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Population of Galactic black holes

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Abstract. Three classes of galactic black holes (BHs): supermassive, intermediate mass and stellar mass ones are briefly reviewed. The recent radio observations of our only supermassive black hole (Sgr A*) permitted us to see (for the first time) the structures on the scale of the event horizon. The evidence for the presence of the intermediate mass black holes in the centers of globular clusters is now somewhat weaker than one year ago (but their presence is entirely possible). There are no new BH candidates (BHCs) from microlensing events (still only 4 are known). A black hole of mass $\gtrsim 10.4$ M$_\odot$ is probably present in triple system V Pup and BHCs are suspected among invisible components of some W-R binaries. Most information about stellar mass BHCs comes still from X-ray binaries (XRBs), which contain 58 BHCs (among them 23 confirmed BHs with mass estimates). Ten BHs have now spin determinations based on modeling the shape of Kα lines and five BHs have spin estimates from fits to the continuum X-ray spectra. Majority of the spin estimates indicate fast or very fast rotation of the investigated BHs. The last chapter of my review is devoted to the mystery of the apparently missing population of XRBs composed of a Be star and a BH. With the help of the most recent stellar population synthesis calculations, it is shown that, at present, the expected number of such systems (1 ± 1) is consistent with the observed number (zero).

Key words. Stars: stellar population synthesis – Stars: binaries – Stars: X-ray binaries – Stars: Be X-ray binaries – Stars: black holes – Stars: neutron stars – Galaxy: globular clusters – Galaxy: Sgr A*

1. Introduction

Our Galaxy contains one supermassive black hole (BH) – Sgr A*. The evidence is, in this case, extremely robust. Our Galaxy contains probably few to few tens of intermediate mass BHs in centers of some globular clusters. The evidence is far from being robust and, in fact, it became weaker during last year. And, finally, our Galaxy contains 10^8 to 10^9 stellar mass BHs. While the total number is only a very rough estimate, the existence of large number of stellar mass BHs (both solitary and as members of binary systems) remains beyond any reasonable doubt.

In this presentation, I will briefly review all three classes of galactic BHs. I will only very briefly summarize the facts known already for some time and will concentrate on new developments for each class. In the last section of my review I will discuss the mystery of the apparently missing population of XRBs composed of a Be star and a BH.

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2. Sgr A*

The most recent estimate of the mass of black hole in the center of our Galaxy is based on new precise astrometric and radial velocities determination of the orbit of the star S-02 and is equal $(4.5 \pm 0.4) \times 10^6$ $M_\odot$ (Ghez et al., 2008). The present level of activity of Sgr A* is extremely low – its luminosity is only ~ 10^{33} erg/s (time-averaged energy of occasional weak X-ray and IR flares). However, in the recent past Sgr A* was substantially brighter. Only ~ 300 years ago, its luminosity was by six orders of magnitude higher than it is now (Murakami et al., 2003). The evidence of this activity comes from the nearby X-ray reflection nebula Sgr B2 which is still glowing due to past irradiation from then much brighter Sgr A* (Murakami et al., 2000).

Considering the new results, one should certainly mention the recent radio observations at 1.3 mm (Doeleman et al., 2008). For the first time, the size of the radio image of Sgr A* was resulting not from interstellar scattering, but was reflecting the true size of the source. In this way, it was possible (again, for the first time in the history) to see the structures on the scale of the event horizon! The radio image obtained by Doeleman et al. has an ellipsoidal shape with the major axis equal 37^{+16}_{-10} μas. The angular diameter of the event horizon of Sgr A* at the distance of the galactic center (8 kpc) should be equal ~ 20μas. However due to light bending, the apparent size of the event horizon for a distant observer should be equal ~ 52μas for non-rotating BH or ~ 45μas for maximally rotating BH. Doeleman et al. conclude that the emission from Sgr A* is not exactly centered on a BH (it might be e.g. the base of the jet or a part of the disc). Yuan et al. (2009) calculated the images for disc emission close to the event horizon assuming radiatively inefficient advection flow. Their conclusion is that either the disc is highly inclined or Sgr A* is rotating fast.

