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POPULATION OF BLACK HOLES IN THE MILKY WAY AND IN THE MAGELLANIC CLOUDS

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Abstract. In this review, I will briefly discuss the different types of black hole (BH) populations (supermassive, intermediate mass and stellar mass BHs) both in the Galaxy and in the Magellanic Clouds and compare them with each other.

Keywords: stars: binaries, stars: X-ray binaries, stars: black holes, black holes: masses, black holes: spins, individual: SgrA*.

1. Introduction

Our Galaxy (MW) contains one supermassive BH (SgrA*), a small number (between zero and a few tens) of intermediate mass BHs (IMBHs) and about 10^7 to 10^8 stellar mass BHs (SM BHs). The Magellanic Clouds (MCs) contain no supermassive BHs and, most likely, no IMBHs. The number of SM BHs in MCs is not well estimated but it is possibly smaller than the number inferred from the the relative mass of the MCs with respect to the MW (~ 0.1): 10^6 to 10^7. In this review, I will briefly discuss all three classes of BHs and compare their populations in the MW and in the MCs.

2. SgrA*

The evidence for the existence of supermassive BH in the center of MW is extremely robust. The most recent estimate of the mass of SgrA* is based on new precise astrometric and radial velocity determination of the orbit of the star S-02 and is equal $(4.5 \pm 0.4) \times 10^6\,M_\odot$ [20]. The present level of activity of SgrA* is extremely low – its luminosity is only $\sim 10^{33}$ erg/s (time-averaged energy of occasional weak X-ray and IR flares).

Recent radio observations at 1.3 mm [11] permitted us, for the first time in history, to see the structures on the scale of the event horizon. For the first time, the size of the radio image of SgrA* did not resulting from interstellar scattering, but reflected the true size of the source. The radio image obtained by Doeleman et al. was ellipsoidal shape with the major axis equal 37^{+16}_{-10} µas. The angular diameter of the event horizon of SgrA* at the distance of the galactic center (8.4 kpc) should be equal to ~ 20 µas. However due to light bending, the apparent size of the event horizon for a distant observer should be equal to ~ 52 µas for non-rotating BHs or ~ 45 µas for maximally rotating BHs. Doeleman et al. concluded that the emission from SgrA* 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. [43] 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 SgrA* is rotating fast.

Recently, a gas cloud on a collision course with SgrA* was discovered [6, 21]. The dusty gas cloud has a mass of $\sim 1.7 \times 10^{28}$ g (about 3 Earth masses) and an estimated temperature of ~ 550 K (from the fact that it is seen in the L but not in the K infrared band). The cloud moves along an elliptic orbit with the eccentricity of 0.94 ± 0.01 and an orbital period of 137 ± 11 yr. The pericentre distance from the BH is rather large: 3140 ± 240 Schwarzshild radii. However, the cloud will not survive the pericentre passage which will occur in the middle of 2013. The cloud evolution simulations [6] indicates that it will be disrupted by the tidal forces and its content will fall onto the central BH. It is estimated the X-ray luminosity SgrA* will reach the level of $\sim 10^{34}$ erg/s, or one order of magnitude higher than it is today. Since we will be able to resolve the emission region, we may expect to obtain interesting information about the processes taking place in the immediate vicinity of the event horizon.

This burst, which we will witness in about one year, will, however be much weaker than the burst which happened about 300 years ago: the activity of SgrA* was then so high, that its luminosity was by six orders of magnitude higher than it is now [29]. The evidence of this activity comes from the nearby X-ray reflection nebula SgrB2 which is still glowing due to past irradiation from then much brighter SgrA* [28].

3. Intermediate mass BHs

There are no ultraluminous X-ray sources (ULXs) in the MW (nor in the MCs). Therefore, the only place one may search for IMBHs as in globular clusters (GCs). Until recently, there was a general consensus 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 [42] analyzed the dynamical evolution of a GC under a variety of initial conditions. She found, that for a cluster consisting initially of 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 subsequently considered 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 contain IMBHs. This conclusion was supported by the finding [18], 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 [13]. 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 ($\sim 2000\,M_\odot$, [19]) and ω Cen ($\sim 50\,000\,M_\odot$, [30]).

Recently, the case for IMBHs in some GCs became weaker after Fregeau at al. [16] 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 an increase in 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.

No attempt has so far been made to search for possible IMBHs in the MCs GCs.

