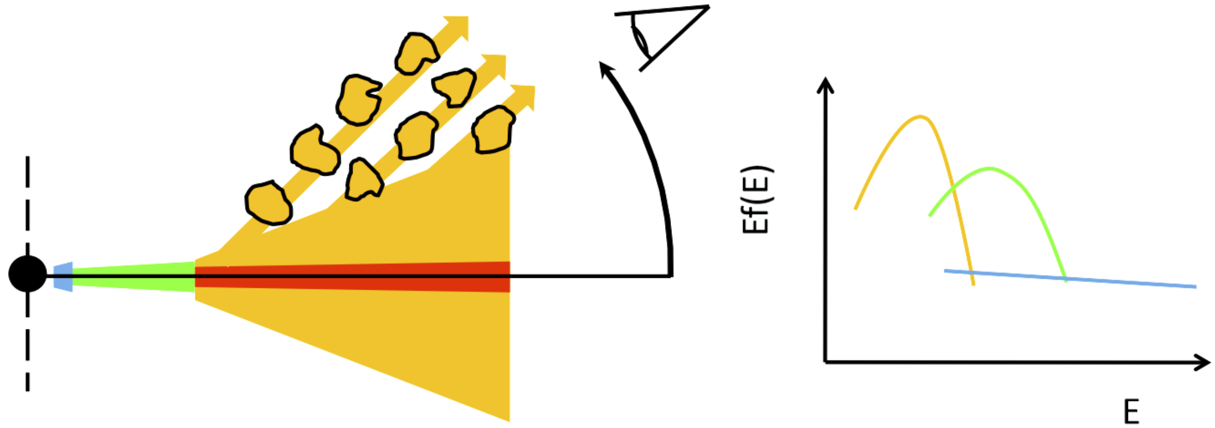

FIG. 4.— Illustration of the physical model suggested for NGC 5408 X-1, whereby soft disk emission (red) is distorted by photosphere (orange) which forms the base for the radiatively driven wind. The green region is an optically thick, stable Comptonization, while blue is the most energetic, highly variable region. This suggests that ULXs with suppressed variability are seen face-on, with direct line of sight to the central regions, and that variability in sources like NGC 5408 X-1 originates due to our line of sight being intercepted by clumpy, optically thick photosphere matter with soft spectrum obscuring the hard component. Image by Middleton et al. (2011).

SN explosion, or it is not associated with stellar formation, however recent observations found massive stellar population nearby—a star cluster of $\sim 4\times10^6\ M_\odot$ (Farrell et al. 2012). Follow-up optical observations of the HLX-1 optical counterpart on *VLT* are consistent with young stellar population of $\sim 10^4\ M_\odot$ and age $\lesssim 10$ Myr, however do not exclude that HLX-1 may instead be associated with a much older, ~ 10 Gyr GC of $\lesssim 2\times10^6$ $M_\odot$, which is also consistent with the data (Soria et al. 2012). Recent radio detections from HLX-1 resulted in IMBH-like mass estimate (Webb et al. 2012), and the ratio of Hα to X-ray luminosities indicates isotropic X-ray source (Farrell et al. 2011).

Another example of an outlier is 2XMM J011942.7+032421, an HLX in NGC 470 that has a counterpart as luminous as an entire stellar cluster (Gutiérrez & Moon 2014). Among other notable HLXs is Cartwheel N10. An interesting case is also Holmberg II X-1, as the studies of emission lines in the associated ULX nebula suggests isotropic emission and, thus, an IMBH (Colbert & Miller 2006). Finally, M 82 X-1 is another HLX, strong IMBH candidate, as, along with its $L_{X,peak} \sim 10^{41}$ erg s^{-1}, it is associated with a cluster of young stars with sufficient central density to spawn an IMBH (Portegies Zwart et al. 2004). This subset of sources, apparently, requires us to consider more massive black holes as a possible explanation of their nature, especially if there is any evidence for their X-ray emission being isotropic.