3. Intermediate mass BHs

Since there are no ultraluminous X-ray sources in our Galaxy, the only place one may search for intermediate mass BHs (IMBHs) are globular clusters (GCs). It was a general consensus during the last few years that some galactic GCs contain black holes at their centers. This opinion was based mainly on modeling of gravitational fields of central regions of these clusters. The modeling, in turn, was based on the the analysis of the brightness profiles of these regions. It was found that a useful parameter during the preliminary analysis of the brightness profiles is the ratio of core radius to the half mass radius r_c/r_h. Trenti (2006) analyzed the dynamical evolution of a GC under a variety of initial conditions. She found, that for a cluster consisting initially from single stars only, the final (after relaxation) value of r_c/r_h was ~ 0.01, for a cluster containing 10 % of binaries this value was ~ 0.1, but for the cluster containing an IMBH the value of r_c/r_h was ~ 0.3. These results confirmed earlier conclusions that IMBH clusters have expanded cores. Trenti considered subsequently 57 dynamically old (relaxed) GCs and found that for at least half of them the value of r_c/r_h is $\gtrsim 0.2$, which implies the presence of an IMBH. It was concluded, therefore , that a substantial fraction of old GCs contains IMBHs. This conclusion was supported by the finding (Gebhardt et al., 2002), that GCs obey the relation (or, rather, an extension of it) between the velocity dispersion in the core and the mass of the central BH, found earlier for the galaxies. The detailed analysis of the brightness profiles was used to obtain quantitative estimates of the masses of the probable central BHs in some GCs. The leading candidates were M15 (~ 2000 $M_\odot$, Gerssen et al., 2003) and ω Cen (~ 50 000 $M_\odot$, Noyola et al., 2006).

Recently, the case for IMBHs in some GCs became weaker after Fregeau at al. (2009) carried out the analysis of the white dwarf (WD) populations in GCs. Their analysis suggests that WDs receive a kick of a few km/s shortly before they are born. The effect of this kick is the increase of both r_c/r_h and velocity dispersion. As a result, at the moment, no globular cluster requires an IMBH at its center. This, of course, does not mean that there are no central BHs in some GCs, but the case for their presence is now far from being robust.

4. Stellar mass BHs

4.1. BH candidates from microlensing events

Microlensing events are, at present, the only method of detecting solitary stellar mass BHs. The method is based on mass estimates for the lensing objects. Such estimates are possible only for so called ”paralax events”. These are the events that are long enough to show the magnification fluctuations, reflecting the orbital motion of the Earth around the Sun. This effect permits to calculate the ”microlensing parallax” which is a measure of the relative transverse motion of the lens with respect to the observer. Assuming standard model of the Galactic velocity distribution, one is then able to perform a likelihood analysis, which permits to estimate the distance and the mass of the lens. With the help of the above analysis, some long events might be selected as, possibly, caused by black hole lenses. The list of such candidates did not change during the last few years. It still contains only four events: MACHO-96-BLG-5 (probable mass of the lens $\sim 3 \div 16$ $M_\odot$, Bennett et al., 2002a), MACHO-98-BLG-6 (probable mass of the lens $\sim 3 \div 13$ $M_\odot$, Bennett et al., 2002a), MACHO-99-BLG-22 = OGLE-1999-BUL-32 (probable mass of the lens $\sim$ 100 $M_\odot$, Bennett et al., 2002b) and OGLE-SC5-2859 (probable mass of the lens $\sim 7 \div 43$ $M_\odot$, Smith et al., 2003).

4.2. BHs in non-X-ray binaries

There are rather few binaries that are not X-ray emitters and still might be suspected of harboring a black hole. The evidence comes, in such cases, from mass functions indicating presence of a massive but unseen member of the system. There are some W-R stars with massive unseen companions, that are mentioned on this occasion (Cherepashchuk, 1998). Quite recently, analysis of a well known binary V Pup (Qian et al., 2008) indicated that the system is probably a triple, and that the third unseen companion is, most likely, a black hole.

4.2.1. WR + unseen companion binaries

About 20 such binaries are known (Cherepashchuk, 1998). Most of them have high values of z-altitude over the Galactic plane, which might indicate that they survived supernova explosion. If so, then unseen companions must be relativistic objects. Their mass estimates derived from the mass functions indicate that at least some of them must be black holes. The strongest case is the binary CD-45^{o}4482 (the lower mass limit of the unseen companion, estimated from radial velocities of WR star, is 5.5 $M_\odot$.

4.2.2. V Pup

Binary system V Pup is known as a high mass eclipsing binary with orbital period 1.45 days and masses of the components equal 15.8 and 7.8 $M_\odot$. However, the orbital solution is not sufficiently accurate, since it produces residuals in the form of cyclic orbital period oscillation with periodicity of 5.47 years. If these residuals are interpreted as caused by an unseen third body, then the mass of this body (orbiting the close pair in 5.47 years) must be $\gtrsim$ 10.4 $M_\odot$ (Qian et al., 2008). It is likely, that this body is a black hole.

