X-ray Binaries and Ultraluminous X-ray Sources

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Abstract Ultraluminous X-ray sources remains mysterious despite all the research which was made recently. The simplest explanation, which involves the intermediate-mass black holes, has other substantial problems. On the other hand, the super-Eddington accretion provides explanation, which aims at connecting these sources with observed X-ray binary population. We showed that powering such a source is feasible even in the most extreme case of the system ESO 243-49 HLX-1, which reaches the luminosity of $1.1 \cdot 10^{42}$erg/s.

Keywords: X-ray binaries, mass accretion, black holes, stellar evolution

1. Introduction

Ultraluminous X-ray Sources are extremely bright ($L_X > 1 \cdot 10^{39}$erg/s; e.g., [1]) point-like objects. Such a large luminosity exceeds the Eddington limit for a stellar mass black hole (sMBH; $M_{\_sMBH} \approx 10 M_{\odot}$). Up to now we discovered about 500 such objects ([2]) but none in our Galaxy (but see [3]).

For a long time it was suggested that ULXs may be the high-luminosity end of X-ray binaries (XRBs). This statement is supported both by observations and by theoretical simulations. For example, Motch [4] observed the variations in the light-curve of the irradiated companion star, which placed a 15 $M_{\odot}$ upper limit on the compact object mass in the NGC 7793 P13 source. This clearly precludes the intermediate-mass black hole (IMBH) accretor. Even more striking result was acquired by Bachetti [5] who found a pulsar in an ULX (source M82 X-2).

There are also a lot of theoretical works on this subject. Feng [1] showed the formation channels for BH ULX, whereas Fragos [6] showed that the formation of ULX with NS is also possible in the light of the stellar evolution. However, there are also counter arguments against this interpretations, which favour the IMBH accretors ([7], [8]).

First, the most important characteristics of XRB population are provided (Section 2), then we move to presentation of recent results in the field of ULX (Section 3), and then we discuss the possibility in which ULXs (at least most of them) are the subgroup of XRBs (Section 4).

2. X-ray Binaries

All confirmed black holes (BH) reside in XRBs. You can find the most up-to-date list in [9]. The progenitors to compact objects are heavier that 8 $M_{\odot}$ but when we include binary interactions (e.g., mass transfer) even lighter stars are potential progenitors of compact objects. Recently Sana [10] has shown that most massive stars tend to born in binaries with a possibility that even all of these stars reside in binaries with tight circular orbits.

XRB comprises a NS/BH accretor and a mass-transferring companion (Fig. 1). In the vicinity of CO the gravitational potential energy of the matter is being converted into thermal energy which results in very large temperatures in the inner part of the accretion disk. That's the place from which X-ray radiation originates.

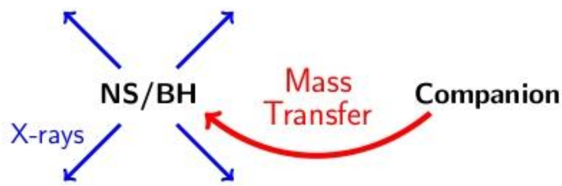

Fig 1. *The schematic picture of an X-ray binary system*

These systems are generally divided in two distinct groups. The first one is called Low Mass XRB (LMXB) and includes systems with companions lighter that about 1 $M_\odot$. The mass transfer in these systems is the outcome of Roche lobe overflow (RLOF) of the secondary star. The orbital periods are in the range from a few hours to a few days. We observe them mostly in the direction of the Galaxy Center and in globular clusters. Such systems have to born as a binary of extremely high mass ratio and with a large orbital separation.

The second group comprises high-mass XRBs (HMXBs) with companions heavier than ~ 10 $M_\odot$. The mass transfer occurs due to wind from the massive secondary. It is though that HMXBs are the predecessors to Thorne-Zytkow objects and also to double compact objects.

It is important to note that there are very few systems in-between (with the companion mass 1-10$M_\odot$) and that all BHs reside in LMXBs (you can find collected information in Table 1).

Table 1. *Parameters of low-mass X-ray binaries comprising black holes. The columns are: name of the system, companion mass, spectral type, black hole type and orbital period. For references and further information see [9] from where the table was taken.*