4. INTERMEDIATE MASS BLACK INTERPRETATION

4.1. *Possible origins, accretion and feeding*

The existence of IMBHs has been proposed in the early 70s (Wyller 1970). There are no direct and unambiguous observations of IMBHs yet. Detailed kinematical observations of stars orbiting them—a technique successfully used with SMBHs—could be considered a direct proof of their existence, however IMBHs' radius of influence is only a few arc seconds. E.g., for a $10^4\ M_\odot$ IMBH, it is $\sim 5''$, assuming central velocity dispersion of 20 km s^{-1} and a distance of ~ 5 kpc (Bender 2005). A successful detection would require next-generation instruments (Konstantinidis et al. 2013). Since, at present time, this class of objects remains hypothetical, it will be of a benefit to begin with a brief overview of our hypotheses of their formation, feeding and sources of mass accretion. The mechanism by which IMBHs form and acquire their accretion sources are highly uncertain. Due to their masses, they cannot form via formation scenarios of their stellar mass counterparts. The following primary scenarios have been proposed to explain their origins, most of which require high-density environments. The first considers them to be the remnants of Population III stars, as recent simulations have suggested they were massive, as per Madau & Rees (2001), however, see Whalen & Fryer (2012). Another scenario, suggested by Miller & Hamilton (2002), involves a $\gtrsim 50\ M_\odot$ black hole sinking into the center of a globular cluster (GC) and merging with smaller black holes. The authors argue that $\sim 10^3\ M_\odot$ black holes may be common in the centers of GCs and may therefore exist in $\sim 10\%$ of them. The third formation scenario involves massive stars rapidly sinking to the centers of dense GCs and colliding there, producing a very massive star (VMS) which, ultimately, collapses directly into an IMBH (Portegies Zwart et al. 2004). Recently, stars of $\gtrsim 150\ M_\odot$ have been discovered in the Large Magellanic Cloud, allowing, potentially, another contemporary IMBH formation channel through their collapse (Belczynski et al. 2014). Finally, IMBHs could be the surviving nuclei of dwarf galaxies. According to the picture of hierarchical merger of structure formation, large galaxies have captured multiple dwarf satellite galaxies that may have contained IMBHs as their nuclei (King & Dehnen 2005).

A couple of scenarios have been proposed for IMBHs to feed. The first describes them as binary systems that feed via Roche lobe overflow, similar to Galactic BHBs.

The companion has to be massive, on an order of a few tens $M_\odot$, with an orbital period measured in days or even years (Kalogera et al. 2004). Another scenario describes IMBHs as transient objects that accrete while they pass through molecular clouds. This enables to associate them with SFRs. As they do this, they acquire disks and remain active for a few 10^5 years, and these accretion episodes may recur multiple times (Krolik 2004).

4.2. *Observational evidence, modeling and problems*

Interpretations of ULX nebulae emission (see § 2.5), QPOs (§ 2.3.5) and spectral hardness allow to assume, at least for a number of sources, that the X-ray emission is isotropic. In particular the evidence for this is very strong with HLX-1. Additionally, twin-peak 3:2 frequency ratio QPOs indicate intermediate mass for the central compact object for a number of sources. If there is no fundamental reason why Eddington limit can be exceeded, empirical source luminosities place a lower limit on the masses of their black holes. That is, assuming IMBHs are defined as having $M \gtrsim 20\ M_\odot$, they have the corresponding $L_{Edd} \gtrsim 3 \times 10^{39}$ erg s^{-1}, which characterizes a significant proportion of the ULX population, although some authors use $10^2\ M_\odot$ as the minimum mass of an IMBH.