4.3. BHs in X-ray binaries

X-ray binaries (XRBs) are still the main source of information about the stellar mass BHs. At present, the list of XRBs harboring BH candidates (BHCs) contains 58 objects. We include here the controversial systems CI Cam and Cyg X-3. Among these 58 binaries, there are 23 containing confirmed BHs with dynamical mass estimates. Here, we include the well known TeV binary LS 5039, although both the interpretation of the mass function and the true nature of the compact object became controversial recently.

If we consider the distribution of BHCs between the class of high mass XRBs (HMXBs) and low mass XRBs (LMXBs), then we find 50 BHCs in LMXBs and only 8 in HMXBs. For confirmed BHs the numbers are: 17 BHs in LMXBs and 6 BHs in HMXBs.

It is also worth to note that 13 BHCs are microquasars (9 in LMXBs and 4 in HMXBs).

4.3.1. Masses of stellar mass BHs

The range of masses did not change recently. Still, the lightest BHs have masses $\sim 4\ M_\odot$ (GRO J0422+32, $M \approx 4 \pm 1\ M_\odot$ (Filippenko et al., 1995; Orosz, 2003); GRS 1009-45, $M \approx 4.4 \div 4.7\ M_\odot$ (Filippenko et al., 1999)) and the heaviest have masses $\sim 15 \div 20\ M_\odot$ (Cyg X-1, $M \approx 20 \pm 5\ M_\odot$ (Ziolkowski, 2005); SS 433, $M \approx 16 \pm 3\ M_\odot$ (Blundell et al., 2008); GRS 1915+105, $M \approx 14 \pm 4.4\ M_\odot$ (Greiner et al., 2001)).

During discussion of the low mass BHs, the question of the Oppenheimer-Volkoff mass (the largest possible mass for a NS) inevitably shows up. During the last two decades there was almost no progress in this area. Theoretical estimates ($1.4 \div 2.7\ M_\odot$) remained highly uncertain (we still do not know the proper equation of state) and the measured values were all consistent with the mass not greater than $\sim 1.4\ M_\odot$. However, recently, new developments took place in the area of observational measurements. First, a substantially higher than any before, mass of a NS was measured with great precision (PSR J1903+0327, $M = 1.67 \pm 0.01\ M_\odot$, (Champion et al., 2008)). Second, an even much more massive NS was probably found (NGC 6440B, Freire et al., 2008). The precise value of its mass is not yet available, but the most likely value was given as $\sim 2.7\ M_\odot$. There is a very good chance (99% probability) that the mass is $> 2\ M_\odot$. The problem will be definitely solved over the next few years, with the more timing data. The outcome might be very exciting.

4.3.2. Spins of stellar mass BHs

There are three basic methods of deducing the spin of an accreting black hole. They are: modeling of spectral energy distribution in X-ray continuum, modeling of the shape of the X-ray Fe Kα line and the interpretation of the high frequency quasi-periodic oscillations (kHz QPOs). The resulting spin estimates are usually expressed with the help of a dimensionless angular momentum parameter a_*, where $a_* = 0$ corresponds to non-rotating (Schwarzshild) black hole and $a_* = 1$ corresponds to maximally prograde (i.e. in the same direction as accretion disc) rotating black hole.

Table 1. Spin estimates based on modeling of X-ray continuum

Name	a_*
LMC X-3	< 0.26
GRO J1655-40	$0.65 \div 0.80$
4U 1543-47	$0.70 \div 0.85$
LMC X-1	$0.81 \div 0.94$
GRS 1915+105	> 0.98

• **Spectral energy distribution (X-ray continuum)**

Zhang et al. (1997) were the first to discuss the X-ray emission from the discs around rotating black holes (Kerr BHs). They found the evidence of rapid rotation for two galactic microquasars: GRO J1655-40 (the dimensionless angular momenta (spin parameter) $a_* \approx 0.93$) and GRS 1915+105 ($a_* \approx 1.0$). In recent years, a very careful and detailed analysis was performed by McClintock and his collaborators. In a series of papers (Shafee et al. (2006), Davis et al. (2006), McClintock et al. (2006), Gou et al. (2009)) they made spectral fits for five X-ray binaries. Their results (shown in Table 1) represent the present state of art in this field and might be considered quite reliable.