Name	$M_{comp}[M_\odot]$	Spec. type	$M_{BH}[M_\odot]$	$P_{orb}[h]$
XTE J1118+480	0.22 ± 0.07	K7/M1V	$6.9 \div 8.2$	4.08
XTE J1550-564	0.3 ± 0.07	K2/4IV	10.5 ± 1.0	37
GS 2000+25	$0.16 \div 0.47(0.315)$	K3/6V	~ 6.55	8.26
GRO J0422+32	~ 0.45	M0/4V	~ 10.4	5.09
GRS 1009-45	~ 0.5	G5/K0V	~ 8.5	6.86 ± 0.12
GRS 1716-249	~ 1.6	K-M	$\gtrsim 4.9$	14.7
GX339-4	$0.3 \div 1.1(0.54)$	KIV	> 7	42
H1705-25	$0.15 \div 1.0$	K3/M0V	$4.9 \div 7.9$	12.55
A0620-00	0.68 ± 0.18	K2/7V	6.6 ± 0.25	7.75
XTEJ1650-50(0)	0.7	K4V	~ 5.1	7.63
XTEJ1859+226	0.7	K5V	7.7 ± 1.3	6.58 ± 0.05
GS2023+338	$0.5 \div 1.0(0.7)$	K0/3IV	12 ± 2	156
GRS 1124-68	$0.3 \div 2.5(0.8)$	K5V	6.95 ± 0.6	10.392
GRS1915+105	0.8 ± 0.5	K1/5III	12.9 ± 2.4	811.2 ± 2.4
GS 1354-64	1.03	G5IV	7.6 ± 0.7	61.07
GROJ1655-40	1.75 ± 0.25	F3/G0IV	5.31 ± 0.07	62.909 ± 0.003
4U1543-47	$2.3 \div 2.6(2.45)$	A2V	$2.7 \div 7.5$	26.8
XTEJ1819-254	$5.49 \div 8.14(6.81)$	B9III	$8.73 \div 11.70$	67.62
CygX-1	19.2 ± 1.9	OI	14.8 ± 0.1	134.4

The typical evolution leading to formation of an LMXB with a BH accretor begins with a binary with a very extreme mass ratio on ZAMS (35$M_\odot$ and 1$M_\odot$) on a very elongated orbit (12000 $R_\odot$). After 5.6 Myr of evolution a common envelope (CE) phase commences which results in a significant shrinkage of the orbit. Up to that time, the primary has lost a large fraction of its envelope in the wind and has a mass of about 17 $M_\odot$. After CE, the system consists of a helium core of the primary (11 $M_\odot$) and an almost unaffected secondary (1$M_\odot$). It has to be stated here that CE is necessary for formation of a LMXB because we know no other process that can lead to fast and effective angular momentum loss (AML) in a wide binary.

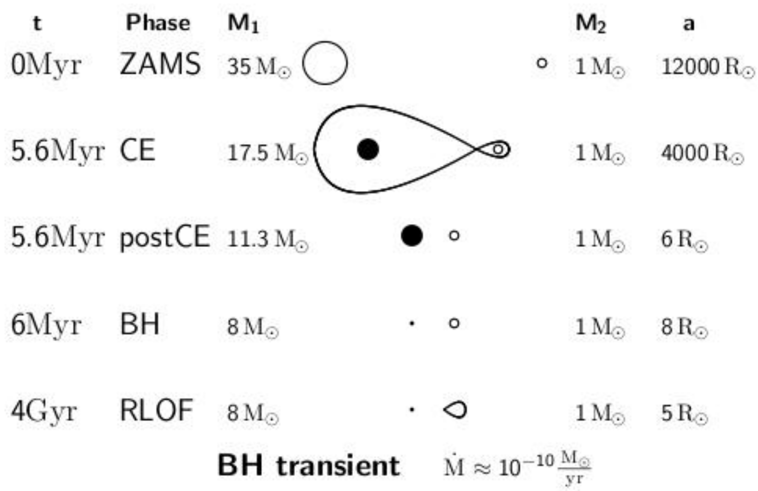

Fig2. *The evolution of typical predecessor to low-mass X-ray binary with a black hole accretor. See text for more information.*

Just after the CE, the naked He core of the primary explodes in a supernova explosion and forms a BH ([24]) with a mass of about 8 $M_\odot$. The binary needed only a few Myr to shorten the orbit from 12000 $R_\odot$ to 8$R_\odot$, but needs another 4 Gyr to lose additional 5 $R_\odot$ due to gravitational wave emission and start MT onto BH. At that moment we acquire the XRB with a mass transfer rate of about 10^{-10} $M_\odot$/yr (see Fig. 2).

Although these results solve the problem of the gap in compact object distribution ([11]), a very significant problem still exists with a mass distribution of companions. A typical evolution suggests a typical donor mass of about 1$M_\odot$, whereas observations show 0.6 $M_\odot$. This problem was investigated by Wiktorowicz [9], who concentrated on the CE phase. Their conclusion was that neither CE model nor efficiency have the influence on XRB population. Therefore this problem with companion masses may be a result of systematic observational error ([12]) or the mass transfer physics is still poorly understood.

