# Masses of Black Holes in the Universe

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**Abstract** The different methods of determination of black holes (BHs) masses are presented for three classes of BHs observed in the Universe: stellar mass BHs, intermediate mass BHs (IMBHs) and supermassive BHs (SBHs). The results of these determinations are briefly reviewed: stellar mass BHs are found in the range of about 3 to about $20\,M_\odot$, IMBHs in the range of a few hundreds to a few tens of thousands $M_\odot$ (the determinations are much less precise for these objects) and SBHs in the range of about $3 \times 10^5\,M_\odot$ to about $6 \times 10^{10}\,M_\odot$.

**Key words:** black holes: mass determination — stars: black holes — intermediate mass black holes — supermassive black holes

## 1 INTRODUCTION

Black holes (BHs) observed in the Universe can be classified into three groups: stellar mass BHs, intermediate mass BHs (IMBHs) and supermassive BHs (SBHs). The case for the existence of IMBHs is still substantially weaker than the case for the two other groups (the existence of which is, practically, beyond any dispute). Therefore, the mass estimates for these two groups are substantially more precise than for IMBHs. This paper is devoted to a brief review of the different techniques used to estimate the masses of BHs and to the brief presentation of the results.

## 2 STELLAR MASS BLACK HOLES

As of today, the stellar mass black holes, essentially, are observed only in the X-ray binaries (XRBs). Only a few rough estimates are available now for single black hole candidates from microlensing events (see the next subsection).

### 2.1 Black Holes in X-Ray Binaries

At present, 58 black hole candidates are known among compact components of XRBs. The masses are determined for 24 of them (see Table 1). Some of these determinations belong to the most precise mass estimates ever derived for any black hole. Below, I briefly summarize the technics used to obtain these estimates.

  • **The mass function**

This is the most important observational parameter used to constrain the mass of the compact component. The mass function $f(M_x)$ is calculated from the radial velocities of the optical companion:

$$f(M_x) = 1.0385 \times 10^{-7} K_{\rm opt}^3 P \, M_\odot, \qquad (1)$$

where $K_{\rm opt}$ is the semiamplitude of the radial velocities of the absorption lines of the optical component (in km s$^{-1}$) and $P$ is the orbital period (in days). The mass function is related to the masses of both components by:

$$f(M_x) = M_x^3 \sin^3 i / (M_{\rm opt} + M_x)^2, \qquad (2)$$

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**Table 1** Masses of Black Holes in X-ray Binaries