• **Modeling of the X-ray Fe Kα line**

The broad Fe Kα lines are observed in the spectra of the growing number of X-ray binaries (the most recent summary is given by Miller et al., 2009). These lines are believed to originate in the innermost regions of the discs due to their irradiation by a source of hard X-rays (most likely a Comptonizing corona). If, due to rapid rotation of BH, the disc extends to smaller radius than it would be possible for non-rotating BH, then the line is expected to be more redshifted and more distorted. The modeling of the shape of Fe Kα line produced re-

Table 2. Spin estimates based on modeling of Fe Kα line

Name	a_*
Cyg X-1	0.05 (1)
4U 1543-47	0.3 (1)
SAX J1711.6-3808	0.2 ÷ 0.8
SWIFT J1753.5-0127	0.61 ÷ 0.87
XTE J1908+094	0.75 (9)
XTE J1550-564	0.76 (1)
XTE J1650-500	0.79 (1)
GX 339-4	0.94 (2)
GRO J1655-40	0.98 (1)
GRS 1915+105	0.98 (1)

NOTE:

The number in parenthesis shows the uncertainty of the last digit.

sults that are generally similar to, but not fully consistent with results obtained from the X-ray continuum fits. The results summarized by Miller et al. (2009) together with the most recent result from Blum et al. (2009) are shown in Table 2.

• **High frequency quasi-periodic oscillations (kHz QPOs)**

No new results were obtained in this area during the recent years. The situation remains as reviewed by me last year (Ziolkowski, 2009).

5. The mystery of the apparent lack of Be X-ray binaries with BHs

In this section I will discuss the mysterious case of the apparently missing population of XRBs composed of a Be star and a BH. At present, 138 XRBs containing a Be star as an optical component are known in the Galaxy and the Magellanic Clouds. In 89 of them the compact component is a confirmed NS (seen as an X-ray pulsar). However, not a single Be/black hole (Be/BH) binary was found so far. This ratio (89:0) is especially striking, if we take into account, that in other (non-Be) XRBs, the ratio of NSs to BHs is only 2:1). Belczynski & Ziolkowski (2009) carried out the calculations of stellar population synthesis (SPS) to try to understand the reasons for this disparity.

5.1. Introduction to Be XRBs

The binary systems composed of a Be star and a compact object (Be XRBs) form the most numerous class of XRBs in our Galaxy and the Magellanic Clouds (138 such systems are known, at present, which is about one third of all XRBs). These systems contain a relativistic object (a NS or a BH) orbiting a Be type star on a rather wide (orbital periods in the range of ∼ 10 to ∼ 650 days), frequently excentric, orbit. In 89 of these systems, the compact component is known to be a NS. The NS has a strong magnetic field and is observed as an X-ray pulsar (with the spin periods in the range of 34 ms to about 1400 s). The Be component is deep inside its Roche lobe. The fact that Be star is much smaller than its Roche lobe is a distinct property of Be XRBs. In almost all other types of XRBs, the optical component always fills or almost fills its Roche lobe (even if the accreted matter is supplied by the winds). The relatively efficient mass accretion on a NS is possible (in spite of wide orbit) due to presence of an excretion disc around Be star.

X-Ray emission from Be XRBs (with a few exceptions) has distinctly transient nature with rather short active phases separated by much longer quiescent intervals (a flaring behaviour). There are two types of flares, which are classified as Type I outbursts (smaller and regularly repeating) and Type II outbursts (larger and irregular). Type I bursts are observed in systems with highly eccentric orbits. They occur close to periastron passages of NS. 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 (∼ few to few tens of years). This recurrence time scale is generally much longer than the orbital period.

It is well known now that Be/NS systems contain two quasi-Keplerian ($V_{\rm rad}/V_{\rm orb} \lesssim 10^{-2}$) discs: excretion disc around Be star and accretion disc around neutron star. Both discs are temporary: excretion disc disperses and refills on time scales ~ few to few tens of years (dynamical evolution of the disc, formerly known as the "activity of a Be star"), while accretion disc disperses and refills on time scales ~ weeks to months (which is related to the orbital motion on an eccentric orbit and, on some occasions, also to the major instabilities of the other disc). Accretion disc might be absent over a longer period of time (~ years), if the other disc is very weak or absent. The X-ray emission of Be/X-ray 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.

At present, 64 Be XRBs are known in the Galaxy (42 of them contain a confirmed NS). The Magellanic Clouds, which have much smaller (by two orders of magnitude) stellar population than the Galaxy, contain even more (74) Be XRBs. In 47 of them, the compact object is a confirmed NS.