3.1. A ULX in a Globular Cluster?

At the end of this section, I should mention an object that might be a ULX in the GC. This object is a bright X-ray source in the unnamed GC which belongs to the Virgo Cluster giant elliptical galaxy NGC 4472 [25]. The source luminosity is $\sim 4 \times 10^{39}$ ergs/sec (which corresponds to a mass of $\sim 25 \div 30\,M_\odot$, if the source emits at the Eddington level). The source exhibits X-ray luminosity variability by a factor of 7 in a few hours, which excludes the possibility that the object is several neutron stars superposed. As the X-ray luminosity of massive X-ray binaries is, typically, substantially smaller than the Eddington luminosity, the mass of the compact object might be significantly higher than the lower limit, given above. It seems likely that the GC in question contains a ULX, that harbors a fairly massive BH (although, perhaps, not an IMBH).

4. Stellar mass BHs

4.1. BH candidates from microlensing events

Microlensing events are, at present, the only method for detecting solitary stellar mass BH candidates (BHCs). 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 the standard model of the Galactic velocity distribution, we are 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 has not changed in the last few years. It still contains only four events: MACHO-96-BLG-5 (probable mass of the lens $\sim 3 \div 16\,M_\odot$, [1]), MACHO-98-BLG-6 (probable mass of the lens $\sim 3 \div 13\,M_\odot$, [1]), MACHO-99-BLG-22 = OGLE-1999-BUL-32 (probable mass of the lens $\sim 100\,M_\odot$, [2]) and OGLE-SC5-2859 (probable mass of the lens $\sim 7 \div 43\,M_\odot$, [39]).

Paczyński [32] promised a substantial increase of the number of possible BH lenses in some 2–3 years since the start of OGLE III project. OGLE III (which started in 2001) was predicted to detect more than 500 events per year and, among them, some 20–30 parallax events. Paczyński expected that a few of them (per year) should be BHCs. However, no new firm detections were reported until end of OGLE III project (2009). Fortunately, OGLE IV project (which started in 2010) detected several long events. These events are now analyzed and supported with supplementary HST observations. There is a hope that the list of possible BH lenses will increase in near future.

4.2. BHs in non-X-ray binaries

There are rather few binaries that are not X-ray emitters but that still might be suspected of harboring a black hole. In such cases, the evidence comes 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 [8]. There are some low mass binaries, in which the observed component displays ellipsoidal type variability due to tidal action of the unseen massive companion (in some cases, possibly, a BH [35]). Quite recently, analysis of a well known binary V Pup [33] 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 [8]. Most of them have high z-altitude values 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°4482 (the lower mass limit of the unseen companion, estimated from radial velocities of WR star, is $5.5\,M_\odot$.

4.2.2. Binaries with ellipsoidal type variability caused by the presence of an unseen massive companion

Sądowski et al. [36] indicated that BHs might be detected in some pre-XRBs. These are the systems in which the mass transfer has not yet started, but the optical component is large enough (with respect to its Roche lobe) to be tidally distorted by its massive unseen companion. The photometric light curve of this system exhibits the characteristic ellipsoidal type variability. Różyczka et al. [35] investigated 11 objects in globular clusters ω Centauri and NGC 6397. These objects were selected photometrically, on the basis of their ellipsoidal type variability. The objects were, subsequently, observed spectroscopically in search for the radial velocities. As a result of these observations, ten of them were found to be binaries. Further analysis indicated that the system named V36 (in NGC 6397) contains an unseen degenerate companion with the mass in the range $2 \div 4\,M_\odot$. It might be either a heavy NS or a light BH.

4.2.3. V Pup

Binary system V Pup is known as a high mass eclipsing binary with on orbital period of 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 $\gtrsim 10.4\,M_\odot$ [33]. 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 stellar mass BHs. At present, the list of XRBs harboring BH candidates (BHCs) contains 64 objects (62 in MW and 2 in MCs). We include here the controversial system CI Cam, although it might appear that it contains a white dwarf and not a BH (both classes of sources have very soft X-ray spectra). Among these 64 binaries, there are 24 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 has recently become controversial. We include also the celebrated system CygRX-3, although its mass estimate only marginally indicates the presence of a black hole (but there are other arguments in favor of its BH nature).

If we consider the distribution of BHCs between the class of high mass XRBs (HMXBs) and low mass XRBs (LMXBs), then we find 56 BHCs in LMXBs (all in MW) and only 8 in HMXBs (6 in MW and 2 in MCs). For confirmed BHs the numbers are: 17 BHs in LMXBs and 7 BHs in HMXBs (5 in MW and 2 in MCs).