| Name | $P_{orb}$ | Opt. Sp | X−r | C | $M_{BH}/M_\odot$ | Ref |
|------|-----------|---------|-----|---|------------------|-----|
| Cyg X−1 | $5^d6$ | O9.7 Iab | pers | $\mu$Q | $20 \pm 5$ | 1 |
| LMC X−3 | $1^d70$ | B3 V | pers | | $6 \div 9$ | |
| LMC X−1 | $4^d22$ | O7−9 III | pers | | $4 \div 10$ | |
| SS 433 | $13^d1$ | $\sim$ A7 Ib | pers | $\mu$Q | $4.4 \pm 0.8$ | 2 |
| LS 5039 | $3^d906$ | O7f V | pers | $\mu$Q | $2.7 \div 5.0$ | 3 |
| XTE J1819−254 | $2^d817$ | B9 III | T | $\mu$Q | $6.8 \div 7.4$ | |
| GX 339−4 | $1^d756$ | F8−G2 III | RT | $\mu$Q | $\gtrsim 6$ | 4 |
| GRO J0422+32 | $5^h09$ | M2 V | T | | $4 \pm 1$ | |
| A 0620 − 00 | $7^h75$ | K4 V | RT | | $11 \pm 2$ | |
| 2S 0921 − 630 | $9^d01$ | K0 III | pers | | $1.7 \div 4.3$ | 5,6 |
| GRS 1009 − 45 | $6^h96$ | K8 V | T | | $4.4 \div 4.7$ | |
| XTE J1118 + 480 | $4^h1$ | K7−M0 V | T | | $8.5 \pm 0.6$ | 7 |
| GS 1124 − 684 | $10^h4$ | K0−5 V | T | | $7.0 \pm 0.6$ | |
| GS 1354 − 645 | $2^d54$ | G0−5 III | T | | $> 7.4 \pm 0.5$ | 8 |
| 4U 1543 − 475 | $1^d12$ | A2 V | RT | | $8.5 \div 10.4$ | |
| XTE J1550 − 564 | $1^d55$ | K3 III | RT | $\mu$Q | $10.5 \pm 1.0$ | |
| XTE J1650 − 500 | $7^h63$ | K4 V | T | $\mu$Q | $4.0 \div 7.3$ | 9 |
| GRO J1655 − 40 | $2^d62$ | F3−6 IV | RT | $\mu$Q | $6.3 \pm 0.5$ | |
| H 1705 − 250 | $12^h54$ | K5 V | T | | $5.7 \div 7.9$ | |
| GRO J1719 − 24 | $14^h7$ | M0−5 V | T | | $> 4.9$ | 10 |
| XTE J1859 + 226 | $9^h16$ | $\sim$ G 5 | T | | $8 \div 10$ | |
| GRS 1915 + 105 | $33^d5$ | K−M III | RT | $\mu$Q | $14 \pm 4$ | |
| GS 2000 + 251 | $8^h3$ | K5 V | T | | $7.1 \div 7.8$ | |
| GS 2023 + 338 | $6^d46$ | K0 IV | RT | | $10.0 \div 13.4$ | |

NOTES: $P_{orb}$ − orbital period; Opt. Sp − optical spectrum; X-r − X-ray variability; C − comments; $M_{BH}$ − mass of black hole component; Ref − references; T − transient; RT − recurrent transient; pers − persistent; $\mu$Q − microquasar
The errors or ranges for $M_{BH}$ are in most cases quoted after original references. The detailed discussion of these estimates is given in Ziółkowski (2003).

REFERENCES: Most of the references are given in Ziółkowski (2003). Additional references are: (1) Ziółkowski (2005); (2) Hillwig & Gies (2006); (3) Casares et al. (2006); (4) Hynes et al. (2003); (5) Shahbaz et al. (2004); (6) Jonker et al. (2005); (7) Gelino et al. (2006); (8) Casares et al. (2004); (9) Orosz et al. (2004); (10) Masetti et al. (1996).

where $M_x$ and $M_{opt}$ are the masses of the compact and the optical components and $i$ is the inclination of the orbit. The value of $f(M_x)$ gives an absolute lower limit to the compact component mass. To obtain a more precise value (not just the lower limit), we have to estimate the mass ratio $q = M_{opt}/M_x$ and the inclination of the orbit $i$.

● **The rotational broadening of the absorption lines of the optical component**

From the measurements of the lines, we determine the projected rotational velocity at the equator of the optical component $v_{rot} \sin i$. Assuming the corotation of the optical component with the orbital motion (for a Roche lobe filling component, it is a very good assumption), we have:

$$v_{rot} \sin i = 0.46 K_{opt}(q/(1 + q))^{1/3}. \tag{3}$$

With the help of this equation, one can determine the mass ratio $q$. The intrinsic width of the absorption lines is very small ($\sim$ few km s$^{-1}$), while the typical rotational broadening is of the order of few tens km s$^{-1}$ and can be, relatively easily, measured. This method has been applied, with a substantial success, to many BH systems (see Orosz 2003).

● **The radial velocities of the emission lines of the accretion disc**

The shifts of these lines reflect the orbital motion of the compact component and so permit us to determine the mass ratio directly:

$$q = K_{em}/K_{opt}, \tag{4}$$

where $K_{em}$ is the semiamplitude of the radial velocities of the emission lines. This method of determining the mass ratio is completely independent of the previous one. Unfortunately, it is rather uneasy to implement, since the emission lines are very broad ($\sim 2000$ km s$^{-1}$), while the orbital shifts are of the order of few tens km s$^{-1}$.

