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Be/X-Ray Binaries with Black Holes in the Galaxy and in the Magellanic Clouds

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Abstract

I will start with the statistics indicating that the objects named in the title of my talk are either non-existing or very elusive to detect (not a single such object is known against 119 known Be/neutron star X-ray binaries). After brief reviewing of the properties of Be/X-ray binaries I discuss several objects that were proposed as the long sought for candidates for Be/black hole X-ray binaries. After three unsuccessful candidates (LS I +61^0 303, LS 5039 and MAXI J1836-194), a successful candidate (AGL J2241+4454/MWC 656) was finally, very recently, announced.

Keywords: stars: binaries – stars: X-ray binaries – stars: Be/X-ray binaries – stars: black holes – stars: Be.

1 Introduction

The objects named in the title of my talk seem not to exist neither in our Galaxy nor in the Magellanic Clouds. Not a single such object is known today (this statement was still true during our conference). At the same time, we know (today) 184 Be/X-ray binaries (74 in the Galaxy and 110 in the Magellanic Clouds).

2 Properties of Be/X-Ray Binaries

Be X-ray binaries (Be XRBs) are the most numerous subclass among high mass X-ray binaries. They outnumber all other high mass X-ray binaries by a factor of three (we know about 180 Be XRBs vs about 60 other high mass X-ray binaries). These systems consist of a Be star and a compact object (a neutron star or a black hole). The Be stars are massive, generally main sequence, stars of spectral types A0-O8 with Balmer emission lines (Negueruela 1998). The Be XRBs are rather wide systems (orbital periods in the range of $\sim 10 - 1180$ days). The orbits are frequently eccentric. A compact component accretes from the wind of a Be star (even massive Be stars are well within their Roche lobes for these wide orbits, so there is no question of Roche lobe overflow). At present, 184 Be XRBs are known in the Galaxy and in the Magellanic Clouds, and in 119 of them, the compact object was confirmed to be a neutron star by the detection of the X-ray pulsations (with the pulse periods in the range of 34 ms to $\sim$ 1400 s). In the remaining cases, whenever we have information concerning the nature of the compact component (such as an X-ray spectrum), it also indicates a neutron star. Although one cannot exclude that a few of these systems contain white dwarfs or black holes, it is safe to state that majority of them contain a neutron star as compact component. However, not a single black hole binary containing a Be type component has been found so far. This disparity (119 Be XRBs with neutron stars versus not a single one with a black hole) seems indeed striking (this was the situation during our conference; today the statistics is 119 to one − see the section 4.2).

The X-ray emission from Be XRBs (with a few exceptions) is of a distinctly transient nature with rather short (days to weeks) active phases separated by much longer (months to tens of years) quiescent intervals (a typical flaring behavior). There are two types of flares, which are classified as Type I outbursts (smaller and roughly regularly repeating) and Type II outbursts (larger and irregular. This classification was defined by Negueruela & Okazaki 2001 and Negueruela et al. 2001. Type I bursts are observed in systems with highly eccentric orbits. They occur close to periastron passages of a neutron star. They are repeating at intervals $\sim P_{\rm orb}$. Type II bursts may occur at any orbital phase. They are correlated with the disruption of the excretion disc around Be star (as observed in Hα line). They repeat on time scale of the dynamical evolution of the excretion disc ($\sim$ few years to few tens of years). This recurrence time scale is generally much longer than the orbital period (Negueruela et al. 2001).

Be XRBs systems are known to contain two discs: excretion disc around Be star and accretion disc around neutron star. Both discs are temporary: excretion disc disperses and refills on time scales $\sim$ few years to few decades (dynamical evolution of the Be star disc, formerly described as "the activity of a Be star" (Negueruela et al. 2001)), while the accretion disc disperses and refills on time scales $\sim$ weeks to months (which is related to the orbital motion of a neutron star on an eccentric orbit and, on some occasions, also to the major instabilities of the other disc). The accretion disc might be absent over a longer period of time ($\sim$ years), if the other disc is very weak or absent. The X-ray emission of Be XRBs binaries is controlled by the centrifugal gate mechanism, which, in turn, is operated both by the periastron passages (Type I bursts) and by the dynamical evolution of the excretion disc (both types of bursts). This mechanism explains the transient nature of the X-ray emission (see Ziółkowski 2002 and references therein).

The more detailed description of the properties of Be XRBs is given, e.g. in Negueruela et al. 2001, Ziółkowski 2002, Belczyński & Ziółkowski 2009, Reig 2011 and references therein.