Standard MCD accretion models, such as DISKBB and DISKPN, can be used in order to describe the X-ray spectra of IMBHs (Fabian et al. 2004; Makishima 2007). Models available are generally not as advanced as with sMBHs. Similarly to the basic two-component sMBH models, IMBHs in the early 2000s were described as soft emission from optically thick MCDs, with hard components described by a power law curve. The problem with this, however, was that this traditional MCD spectral fitting resulted in the requirement of excessive inner disk temperatures, 1.0–1.8 keV. This is inconsistent with traditional accretion disk models that state that the innermost accretion disk radius R_{in} is inversely proportional to the temperature. The mass of the black hole, then, derived from this radius, $M_X = R_{in}/8.86\alpha\ M_\odot$, where parameter $\alpha = 1$ for a Schwarzschild black hole, is uncomfortably low. This can be circumvented by the assumption that IMBH is a rapidly spinning (Kerr) black hole, as α, in this case, could scale down to as low as 1/6 (Makishima et al. 2000). It is also possible to apply the slim disk model (see § 2.3.3) in order to explain disk temperature excess, and yet another option came from Fabian et al. (2004) who have shown that a correction factor must be applied, as the apparent spectrum is hardened because the inner disk becomes optically thin at higher energies. Stobbart et al. (2006) have shown that the IMBH MCD fits are not adequate to the hard component curvature exhibited by the spectra of some ULXs. However, it is worth recalling at this point that in a more self-consistent energetically coupled DKBBFTH modeling using similar data set by Gladstone et al. (2009), a third of ULXs were best fit with < 0.5 keV disks, implying IMBHs of 80–430 $M_\odot$ if the assumptions of Eddington limit and isotropy hold.

As much as sMBH models have difficulties explaining extreme luminosities of HLX sources, there are principal reasons why IMBHs cannot represent the entirety of the ULX population. First, if we assume ULXs are IMBHs, a problem appears with explaining their abundance and

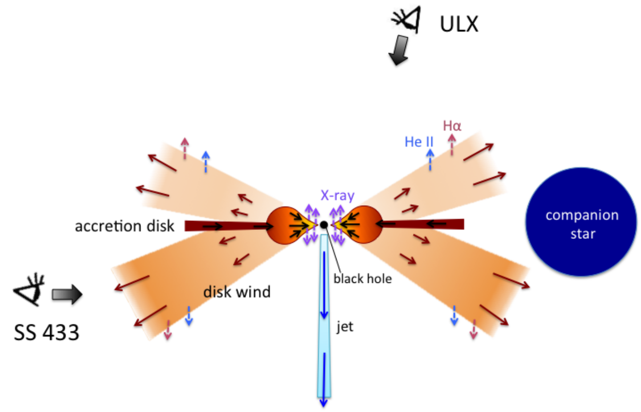

FIG. 5.— Schematic view of a SS 433 system that would appear ULX-like, if seen face-on. Figure courtesy Kyoto University.

also their centrally peaked surface distribution and the association with SFRs (see § 2.2). For example, in the Cartwheel galaxy, given IMBHs are accreting binaries, it would take an infeasibly large mass of stars ($\gtrsim 10^{10}\ M_\odot$) to form them (King 2004b). This result, however, assumes IMBHs are produced due to runaway collisions in star clusters, and Madhusudhan et al. (2006) have shown this formation channel is not efficient. Thus, if Cartwheel ULXs are indeed IMBHs, they must have been formed somehow else. Second problem has to do with the luminosity function (LF; see § 2.1) of X-ray sources in galaxies. We know that LF follows a form of a power law up to $L_X \sim 10^{40}$ erg s^{-1}, with XRBs representing lower luminosities. Then, a break occurs which corresponds to $\sim$ 10% L_{Edd} for a $\sim 1000\ M_\odot$ black hole. Assuming IMBHs represent ULX sources they would have to contrive not only to take over LF smoothly from BHBs at $L_X \sim 10^{39}$ erg s^{-1} but also cease accreting at $\sim$ 10% L_{Edd}, which is difficult to explain, as no other accreting source class behaves in this manner (Roberts 2007).