**• The amplitude of the ellipsoidal light variations**

Due to filling of the Roche lobe, the optical component is tidally distorted and due to rotation it exhibits the ellipsoidal light variations (double sinusoid per orbital period if the rotation is synchronous). The amplitudes of these variations in $V$ and $I$ are given by:

$$\Delta V = 0.26 \sin^2 i/(1+q), \tag{5}$$

$$\Delta I = 0.24 \sin^2 i/(1+q). \tag{6}$$

As may be seen, the dependence on the mass ratio $q$ is rather weak (for most of the BH XRBs $q$ falls in the range $0.05 \div 0.2$) and, therefore, the ellipsoidal light variations provide us with a valuable information about the inclination $i$ (even, if we do not know $q$). In practice, the procedure is not that simple, since the optical light is usually (even in the quiescence) contaminated by the residual contribution from the accretion disc. To make the situation worse, this residual contribution is frequently variable. Extraction of the true value of the inclination requires, often, a very careful modeling (Froning & Robinson 2001; Gelino et al. 2001).

**• The mass-spectral type relation for the optical component**

The typical optical components of BH XRBs are the lower main sequence stars, which satisfy reasonably well the mass-spectral type relation. This relation may be used to estimate the mass of the compact component, if the mass ratio is unknown. Since the mass of the optical component is usually quite small (below 1 $M_\odot$), even substantial uncertainty (say factor of two) does not influence dramatically the mass estimate for the compact component.

**• High frequency QPOs and X-ray spectra**

Using this method, one can estimate simultaneously the spins and the masses of black holes. The spin can be estimated from careful analysis of either continuum X-ray spectrum (Shafee et al. 2006; Davis et al. 2006; McClintock et al. 2006) or spectral X-ray lines (Miller et al. 2002; Miller et al. 2004; Miller et al. 2005; Miniutti et al. 2004). The first approach gives, at present, the more reliable results. Once the spin is known, we can use the observed high frequency QPOs to derive the mass of a given black hole. To do so, one has to apply one of the theories of high frequency QPOs in the systems containing accreting black holes. The most successful one seems to be, at the moment, the parametric epicyclic resonance theory (Abramowicz & Kluźniak 2001; Abramowicz et al. 2004; Kluźniak et al. 2004; Lee et al. 2004; Török et al. 2005). For a brief summary of this theory, the reader is referred to e.g. Ziółkowski (2007).

The results of mass estimates carried out with the help of all the technics described above are given in Table 1.

## 2.2 Black Hole Candidates from Microlensing Events

Among several hundreds of microlensing events observed so far there are about 30 so called "paralax events". These events 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, three long events were selected as, possibly, caused by black hole lenses. The candidates are: MACHO-98-BLG-6 (probable mass of the lens $\sim 3 \div 13\, M_\odot$, Bennett et al. 2002a), MACHO-96-BLG-5 (probable mass of the lens $\sim 3 \div 16\, M_\odot$, Bennett et al. 2002a) and MACHO-99-BLG-22 = OGLE-1999-BUL-32 (probable mass of the lens $\sim 100\, M_\odot$, Bennett et al. 2002b). Only the last of them seems to be a robust candidate. I will also add, that Paczyński (2003) promised more BH lenses from OGLE III project in some $2 \div 3$ years. OGLE III detects currently more than 500 events per year and, among them, some $20 \div 30$ paralax events. Based on the present (rather poor) statistics, we might expect that few of them (per year) should be BHCs. However, as no new firm detections were reported so far, it seems, that Paczyński's prediction was slightly overoptimistic.

## 3  INTERMEDIATE MASS BLACK HOLES

The case for the existence of intermediate mass black holes (IMBHs) is still not very strong but slowly it gets stronger. There are two classes of objects where we expect IMBHs to be present: some ultraluminous compact X-ray sources (ULXs) and centers of some globular clusters (GCs).