Considering the numbers of different (neutron star vs black hole) Be XRBs, it is important to note, that if we take all other XRBs (both high and low mass), except Be XRBs, then the ratio of neutron star systems to black hole systems is about 2:1 (Remillard & McClintock 2006, Ziółkowski 2008). For Be XRBs this ratio is 119 to zero. The disparity is indeed striking. This disparity is referred to as a missing Be – black hole X-ray binary problem.

Trying to understand the reasons for which we do not observe Be – black hole XRBs, Belczyński & Ziółkowski (2009) carried out stellar population synthesis calculations aimed at estimating the ratio of neutron star to black hole Be XRBs, expected on the basis of the stellar evolution theory. The results of their calculations predict that for our Galaxy the expected ratio of Be X-ray binaries with neutron stars to the ones with black holes $F_{\mathrm{NS/BH}}$ should be, most likely, equal ~ 54. Since we know 48 neutron star Be systems in the Galaxy, then it comes out that the expected number of black hole systems should be just one. The observed number (zero) is consistent with this prediction.

Ziółkowski & Belczyński (2010) carried out also preliminary stellar population synthesis calculations for the Magellanic Clouds. This time, the result was that the expected ratio $F_{\mathrm{NS/BH}}$ for Magellanic Clouds Be XRBs should be equal ~ 9. Since we know 71 neutron star systems in the Magellanic , then the expected number of black hole systems should be about 8. This time, the observed number (zero) is not consistent with the prediction. The most likely reason for this discrepancy is a different history of the star formation rate in the Magellanic Clouds, with respect to the Galaxy. The calculations mentioned above used the galactic scenario for the star formation history. The new, more realistic calculations for Magellanic Clouds are necessary.

3 New Be/X-Ray Binaries

Ziółkowski & Belczyński (2011) published a full list of the 170 Be/X-ray binaries known in 2011 (72 in the Galaxy and 98 in the Magellanic Clouds). Table 1 of this paper contains the list of the 14 new objects belonging to this class which were discovered in meantime (2 of them lie in the Galaxy and 12 – in the Magellanic Clouds). This list contains two interesting systems (added after the end of our conference). One of them is system with the longest orbital period (Swift J010745.0-722740 with $P_{\mathrm{orb}} \approx 1180$ days). The second is the first long sought Be/black hole X-ray binary (AGL J2241+4454).

4 Candidates proposed for Be/Black Hole X-Ray Binaries

4.1 Unsuccessful candidates

4.1.1 LS I +61^0 303

This binary of the orbital period 26.5 d consists of a B0Ve star and a compact object the nature of which is not firmly established yet. No pulsations were detected in the X-ray emission. The radio emission also does not show pulses. This might indicate a black hole rather than a neutron star. However, in many respects, the system reminds another X-ray and radio binary – PSR B1259-63, the nature of which is already well understood. PSR B1259-63 belongs to the category of so called colliding winds binaries. This wide (3.4 y orbital period) binary consists of an O9.5Ve star and a neutron star which is observed as a fast ($P_{\mathrm{spin}} = 47.7$ ms) radio pulsar. Neutron star moves along a very eccentric ($e = 0.97$) orbit. The system is also a source of TeV emission (in fact, it was the first binary detected in this energy range). In all three energy ranges (radio, X-ray and TeV) the emission is modulated with the orbital period.

The binary was most recently extensively discussed by Dubus (2013). After reviewing both the observations and the numerical simulation modeling, he strongly supports the much earlier idea of Tavani et al. (1994) that both X-ray and TeV emission are due to collision of two winds: stellar wind from Be star and pulsar wind

Table 1: New Be X-ray Binaries[a]

Name	$P_{\rm orb}$ [d]	$P_{\rm spin}$ [s]	$L^{\rm b}_{\rm x,max}$ [erg/s]	Spectral type	Ref[c]
XMMU J004814.0-732204		11.866	4.2×10^{36}	B1.5-2.5Ve	1
XMMU J005011.2-730026	29.9	214	5.0×10^{34}	Be	2,3,4
IGR J00569-7226	17	5.05	5.5×10^{37}	B0.5e	5,6,7,8
CXOU J005758.4-721620	40.03	7.918	4×10^{35}	Be	9,10
2XMM J010247.4-720449	490 ?	521.4	2.8×10^{35}	Be	11,12
Swift J010745.0-722740	1180			Be	13
IGR J01217-7257	84		$\sim 1 \times 10^{37}$	Be ?	14
CXO J012745.97-733256.5	656	1062	6.3×10^{35}	B0-0.5IIIe	15,16,17
IGR J0154-7253	36.3	11.483	2.5×10^{37}	O9.5-B0IV-Ve	18
IGR J015712-7259	35.1	11.6	4×10^{36}	Be	19,20,21
Swift J04558.9-702001			5.1×10^{35}	Be	22
Swift J053041.9-665426	~ 415		9.7×10^{36}	Be	23,24,25
MAXI J1932+091				Be	26,27
AGL J2241+4454	60.37		3.7×10^{31}	B1.5-2IIIe	28,29,30,31,32