It is also worth to note that 14 BHCs are microquasars (all of them in MW: 9 in LMXBs and 5 in HMXBs).

4.3.1. Masses of stellar mass BHs

The smallest mass of a probable BH ($\sim 2.5\,M_\odot$) was recently found for Cyg X−3 [44]. Unfortunately, this estimate is not very precise (the permitted value of the mass is in the range 1.3 to $4.5\,M_\odot$). Moreover, one should remember that many, wildly different, estimates of the mass of the compact object in Cyg X−3 were given earlier in the literature (one recent estimate was by Shrader et al. [38]). The estimate by Zdziarski et al. is not the last word in this area.

If we consider the more precise determinations, then we find that the range of the masses has not changed recently. Still, the lightest BHs have masses $\sim 4\,M_\odot$ (GRO J0422+32, $M \approx 4 \pm 1\,M_\odot$ [14, 31]; GRS 1009−45, $M \approx 4.4 \div 4.7\,M_\odot$ [15]) and the heaviest have masses $\sim 16\,M_\odot$ (SS 433, $M \approx 16 \pm 3\,M_\odot$ [4]; Cyg X−1, $M \approx 16 \pm 3\,M_\odot$ [47]; GRS 1915+105, $M \approx 14 \pm 4.4\,M_\odot$ [24]).

During discussion of the low mass BHs, the question of the Oppenheimer–Volkoff mass (the largest possible mass for a NS) inevitably shows up. Theoretical estimates ($1.4 \div 2.7\,M_\odot$) remain highly uncertain (we still do not know the proper equation of state). There has, however, been progress in observational measurements. Until quite recently, the measured values were all consistent with the mass not greater than $\sim 1.4\,M_\odot$. This is no longer true. The first NS mass substantially higher than $1.4\,M_\odot$ was measured with great precision by Champion et al. [7] (PSR J1903+0327, $M = 1.67 \pm 0.01\,M_\odot$). Then Demorest et al. [10] found (from the general relativistic Shapiro delay) that the mass of the radio pulsar PSR J1614−2230 is equal $1.97 \pm 0.04\,M_\odot$. We should emphasize that this is a high precision determination. Therefore, at present, the upper mass limit for a NSs is $\gtrsim 1.97\,M_\odot$.

That is not the end of the story. A few years ago, Freire et al. [17] analyzed the radio pulsar NGC 6440B (in globular cluster NGC 6440). The mass estimate, as for radio pulsar, is still very imprecise (it is based on only one year of observations). However, it indicates the mass larger than $2\,M_\odot$, with probability greater than 99 %. The most likely value is $2.74\,M_\odot$. The precision of this determination will improve substantially after a few more years of observations. The outcome might be very exciting. If the value in excess of $2.5\,M_\odot$ is confirmed, it would mean a disaster for most of the equations of state for dense matter,

Name	a_*
LMC X−3	< 0.26
XTE J1550−564	$0.34^{+0.37}_{-0.45}$
GRO J1655−40	$0.65 \div 0.75$
4U 1543−47	$0.75 \div 0.85$
LMC X−1	$0.92^{+0.05}_{-0.07}$
Cyg X−1	> 0.95
GRS 1915+105	> 0.98

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

but it would also mean that very heavy NSs do exist. This would make the discrimination between NSs and BHs, based on the mass of the compact object, more difficult, as the light BHs of similar mass ($\sim 2.5\,M_\odot$) can also exist (and Cyg X−3 might be an example).

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 interpenting 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.

Spectral energy distribution (X-ray continuum) Zhang et al. [45] were the first to discuss the X-ray emission from the discs around rotating black holes (Kerr BHs). Using very rough estimates, 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 [9, 22, 23, 26, 37] they made spectral fits for six X-ray binaries. Their results are shown in Tab. 1. The table also contains one determination made by Steiner et al. [41] for the system XTE J1550−564. As we may see, Steiner et al. are less optimistic about the precision of the continuum fit determination than McClintock's group.

Generally, they might be considered rather reliable, with the possible exception of Cyg X−1.

Modeling of 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. [27]). 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. Modeling of the shape of Fe Kα line produced results that are generally similar to, but not fully consistent with, the results obtained from the X-ray continuum fits. Table 2 contains the results summarized by Miller et al. [27] together with the more recent determinations for GRS 1915+105 [3], SWIFT J1753.5−0127 [34], XTE J1550−564 [41], Cyg X−1 [12] and LMC X−1 [40].