5. ALTERNATIVE INTERPRETATIONS

The study of ULXs, at some point, began to concentrate exclusively on accreting systems. One may find consensus that ULXs have to be defined as either near- or super-Eddington sMBHs or sub-Eddington high-mass accretors (Arp et al. 2004; Swartz et al. 2011), however this still allows interpretations outside sMBH and IMBH frameworks described above. Prior to making any attempts at constructing a unified ULX paradigm, these must be considered here, at least in general terms.

5.1. *SS 433 systems (microquasars)*

Due to its compactness, in principle, it is possible to fit a ULX model based on such an exotic system as the SS 433 into the range of sMBH interpretations. Being the first ever discovered microquasar, SS 433 can be characterized as a stellar binary system in an evolutionary phase that automatically follows a fairly normal HMXB phase. In it, the expanding blue supergiant companion is more massive than the compact stellar-mass accretor and fills its Roche lobe. The accretion disk gives off intense

X-rays and opposing jets of hot hydrogen along the axis of rotation. The material in jets travels at relativistic speeds (Cherepashchuk 2002; King & Lasota 2014). As jets align with our line of sight, super-Eddington luminosities are detected. Systems of this type, however, are not universally accepted as describing the ULX population as a whole, yet their connection with ultraluminous sources was suggested early (King et al. 2001; Koerding et al. 2001). For example, Fabrika (2004) argued that the W 50 nebula around SS 433 is reminiscent of ULXBs, so SS 433 would appear as ULX, if it was seen face on—see Figure 5. Any galaxy with recent star formation can host systems like this, and King & Lasota (2014) argue we should see more examples of SS 433-like objects with jets aligned towards us, if we search deep enough. The same authors have successfully fitted the SS 433 model to HLX-1, with the precession of jets giving a consistent physical interpretation of $\sim$ 1 yr periodic variable behavior of this source.

Just recently, Fabrika et al. (2015), based on the data from *Subaru*, have gone further and suggested that all ULXs ever spectroscopically observed exhibit almost the same type of spectra as late nitrogen Wolf–Rayet stars or luminous blue variables in their hot state. The optical spectra, they argue, is similar to SS 433, with broad emissions of ionized nitrogen and helium or carbon, concluding that SS 433 is intrinsically the same as ULXs, and that ULXs with $L_X \sim 10^{40}$ erg s^{-1} represent homogeneous class of objects with super-Eddington accretion. Because their paper came a few months earlier than this work, there are no fresh arguments against this statement, however I would like to note that the requirement of a face-on view onto an SS 433 system would require, in order to explain short-term variability of ULXs, a mechanism principally different from that described by Sutton et al. (2013). As it has been found earlier that short timescale variability was detected predominantly with ULXs of S-UL spectral type—which are also the brightest—and that the variability was the strongest within the hard part of the spectrum, this indicated that the hard component was most likely obscured by soft emission coming, perhaps, from the clumpy material in the outflows—see § 3.2. In the SS 433 ULX model, however, it is required that the source is viewed face-on along its jets in order to explain ULX-like luminosity, and the outflows at this inclination should not intercept the line of sight to the hard component. It should be of a benefit, thus, to research whether existing SS 433 models are capable of explaining short-term ULX variability in the *XMM-Newton* data within the limited range of inclination angles.

5.2. *Accreting neutron star X-ray binaries, accretion-powered and young pulsars*