### 3.1  Ultraluminous X-ray Sources (ULXs)

The term ULXs is probably a sort of an umbrella covering several different classes of objects. However, the evidence is growing that one of these classes is, most likely, a class of XRBs containing IMBHs.

Below, I briefly list the arguments supporting this hypothesis:

• Some of them **are confirmed XRBs**

• Some of these XRBs **must be massive XRBs** since they contain young massive optical components (O8 V in M 81 X-1 (Liu et al. 2002), mid-B sg in M 101 X-1 (Kuntz 2005), B0 Ib in NGC 5204 X-1 (Liu et al. 2004))

• Many of the ULXs are found in star forming regions and young stellar clusters.

• Many of them exhibits X-ray variability on time scales hours to years.

• X-ray emission of some ULXs shows QPOs on time scales of few to few tens seconds, consistent with accretion discs around IMBHs.

• X-ray spectra of many ULXs are consistent with relatively cool accretion discs around IMBHs.

• Energy input into giant ionization nebulae surrounding many ULXs exclude substantial beaming (Ho II X-1, M 81 X-9, M 81 X-6, NGC 1313 X-2, NGC 1313 X-1, NGC 5408 X-1, IC 342 X-1, NGC 5204 X-1 and others). For a discussion of these objects see Pakull & Mirioni (2003) and Miller et al. (2005).

### 3.1.1  Mass Estimates for the Compact Components of ULX XRBs

The mass of such objects can be estimated from the X-ray luminosities and the QPO frequencies (if observed). No estimate based on the mass function is available so far.

### 3.1.2  M82 X-1 – the Strongest ULX Candidate for Containing an IMBH

The observed X-ray emission of this source corresponds to an isotropic luminosity of $(2.4 \div 16) \times 10^{40}$ erg s$^{-1}$ (which corresponds to the mass of $150 \div 1000 \, M_\odot$, if the source emits at the Eddington level). The source exhibits 0.054 Hz and 0.114 Hz QPOs. The source is, most likely, an X-ray binary with an orbital period of $\sim 62$ days. It belongs to the young stellar cluster MGG-11 (7 to 12 Myr old).

The analysis of these properties leads to the conclusion that, most likely, the system contains an IMBH of 200 to 5000 $M_\odot$ accreting from a giant of $\sim 25 \, M_\odot$, filling its Roche lobe (Patruno et al. 2006).

The mass estimates for two other probable ULX IMBHs are given in Table 2.

**Table 2**  Masses of some Intermediate Mass Black Holes

| Name | $M_{\mathrm{BH}}/M_\odot$ | Ref |
|------|------|------|
| Ultraluminous X-ray sources | | |
| M 82 X-1 | $200 \div 5000$ | 1 |
| MCG 03-34-63 X-1 | $\gtrsim 2000$ | 2 |
| Cartwheel N.10 | $\gtrsim 1000$ | 3 |
| Stellar clusters | | |
| G1 | $\sim 20\,000$ | 4 |
| M15 | $\sim 2000$ | 5 |
| $\omega$ Cen | $\sim 50\,000$ | 6 |
| NGC 6752 | few$\times(100 \div 1000)$ | 7 |
| IRS 13 | $\sim 1300$ | 8 |

REFERENCES:  (1) Patruno et al. (2006); (2) Miniutti et al. (2006);
(3) Wolter et al. (2006); (4) Gebhardt et al. (2005); (5) Gerssen et al. (2003);
(6) Noyola et al. (2006); (7) Ferrano et al. (2003); (8) Maillard et al. (2004).

### 3.2  Globular Clusters

Modeling of the gravitational field in the central regions of some GCs indicates that they contain fairly massive ($\sim 10^3$ to $10^4\, M_\odot$) compact objects. It is likely that these objects are IMBHs (although, in some cases, a very dense cluster of neutron stars cannot be ruled out).