3. Ultraluminous X-ray Sources

For a long time it was believed that an accreting object cannot breach the so called Eddington limit. This constraint stems from the fact that accreted matter must overcome the radiation pressure. Increasing of the accretion also increases the emission which results in higher radiation pressure. At some point we will obtain the equality between the pressure of falling mass and the pressure of radiation.

ULXs are observed as point-like objects with luminosity far exceeding 10^{39}erg/s (the Eddington limit for an sMBH). Their spectrum strongly resembles the XRBs' one and the other similarity is that ULXs appear to be point-like sources. What is more, their spectrum seems to agree with a multi-color disk which is an indication of disk accretion. These two facts provide two most common solutions to the problem of the nature of ULXs.

The first solution involves the hypothetical IMBH. The idea is very simple. The larger is the accretor mass the larger is the Eddington limit. Then we do not have to break it. However the problem appears during the evolution as there are no evolutionary routes that can produce IMBHs from stars. What is more, it was shown that IMBH cannot be present in all observed ULXs ([13])

The second possibility, on which we concentrate, is that the ULXs are a high-luminosity tail of the XRB distribution. There are several processes that can lead to breakage of the Eddington limit. If we assume that there is no spherization of matter, what is supported by recent detailed accretion flow calculations ([14], [15], [16]), the emission may be beamed, which will result in an apparent higher luminosity ([17]). Another possibility is the photon bubbles ([18]). The advection may result either in a lower luminosity (the advection dominated accretion flow) or help to emit the radiation through magnetic buoyancy ([15]). The relativistic jets, observed in many systems, may result in a very high energetic radiation if observed along the axis or in a low accretion if observed perpendicularly ([19]).

4. ULX as XRB

A strong support for ULX as a part of XRB comes from the XLF (e.g., [20]). It presented no visible features near 10^{39}, where is the transition between XRBs and ULXs, but extends up to a few times 10^{40} erg/s, which includes most of the ULXs. However this argument works only for regular ULXs while the problem still exists with these with luminosities above the cut-off.

The most luminous ULXs is ESO 243-49 HLX-1 with an enormous luminosity well above the XLF cut-off (1.1×10^{42}erg/s; [21]). The outbursts, during which this luminosity is reached, are very regular (dt ~ 1 yr; [22]). It was suggested recently that this source may be a face-on version of SS433 system, which resides in our Galaxy ([3]).

The results presented in paper [23] show that it is possible to obtain the mass accretion rates high enough to powers such a source as HLX-1 in XRB system with sMBH. They presented several evolutionary channels and discussed typical evolutionary routes. What is very significant, the study showed that even NS accretors are capable of obtaining such large accretion rates.

The typical evolutionary route doesn't differ significantly from typical XRB. We start the evolution with a heavy secondary (~10 $M_{\odot}$). If we omit the Eddington luminosity, the beginning of the mass transfer will give as a very large mass flow for a very short time (100-10000yr; see Fig. 3). The companion will be quickly stripped of mass and the mass transfer rate will decrease. After this extremely luminous phase the system will become a regular ULX. The conclusion of [23] is that a lot of systems evolves through the extreme ULX phase, but it is extremely short, which give us in result only few potential observations currently. Probably the case is similar for all ULXs but this thesis is being investigated in the on-going study (Wiktorowicz et al. In preparation).

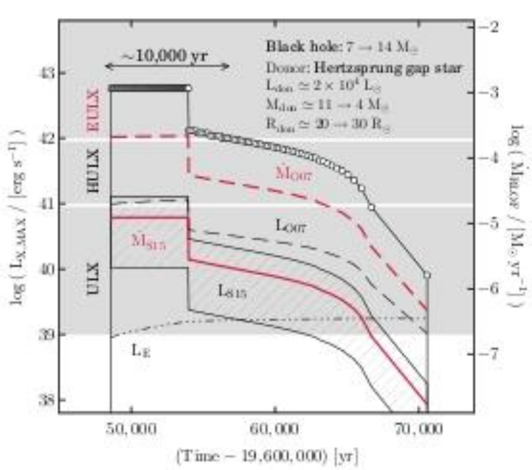

Fig3. *The ULX phase. A few accretion models and parameter changes are presented. For more details see [23].*

5. Conclusions

A lot of observations support the statement that ULXs are a high-energy tail of XRB population. However, the most luminous systems are still the best candidates for the elusive IMBHs. In [23] the mass transfer rates in XRBs were investigated. The disk accretion models are still under development, so the work was limited to examine the amount of available mass flow.

It was proved that we can obtain mass accretion rates high enough to power even the most luminous ULXs. Therefore if we assume that the Eddington limit may be breached by some kind of process, we are able to explain the ULX population without the need for IMBH. It appears that the ULX (extreme and possibly also regular) is just a short phase (100–10000 yr) during the evolution of a significant number (~1%) of XRB. These numbers result in a few observations that should be visible currently.

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