Name	a_*
4U 1543−47	0.3 (1)
SAX J1711.6−3808	$0.6^{+0.2}_{-0.4}$
XTE J1550−564	$0.55^{+0.15}_{-0.22}$
GRS 1915+105	$0.56^{+0.02}_{-0.02}$
SWIFT J1753.5−0127	$0.76^{+0.11}_{-0.15}$
XTE J1908+094	0.75 (9)
XTE J1650−500	0.79 (1)
LMC X−1	$0.97^{+0.01}_{-0.13}$
Cyg X−1	$0.97^{+0.014}_{-0.02}$
GRO J1655−40	0.98 (1)

Table 2. Spin estimates based on modeling the Fe Kα line. NOTE: The number in parenthesis shows the uncertainty of the last digit.

High frequency quasi-periodic oscillations (kHz QPOs) QPOs in BH binaries are still not well enough understood and no progress has been made in this area during the recent years. The situation remains as it was when reviewed by me four years ago [46].

Summary of BHs spins Before summarizing of the situation, I have to note that the precision of both principal methods (i.e. the spectra of the discs and the shape of Fe Kα lines) are being questioned. It is indicated that the fitting of the continuum spectra is model-dependent and sensitive to the uncertainties of absorption corrections [9]. As for the shape of the Kα line, the fitting is sensitive to the uncertainty of the continuum level determination (e.g. [5]). The sort of widespread scepticism was supported by the large (sometimes very large) disagreements between the results of the two methods. For example, for Cyg X−1, the continuum fit method gave the result $a_* > 0.95$ [23], but the iron line fitting method gave the result $a_* = 0.05^{+0.01}_{-0.01}$. Fortunately, recently, the results of both methods seem to be converging. Teams using one or another method are joining efforts and publishing joint papers. Sometimes, both methods are used in one paper and the results are compared (Steiner et al. [41] for XTE J1550−564 or Blum et al. [3] for GRS 1915+105).

Having said that and comparing the content of Tabs. 1 and 2 in the context of the history of the topic, one can make the following observations:

Name of the class	MW	LMC	SMC
Total mass of the galaxy (in M_{SMC} units)	100	10	1
HMXRBs	118	26	83
in this BeXRBs	72	19	79
LMXRBs	197	2	–
BHCs	62	2	–

Table 3. Comparison of numbers of different classes of XRBs in the MW and in the MCs.

(1.) Some systems (Cyg X−1, LMC X−1) probably have rotation close to nearly maximal spin ($a_* > 0.9$).

(2.) Several other systems (GRO J1655−40, XTE J1650−500, XTE J1908+094 and SWIFT J1753.5−0127 have large spins ($a_* \gtrsim 0.65$).

(3.) The case of GRS 1915+105 is not decided yet. McClintock et al. [26] got, from continuum fit method, $a_* > 0.98$. Blum et al. [3], from iron line fitting method, got $a_* = 0.56^{+0.02}_{-0.02}$. However, the same authors (Blum et al.), in the very same paper, using continuum fit method, got $a_* = 0.98^{+0.01}_{-0.01}$.

(4.) Not all accreting black holes have large spins (robust (?) result $a_* < 0.26$ for LMC X−3).

(5.) There are still substantial discrepancies between the results of two methods, but they are significantly smaller than a few years ago.

5. Comparison of different classes of XRBs in the MW and in the MCs

Looking at the above table, we may observe in the MCs (in comparison with the MW):

- lack of LMXRBs,
- relative surplus of HMXRBs,
- deficit of BHs.

These differences are real (it would be difficult to attribute them to selection effects). They are, probably, mostly due to a different star formation history in the MCs than in the MW.

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Discussion

Maurice van Putten — As a comment, candidates for low a/M are just as important as those for high a/M, in that they reflect possible lower bounds reflecting interaction between the spin and the inner disk (van Putten, M.H.P.M., 1999, Science, 284, 115).

Janusz Ziolkowski — Yes, thank you for the comment.

Laura Brenneman — Continuum fitting and Fe Kα line groups now working together to make sure. BHs spins measured in Galactic BHBs are consistent between two methods.
Active work to revise both models: to parametrise spectral hardening in continuum fitting and to take into account ionization of disk, thermal X-ray emission of disk in Fe Kα. Fabian, Novak have recently revised Cyg X−1 spin to high values ($a \geq 0.9$) using revised Fe Kαmodels.

Janusz Ziolkowski — Thank you for this comment. It is, certainly, encouraging news.
[Following the referee's suggestion, I have updated the relevant part of the written version of my review talk].