*3.2.1  Mass Estimates for the Compact Objects in the Centers of some GCs*

The principal method is the analysis of the brightness profiles of the central regions of GCs. Additional information might be obtained from the estimate of the velocity dispersion in the cores of the clusters.

The useful parameter for detecting a probable presence of a central black hole during the preliminary analysis of the brightness profiles is the ratio of core radius to the half mass radius $r_c/r_h$. Trenti (2007) 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 $\sim 0.01$, for a cluster containing 10% of binaries this value was $\sim 0.1$, but fot the cluster containing an IMBH the value of $r_c/r_h$ was $\sim 0.3$. 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 seems, therefore, that a substantial fraction of old GCs contains IMBHs. The case, however, is not closed, since a very dense cluster of neutron stars can mimic the gravitational potential of an IMBH.

More detailed analysis of the brightness profiles leads to some quantitative estimates of the masses of the probable central BHs. Some of these estimates are given in Table 2.

As far, as the velocity dispersion is concerned, it was noted (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 relation might be useful for preliminary estimates of the central black hole mass, if the data about velocity dispersion are available.

Finally, one should mention that other techniques were also used to estimate the central BHs masses in the stellar clusters. This includes the kinematics of milisecond pulsars (NGC 6752, Ferraro et al. 2003) and kinematics of the massive hot stars in the central region (IRS 13, Maillard et al. 2004). The results are also given in Table 2.

### 3.3  A ULX in a Globular Cluster?

At the end of this section, one 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 (Maccarone et al. 2007). The source luminosity is $\sim 4 \times 10^{39}$ erg s$^{-1}$ (which corresponds to the 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. It seems likely that the GC in question contains a ULX, which harbors a fairly massive BH (although, perhaps, not an IMBH yet).

## 4  SUPERMASSIVE BLACK HOLES

The term supermassive black holes (SBHs) is used for BHs with the masses in the range $\sim 10^5$ to $10^{11}\, M_\odot$. Initially, such objects were believed to reside only in the centers of Active Galactic Nuclei (AGNs). During the last decade, the evidence was accumulated, which indicates, that virtually every "normal" galaxy contains in its center a SBH.

### 4.1  Methods of Mass Estimates for Black Holes in the Centers of Galaxies

At present, the four methods, listed below, are being used:
- **Kepler's law**
- $M_{\rm BH} - M_{\rm bulge}$ **relation**
- **"Reverberation" method**
- **"Variance" method**

### 4.2 Kepler's Law

This method is based on measuring the motions of the objects following the Keplerian orbits around the central BH. The objects might be either individual stars or stellar aggregates or water masers in the accretion disc. This method produces the most precise estimates, especially, if applied to individual stars or water masers.

In particular, the mass of Sgr A$^*$, the SBH in the center of our Galaxy was estimated from the motions of the several stars. In this case, both radial velocities and astrometric positions could be measured. These observations demonstrated that the common focus of the elliptical stellar orbits must harbor an invisible (except the rare X-ray or IR flares) mass of $(3.6 \pm 0.4) \times 10^6 \, M_\odot$ (Ghez et al. 2003). The pericenter distance of one of the stars (S0-16) is only about 8 light hours, so the size of the invisible object must be smaller. It could be nothing but BH.

For our twin galaxy M31, the orbits of individual stars could not be used and only the kinematics of stellar aggregates was investigated. From the complex modeling of the gravitational potential, the value $1.4 \times 10^8 \, M_\odot$ was derived for the mass of the central BH.

For a handful of nearby galaxies water maser sources were observed within the accretion disc (sometimes a few different sources at different distances from the center for a given galaxy). Their orbital motions yield quite precise estimate of the central mass. As an example, one may quote the galaxy NGC 4258 for which the value $(3.9 \pm 0.1) \times 10^7 \, M_\odot$ was found for the mass of the central BH (Herrnstein et al. 1999).