[a]Since this table is a natural supplement to tables 1 and 2 of Ziółkowski & Belczyński (2011), I should add following updates to these tables:

Swift J0513.4-6547 $P_{\rm orb} \approx 27$ d (Coe et al. 2013d)
RX J0520.5-6932 $P_{\rm spin} = 8.035$ s (Vasilopoulos et al. 2013b), $P_{\rm orb} = 23.93$ d (Kuehnel et al. 2014)
SMC SXP707 $P_{\rm spin}$ is unknown (707 s is an instrumental effect, Maggi et al. 2013)

[b]Maximum X-ray luminosity

[c] (1) Sturm et al. 2011a; (2) Coe et al. 2011; (3) Schmidtke & Cowley 2011; (4) Schmidtke et al. 2013a; (5) Coe et al. 2013a; (6) Kennea 2013; (7) Schmidtke & Cowley 2013a; (8) Coe et al. 2013b; (9) Israel et al. 2013; (10) Schmidtke & Cowley 2013b; (11) Sturm et al. 2011b; (12) Sturm et al. 2013; (13) Maggi et al. 2014; (14) Coe et al. 2014; (15) Henault-Brunet et al. 2012; (16) Schmidtke et al. 2012a; (17) Schmidtke et al. 2012b; (18) Townsend et al. 2011; (19) Coe et al. 2008; (20) Bodaghee et al. 2009; (21) Schmidtke et al. 2013b; (22) Vasilopoulos et al. 2013a; (23) Sturm et al. 2011c; (24) Charles et al. 2011; (25) Sturm et al. 2011d; (26) Negoro et al. 2014; (27) Itoh et al. 2014; (28) Williams et al. 2010; (29) Casares et al. 2012; (30) Casares et al. 2014; (31) Paredes & Ribo 2014; (32) Munar-Adrover et al. 2014.

from rapidly rotating neutron star. The shock formed as a result of the collision gives the rise to a non-thermal emission in a similar way as in the pulsar wind powered nebulae. The characteristic element of such model is elongated radio emission with position angle dependent on orbital phase. Elongated emission is pointing from the vicinity of the pulsar in the direction opposite to the direction towards the Be star. Such "comet tail" behavior of radio emission is clearly observed for PSR B1259-63. At present, there are no significant doubts that the system is powered by the pulsar spindown and that the colliding winds model is, in general, a correct explanation of the properties of this binary.

LS I $+61^0$ 303 is, in many respects, similar to PSR B1259-63. In particular, the spectral and timing properties of the emission (through all ranges of electromagnetic spectrum) are very similar. Also the "comet tail" behavior of radio emission is clearly seen for LS I $+61^0$ 303 (Dhawan et al. 2006). As I mentioned earlier, no pulsations were detected and, therefore, the case is not so clear cut as for PSR B1259-63. This system (LS I $+61^0$ 303) is also discussed by Dubus (2013) and he concludes that indirect evidence strongly supports the colliding winds case. The compact object is, most likely, a rapidly rotating pulsar. The lack of the observed pulsations might be explained as the result of the absorption of the radio emission by the circumstellar material. Even in PSR B1259-63 the pulsed radio emission disappears for about 40 days around periastron. LS I $+61^0$ 303 is much more compact binary (orbital period is ~ 50 times shorter) and the absorption is strong throughout all orbital cycle. Since the compact component is, most likely, a neutron star, the system is not a good candidate for a Be/black hole binary.

4.1.2 LS 5039

This binary of the orbital period 3.9 d consists of an O6.5((f)) star and a compact object the nature of which is still a subject of controversy. No pulsations were detected neither in the X-ray nor in the radio emission. Both X-ray and TeV emission are modulated with the orbital period. The radio emission is variable but the flux is not modulated with the orbital phase. The morphology of the radio emission (which has an elongated shape) is variable with the orbital phase but the positional angle, at first look, seems to be roughly constant (Moldon et al. 2012). This would not be a typical "comet tail" behavior observed in PSR B1259-63 and in LS I $+61^0$ 303. However, analyzing more subtle changes in radio morphology and modeling radio emission with colliding winds model, Moldon et al. (2012) demonstrate that the observed radio emission is compatible with the presence of a young non-accreting pulsar in the system. The authors obtain the best fit for a relatively high inclination of the orbit ($i \approx 70^0$). As they note, this value has deep implication for the estimate of the mass of the compact component.