For more information on Be XRBs, the reader is referred to Belczynski & Ziolkowski (2009) and references within.

5.2. Definition of a Be XRB for the purpose of SPS calculations

The most characteristic observational property of Be stars distinguishing them from other B stars is the presence of excretion discs producing the characteristic emission lines. The underlying cause of the presence of this disc is, in turn, rapid rotation. In the context of XRBs, the presence of an excretion disc is crucial, because it permits the relatively efficient accretion on the compact companion, even in the case of large orbital separation. It is not clear how Be stars achieved their fast rotation. One of hypothesis suggests a spin-up due to binary mass transfer or even due to merger, another advocates rapid rotation at birth (see e.g. McSwain & Gies, 2005). The fraction of Be stars among all B stars is similar for single stars and for those in binary systems (one fifth to one third).

For the purpose of our calculations, we assumed, for simplicity, that one quarter of all B stars are always Be stars and that these stars are always efficient mass donors, independently of the size of the binary orbit (as is, in fact, observed in Be/NS XRBs). Therefore, according to our definition, a Be XRB is a system composed of a compact object (NS or BH) and a main sequence B star (and we apply a factor 0.25 to the number of such systems, to account for the fact that not every B star is a Be star). Further, we assume that the mass of our B star should not be smaller than 3 $M_\odot$ in order to qualify our system as a Be XRB (the estimated masses of observed Be stars cover the range from ~ 2.3 $M_\odot$ (Lejeune & Schaerer, 2001) to ~ 25 $M_\odot$ (McSwain & Gies, 2005)). Finally, we take into account only systems with orbital periods in the range $10 \leq P_{\rm orb} \leq 300$ days (in agreement with the range found for observed galactic Be XRBs).

5.3. Calculations

We used the most recent version of SPS code `StarTrack` (Belczynski et al. 2008, Belczynski et al. 2009a). This version treats especially carefully the evolution of binary stars. It also employs a physical model to delineate the formation of NSs from the formation of BHs. This element of the code plays an important role in determining the expected number of Be XRBs with different accretors. Therefore, we do not assume some critical value of the initial mass of the star separating the progenitors of NSs and BHs (as most SPS codes do). Instead, we follow the evolution of a given star, note the final mass of its FeNi core and then we use the results of hydro core-collapse simulations to estimate the mass of the compact object a given star forms. Once we have the mass of a compact object we use the maximum NS mass (assumed to be

2.5 $M_\odot$) to tell apart neutron stars from black holes. The full description of this scheme is given in Belczynski et al. (2008; and see the references within). As it happens, our scheme (for single stars) results in the black hole formation for $M_{ZAMS} > 20$ $M_\odot$ (see Belczynski et al. 2009b).

5.4. Conclusions

The calculations carried out with the standard version of `StarTrack` code predict the ratio of the expected number of Be/NS XRBs to the expected number of Be/BH XRBs in our Galaxy equal 27.

This standard version assumes that the natal kicks compact objects receive at birth are described by a Maxwellian with σ = 265 km s^{-1} for neutron stars that are formed in regular core-collapse supernovae. This value is based on the radio pulsar birth velocity distribution derived by Hobbs et al. (2005). Natal kicks for black holes are decreased proportionally to the amount of fall back expected during core collapse/supernova explosion (e.g. Fryer 1999; Fryer & Kalogera 2001). However, there are some indications that kicks neutron stars receive at birth are smaller for stars in binaries as compared to single stars (e.g. Podsiadlowski et al. 2004, Belczynski et al. 2009b). Therefore, we carried out also calculations with smaller natal kicks, described by a Maxwellian with σ = 133 km s^{-1}. These calculations predict the ratio of the expected number of Be/NS XRBs to the expected number of Be/BH XRBs in our Galaxy equal 54.

To conclude: according to our calculations, the expected ratio $N_{\rm Be/NS}/N_{\rm Be/BH}$ for our Galaxy is $\sim 30 \div 50$. Since the observed number of Be/NS systems $N_{\rm Be/NS}$ is equal 42, then the expected number of Be/BH systems $N_{\rm Be/BH}$ should be 1 ± 1, which is consistent with the observed number (zero). Therefore, there is no problem with missing Be XRBs with BHs in the Galaxy.

We plan to carry out a similar study of Be XRBs in Magellanic Clouds, taking into account the different star formation history and different metallicity of these galaxies.

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