Most theoretical models of ULXs are based on the accretors being black holes. More than a decade ago, Perna & Stella (2004) have suggested that young Crab-like pulsars, the X-ray emission of which is powered by rotation, could explain a fraction of the ULX population. This was based on a number of observational diagnostic factors compatible with ULXs, such as statistical properties, photon indices, association with SFRs and young SN remnants (SNRs), binarity, and also optical and radio emission. A young pulsar can also develop a surrounding accretion disk from the fallback of material from the SN explosion or from a companion, if it finds itself in a binary configuration. Recently, the study of accreting pulsars have enabled to extend the coverage of this class of objects to more luminous X-ray sources. There are examples of accretion-powered X-ray pulsars (AO538-66, SMC X-1, and GRO J1744-28) that reach ULX-like luminosities of $\sim 10^{39}$ erg s^{-1}. The physical description of these objects is basically that of an XRB: a magnetized neutron star (NS) in orbit with a normal stellar companion. The magnetic field at the NS surface is typically $\sim 10^8$ T. The accretion occurs via Roche lobe overflow. Accretion disks couple to strong dipolar magnetic field and, in such configuration, the material is funneled along the magnetic axis, allowing the object's luminosity to exceed its Eddington limit. Due to the rotation of the star, it is detected as an X-ray pulsar. Just until recently, such magnetized neutron stars have not been considered as capable of explaining more luminous ULX sources, however this model has experienced a revival with a publication of work by Bachetti et al. (2014). They have detected a 1.37 s pulsation from ULX M 82 X-2, establishing its nature as a magnetized neutron star with 2.5-day sinusoidal modulation arising from its binary orbit. The pulsed flux corresponds to the $L_X = 4.9 \times 10^{39}$ erg s^{-1}, which is $\sim$ 100 times the Eddington limit for a 1.4 $M_\odot$ compact object. This poses a challenge to traditional physical models for the accretion of matter on magnetized compact models, implying that NSXBs among ULXs may not be rare. Shao & Li (2015) have modeled the formation history of such NSXB ULXs in galaxies like M 82 and the Milky Way and concluded that a significant proportion of the ULX population may be comprised of pulsars—neutron star X-ray binaries (NSXBs). On the other hand, Soria (2007) has earlier indicated that long-term fluctuations and flux variability of the most of the ULXs is inconsistent with pulsar models. Recently, Doroshenko et al. (2015) have found no evidence of pulsations for ULXs in *XMM-Newton* archives, however this may signify that pulsations can be transient in nature or simply beyond detection in that data. It has been shown that NS accreting systems like M 82 X-2, in principle, are not unusual and should exist in $\approx 13\%$ of the galaxies with star formation history similar to M 82 (Fragos et al. 2015).

5.3. *Recoiling SMBHs, background AGNs, type IIn SNe and young SNRs*

This section will briefly touch alternative, circumstantial interpretations of bright X-ray sources. As objects of these classes have difficulties fitting all the ULX data, it is considered unlikely they will be ever capable of explaining, and, thus, defining the whole ULX population. The value of this overview, however, is in having a complete picture of what classes of sources, in principle, can be considered within a unified ULX model. For example, AGNs, recoiling SMBHs and SNe commonly exceed HLX luminosities, thus there is nothing "ultraluminous" about them. Understanding which sources are truly, intrinsically ultraluminous allows to circumscribe outliers, define the ULX category and build a valid unified model.

Traditional SMBHs have been rebutted as an explanation of the ULX population as they sink to the centers of galaxies in much less than the Hubble time (Tremaine et al. 1975). An important fraction of ULX sources in different catalogs is, under additional scrutiny, being excluded as being background AGNs. In a survey of *Chandra* data by Swartz et al. (2004), for example, $\sim 25\%$ of sources may be background objects. If a reliable distance estimate is not available then it is possible to use, for example, X-ray to optical flux ratio $\log(f_x/f_v)$ and short timescale variability in order to discern between stellar mass and supermassive systems. E.g., Tao et al. (2011) have used detection of variability on timescales of 10^3 s in order to conclude M 101 ULX-1 and M 81 ULS1 are not likely AGNs. The $\log(f_x/f_v)$ distribution in their sample peaked around 3, if compared to AGNs or BL Lac objects, whose $\log(f_x/f_v)$ ranges from -1 to 1.2 or 0.3 to 0.7. Recent simulations, however, have shown that SMBHs can be ejected from their nuclei during galactic mergers. If the recoil velocity of a black hole is smaller than the escape velocity of the host galaxy then such a recoiling SMBH may appear as a bright off-nuclear X-ray source. If these SMBHs accrete from surrounding ISM then their luminosities can exceed those of the typical ULXs, or even $\sim 10^{45}$ erg s^{-1}, if they are ejected into the galactic disk. Recoiling SMBHs have, thus, been proposed as a possible interpretation for a number of ULXs (Jonker et al. 2010), however, the probability of observing traveling SMBH with $L_X \gtrsim 3 \times 10^{39}$ erg s^{-1} in a galaxy is $\lesssim 0.01$ as per Fujita (2009), which is inconsistent with the empirical frequency of ULXs (see § 1). A notable case in this category is 2XMM J134404.1-271410—the second most brightest of all HLXs—which has recently been identified as a background quasar, and not associated with the IC 4320 galaxy. In the paper titled "another HLX bites the dust," Sutton et al. (2015) argue that with the exclusion of this particular object from the HLX subset, there is a large gap in properties between the ESO 243-49 HLX-1 and the remaining handful of objects in this class.