### 4.3 $M_{\mathrm{BH}} - M_{\mathrm{bulge}}$ Relation

Magorrian et al. (1998) found an empirical relation between the mass of the bulge of the galaxy and the mass of the central BH. The more recent version of this relation may be found e.g. at Häring & Rix (2004). As the mass of the bulge is estimated from the stellar velocities dispersion, this relation is, in fact, the relation between the stellar velocities dispersion and the mass of the central BH (which is obeyed also by some GCs, as was mentioned in the Section 3.2.1). This relation may be quantified as:

$$M_{\mathrm{BH}} = 1.35 \times 10^8 (\sigma/200 \, \mathrm{km \, s^{-1}})^{4.02} \, M_\odot \,. \tag{7}$$

### 4.4 "Reverberation" Method

This method can be applied in the case of active galaxies, where the previous method cannot be used (the emission from the active nucleus overshines the stellar component and the velocity dispersion which is based on stellar absorption lines cannot be determined). The reverberation method is essentially based on Kepler's law ($M_{\mathrm{BH}} = v^2 R/G$) applied, in this case, to broad line region (BLR). The velocity $v$ of the matter in this region is estimated from the width of the H$\beta$ emission line and the distance from the center $R$ from the time delay of the variability of the emission from BLR with respect to that from the central region. Since both the radius $R$ and the velocity $v$ (or the H$\beta$ width $\Delta\lambda$) were found empirically to scale with the total luminosity of the nucleus, the relevant formula can be simplified to (Kaspi et al. 2000):

$$M_{\mathrm{BH}} = 5.71 \times 10^7 L_{44}{}^{0.545} \, M_\odot \,, \tag{8}$$

where $L_{44}$ is the luminosity in the units of $10^{44}$ erg s$^{-1}$.

This method was successfully applied to many active galaxies. Unfortunately, its accuracy is rather low, since the result depends on the inclination of the plane of BLR (which is unknown) and on the assumption about the geometry of motions of the gas in BLR (which probably is not exactly keplerian).

### 4.5 "Variance" Method

This method (Papadakis et al. 2004; Nikołajuk et al. 2004) is based on the analysis of the variability in the X-ray band (long sequences of good quality observations are necessary). The mass of the central object can be estimated from the high frequency break in the power density spectrum (the frequency scales approximately linearly with the mass). This method is completely independent of the previous one. The new calibration of the relevant formula (Nikołajuk et al. 2006) was based on the variability of the system Cyg X-1 (and on the new determination of its mass (Ziółkowski 2005)). It is, certainly, encouraging that the masses determined by two completely independent methods (reverberation and variance) agree well with each other (Nikołajuk et al. 2006).

**Table 3** Masses of some Supermassive Black Holes

| Name | $M_{\mathrm{BH}}/M_\odot$ | Ref |
|------|------|-----|
| Low mass supermassive black holes | | |
| NGC 4395 | $3.6 \times 10^5$ | 1 |
| NGC 4051 | $\sim 5 \times 10^5$ | 2 |
| Sgr A* | $3.6 \times 10^6$ | 3 |
| High mass supermassive black holes | | |
| [BH89] 1346–036 | $0.9 \times 10^{10}$ | 4 |
| LBQS 0109+0213 | $1.0 \times 10^{10}$ | 4 |
| [BH89] 0329–385 | $1.3 \times 10^{10}$ | 4 |
| 2QZ J222006.7–280324 | $1.4 \times 10^{10}$ | 4 |
| [BH89] 1246–057 | $1.7 \times 10^{10}$ | 4 |
| TON 618 | $6.6 \times 10^{10}$ | 4 |

REFERENCES:; (1) Peterson et al. (2005); (2) Shemmer et al. (2003); (3) Ghez et al. (2003); (4) Shemmer et al. (2004).

Mass estimates were carried out for a large number of SBHs. Short selection of some results is given in Table 3. It is worth noticing that the range of masses covers more than five orders of magnitude.

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