Radial velocities of LS 5039 (the optical component) were measured by Casares et al. (2005). Assuming pseudo-synchronization at periastron, they got $i \approx 20^0$ for the inclination of the orbit and $M_\mathrm{X} = 4.0 \div 7.3$ $\mathrm{M}_\odot$ for the mass of the compact component. This value clearly indicates a black hole. However, using the same radial velocities with the inclination derived by Moldon et al. (2012), one gets only $M_\mathrm{X} = 1.3 \div 2.7$ $\mathrm{M}_\odot$ for the mass of the compact component. This value corresponds to a neutron star and is compatible with the observed variability of radio morphology. It seems, that at present we cannot firmly establish the nature of the compact component. The black hole still cannot be excluded but its presence became somewhat doubtful.

Even if the presence of a black hole in the system would be confirmed, it is clear that the stellar component is not a Be star and therefore the system is not a good candidate for a Be/black hole binary.

4.1.3 MAXI J1836-194

This system was discovered as an X-ray source by MAXI in August 2011 (Negoro et al. 2011). Further observations strongly suggested that the system contains an accreting black hole (spectral states, timing characteristics, ejection of a radio jet). However, to classify the system as a Be/black hole binary, we need a second ingredient − namely a Be component. Initially, it seemed that it is indeed present in the system. Cenko et al. (2011) after spectroscopical observations of the optical counterpart with the 8 m Gemini South telescope concluded that it is a Be star. This finding was questioned by Rau et al. (2011), who noted that the archival search of Kennea et al. (2011) indicates that the optical counterpart undergoes outbursts of at least 4-5 magnitudes which is very unlikely for a Be star. Subsequent spectroscopical observations were made by Pakull & Motch (2011) who used VLT UT1 telescope. They found that the optical spectrum is not that of a Be star.

In this way, MAXI J1836-194 joined the ranks of unsuccessful candidates.

4.2 The first successful candidate

4.2.1 MWC 656

This system was first discovered by AGILE as a gammma-ray source AGL J2241+4454 (Williams et al. 2010). The discovery paper identified the optical counterpart as a Be star HD 215227 (known also under the name MWC 656) and determined the orbital period as equal 60.37 d. The nature of the optical component (of spectral type B1.5-2IIIe) permits no doubts − it is a Be star. The nature of the compact component was not established until very recently. Casares et al. (2012) measured the amplitude of the radial velocities of MWC 656 and its rotational broadening obtaining 41.7 ± 6.8 km/s and 346 ± 10 km/s respectively. Next, they analyzed Fe II lines reflecting the the Keplerian rotation in the excretion disc around Be star and under some assumptions estimated the inclination of the orbit as $i = 67 \div 80^0$. Finally, they estimated the mass of the compact component to be in the range 2.7 to 5.5 $\mathrm{M}_\odot$. This range suggested rather a black hole but a neutron star could not be excluded. Taking into account the overall low precision of this estimate, the nature of the compact component remained undecided. Authors made more observations and published their analysis in a most recent paper in Nature (Casares et al. 2014). This time they got two sets of radial velocities: they measured the accretion disc emission line He II 4686 reflecting the orbital motion of the compact component and they improved the measurements of radial velocities of Be star by using sharp Fe II lines of the equatorial excretion disc. As a result they could come to a firm conclusion that the compact component is a black hole of the mass 3.8 to 6.9 $M_\odot$. In this way the first Be/black hole binary was finally found!

The authors noted that the system seems to be X-ray quiescent ($L_x < 10^{32}$ erg/s). This led them to a general comment that due to lack of a solid surface and a very low mass transfer rate (leading to extremely long outburst recurrence periods), Be binaries with black hole companions might be difficult to detect by conventional X-ray surveys. After completing their work, the authors requested and obtained observing time with XMM Newton. They found that the system emits X-rays, after all (Munar-Adrover et al. 2014), but at a very low level $L_x \approx 3.7 \times 10^{31}$ erg/s, similar to the quiescent luminosity of black hole X-Ray Novae. This result does not change their conclusions.

5 Summary

During our conference, the statistics of Be X-ray binaries in our Galaxy indicated that we know 72 such systems. Among them, 48 contain a confirmed neutron star and none, so far, is known to contain a black hole. The stellar population synthesis calculations (Belczyński & Ziółkowski 2009) indicate that the expected ratio of Be X-ray binaries with neutron stars to the ones with black holes, $F_{NS/BH}$ is equal ~ 54. This ratio implies that, if we know 48 neutron star systems, then the expected number of black hole systems should be just one. Few months after the conference this one system was just found! It is a binary AGL J2241+4454/MWC 656.

The problem for Magellanic Clouds remains unsolved (8 expected black hole Be X-ray binaries and none observed).

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