Finally, the interaction between the ejecta in SN explosion and the dense circumstellar medium of the progenitor star can produce emission with $L_X \sim 10^{40}$ erg s^{-1} (Pooley et al. 2002; Gao et al. 2003). In particular, the SNe that are the brightest in X-rays, are of type IIn (Immler & Lewin 2003). Jonker et al. (2010) argue that they can, in principle, be responsible for a subset of very bright ULXs, however this can be diagnosed by analyzing source variability in both X-ray and optical bands. Additionally, Soria (2007) mentions that most ULXs lack X-ray emission lines that are present in the typical SNR spectra.

6. DISCUSSION

Primary interpretations of the ULX phenomenon have thus far been presented. A number of trends can be identified. The empirical association of many ULXs with dusty SFRs in galaxies along with the centrally peaked surface distribution provides a strong signal indicating their stellar origin. ULX LFs are consistent with those of the XRBs, until the break of the power law curve occurring at $L_X \sim 10^{40}$ erg s^{-1}. The fact that the less luminous ULXs are found in ellipticals and the most luminous are found predominantly in late-type galaxies is consistent with the traditional classification of LMXB and HMXB sources. Optical photometry exhibits a wide range of properties, however unambiguous observations imply stellar black hole masses, or those of MsBHs. ULXs are found to transition between power law-like and complex spectra, similar to the canonical states of Galactic BHBs; the persistent nature of ULXs, however, is incompatible with the fact that Galactic BHBs are mostly transient sources, implying that most probably a different accretion regime is involved. Within the framework of sMBH interpretation, a number of models have been suggested in order to explain soft excess and hard curvature in ULX spectra. With two-component models, solutions are generally found with optically thick Comptonized coronae which also favors an introduction of a new accretion regime, as they are typically expected to be thin in "traditional" Galactic BHBs. More self-consistent models are, however, those based on energetically-coupled disk and corona. The most advanced model is based on the super-Eddington regimes described by Sutton et al. (2013). This is a strong candidate for a unified ULX model that fits both spectral and timing properties of the majority of the ULX population. Another options within the sMBH framework are interpretations based on the SS 433 microquasar and NSXB systems. As has recently been shown, they are capable of explaining a significant proportion of the ULX population, however more observations are needed in order to confirm whether they fit spectral and timing properties of the primary ULX population. A physically less extreme sMBH framework is suggested by Roberts (2007) with $\sim 100\ M_\odot$ MsBHs: these would require accretion at or below the Eddington limit in order to explain the vast majority of ULXs.

In a number of cases, the observations of ULXBs and nebular emission lines point to non-beamed, isotropic emission. This, it appears, comprises the major piece of support for IMBH interpretations of the underlying X-ray emitters. Observations of QPOs also favor intermediate black hole masses, especially with the 3:2 twin-peak QPOs. Assuming Eddington limits and isotropy hold in all cases, IMBH models are capable of explaining even the most brightest of the ULXs well. There are principal problems, however, with that. It is difficult to provide a physical explanation how IMBHs can pick up LF curve so smoothly from XRBs and then suddenly cease accreting at higher luminosities. Also, infeasibly large masses of stars would be required to form all of them, as was shown, e.g., in the case of the Cartwheel galaxy.

Finally, we have alternative, circumstantial interpretations of ULXs, such as recoiling SMBHs, background AGNs, type IIn SNe and young SNRs. These, in principle, exclude objects from the ULX category itself. A dichotomy, hence, is apparent in the sense of that interpretations based on the stellar origin fit the majority of the ULX observations well, while IMBHs or alternative models are required only for a rather limited subset of sources. At the same time, existing data indicates there are fundamental difficulties with employing IMBHs for the primary ULX population. This implies that ULXs may, in fact, be heterogeneous: the primary population is probably represented by the high-luminosity tail of BHBs or other stellar objects, while the most brightest of ULXs could be the objects of completely different nature. The discussion, hence, can be shaped further by the following questions. What is the physical nature of the primary ULX population at $L_X \sim 10^{39-40}$ erg s^{-1}? If these objects are of a stellar origin, then are they sMBHs, microquasars or NSXBs, and what are their X-ray luminosity limits? How the remaining HLXs, then, can be interpreted? Is there an unambiguous case confirming the existence of IMBHs?

In order to progress further, it is crucial to recall that at present time, only a handful of HLXs are confirmed—see Figure 1 and § 1. Some very luminous sources have recently been excluded from the HLX category after being identified as, for example, background quasars, SNe or multiples of fainter ULXs. With the recent exclusion of the second brightest of all HLXs, 2XMM J134404.1-271410 in the galaxy IC 4320, a gulf in properties between HLX-1 and the rest of the HLXs is becoming apparent. As Sutton et al. (2015) point out, given the scarcity of the remaining HLXs, it is important we scrutinize each one of those remaining. Asides from the HLX-1, the case of IMBHs in them is not necessarily strong. Along with being significantly fainter, other HLXs are located in late-type galaxies. M 82 X-1 has a wide range of estimated black hole masses (Pasham et al. 2014). The N10 is strongly associated with the SFR ring of the Cartwheel galaxy. The spectra of both M 82 X-1 and 2XMM J011942.7+032421 exhibit ~ 1 keV disc temperatures, indicative of stellar black hole masses rather than IMBHs. The $L_{X,peak}$ of these remaining objects is, in principle, compatible with existing sMBH models that are capable of exceeding $\sim 10^{42}$ erg s^{-1} if Eddington limit is disregarded (Wiktorowicz et al. 2015). The support is growing for supercritical accretion to be common in our universe (Motch et al. 2014). Even for the HLX-1 itself, a consistent solution of stellar origin based on the SS 433 microquasar has been proposed, not favoring an IMBH (Lasota et al. 2015).

Those ULXs that still remain to be strong candidates to harboring IMBHs may eventually provide a confirmation of the existence of this class of black holes that is of both cosmological and astrophysical importance. Foremost, IMBHs may be intimately linked to the evolution of galaxies and structure formation in our universe. This stems from the fact that the suggested formation scenarios of SMBHs in galactic nuclei are, in principle, extensions of those of IMBHs discussed in § 4.1, based mostly on the events of merging and accretion (Ebisuzaki et al. 2001; van der Marel 2004). The detection of high-redshift quasars at $z \sim 6$ implies very early formation of SMBHs when the Universe was only ~ 1 Gyr old (Li et al. 2007). Assuming IMBHs act as seeds for SMBH growth, this places certain constraints on the galaxy formation models and also enables to test our understanding of the structure formation in the Universe. One option, for example, is based on multiple IMBHs sinking, due to the dynamical friction, into the center of galaxy as it assembles itself via hierarchical merging; there, it is plausible for IMBHs to coalesce into a $\sim 10^9\ M_\odot$ nuclear SMBH (Haiman & Loeb 2001; Matsubayashi et al. 2004). In some cases, not all galaxies can develop supermassive black holes, thus leaving IMBHs as their nuclei.

Because IMBH cosmic mass density could exceed that of SMBHs, observations do not rule out that IMBHs may account for all of the missing baryonic dark matter in the Universe (van der Marel 2004). The standard cosmological model, ΛCDM, shows that the matter density of our universe is $\Omega_m \equiv \rho_m/\rho_{critical} \approx 0.24$, with the remaining $\Omega_\Lambda \approx 0.76$ representing the dark energy (Spergel et al. 2003). The baryon density of the matter is $\Omega_b = 0.0416 \pm 0.001$, however detailed inventory of the visible baryonic matter yields only $\Omega_v = 0.021$. This means that about the half of the baryons in the Universe are in some dark form, perhaps IMBHs. Although consensus is, supported by hydrodynamical simulations, that the missing baryons must comprise the low-density gas in Warm-Hot Intergalactic Medium (WHIM) and its phases surrounding virialized structures in the inter-galactic space (Nicastro et al. 2008; Kaastra et al. 2013). The missing baryons problem still remains on the frontier of modern research (Nicastro 2014).

7. CONCLUSION

Despite the influx of high-quality data from *Chandra*, *XMM-Newton*, *VLT* and other modern instruments, the existing data on ULXs is still scarce enough for one to be able to fit a wide range of solutions to it. Stellar origin interpretations provide arguably the best fit to the primary ULX population to date. Even the most brightest of HLXs can be interpreted within the sMBH framework as the extreme and most luminous (massive) cases of the primary population. Given that SS 433 has been proposed as a plausible model of HLX-1, this virtually relieves from the necessity of involving IMBHs within the unified ULX model. However, current observations are unable to exclude the presence of this class of black holes completely.

Further observations are needed in order to refine our understanding of ULXs. For example, Sutton et al. (2013) predict that the winds in the ultraluminous super-Eddington state they describe should be highly ionized, showing specific absorption fingerprint, thus, high-quality spectroscopy will be a good diagnostic for this model. Along with that, a way to constrain the range of plausible physical models of super-Eddington emission of sMBHs could be the development of better understanding of the ULX variability both on short and long timescales. As was mentioned in § 5.1, a microquasar model will, due to its inclination constraints, require a variability mechanism of completely different nature, if compared to the model based on super-Eddington sMBHs with optically thick outflows. Middleton et al. (2015) have proposed a spectral-timing model for the primary ULX population based on the two distinct methods of generating variability, however there is still a great deal of work left to be done in this direction. A good overview of the subject of variability of ULX sources is available from Webb et al. (2014).

A breakthrough in the ULX research may come from deeper homogeneous all-sky surveys confirming whether the LF of these sources extends unbroken beyond $L_X \sim 10^{40}$ erg s^{-1}. Searching for compact radio jets down to $\sim 1\ \mu$Jy would also enable to constrain black hole masses (Feng & Soria 2011). McKernan et al. (2014) describe a number of observational signatures IMBHs should exhibit if they exist in gas discs around AGNs. The increased astrometric accuracy of next-generation near-infrared instruments, such as *VSI* or *GRAVITY*, along with the *VLTI*, would possibly allow for detecting the innermost kinematics of a GC around a potential IMBH, hence, providing unambiguous proof of the existence of this class of black holes (Konstantinidis et al.

2013). It should also be noted that *NGO* (also known as *eLISA*, scheduled for launch in 2020s) will be able to detect low-frequency gravitational waves from coalescences of IMBHs that may occur in dense stellar clusters—as many as few events per year, out to a few Gpc (Amaro-Seoane et al. 2012).

Revealing the nature of ULXs is of cosmological importance. Within the stellar origin framework, these objects open horizons towards new super-Eddington accretion regimes. If the existence of IMBHs is confirmed by future observations then this will provide an important piece of support to certain class of models explaining the origins of AGNs. Such a discovery would refine our understanding of galaxy formation and evolution and will shed more light on the epoch between the primordial time that followed the dark ages at $z \sim 60$–20 and the era of quasars at $z \lesssim 6.4$ when first AGN engines have appeared.

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