# SEARCHES FOR BLACK HOLES. THE MOST RECENT RESULTS

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Black holes were predicted by Einstein General Relativity (GR). Because of unusual properties of these objects their existence is almost unbelievable. There are gravitation theories which do not predict the black hole appearance. By now, astronomers discovered a few hundreds of massive and highly compact objects with observational features which are very similar to the properties of black holes predicted by GR. To confirm existence of black holes in the Universe, a number of groundbased and space experiments are planned to be held in the coming decade.

## 1 Introduction

The story of searching for black holes is not completed yet. Although it is worthwhile emphasizing that about 200 massive and highly compact objects have been discovered so far which possess properties very similar to those of black holes. A black hole (BH) is an object which has an escape velocity equal to the speed of light in vacuum, $c = 300,000$ km/s. Conception of black hole arose after discovery of Newton's law of universal gravitation in 1687. In 1783 John Michell expressed an idea of dark stars having gravitational field so strong that even the light cannot escape outwards. The same idea was put forward in 1798 by Pierre-Simon Laplace. The existence of black holes is predicted in Einstein's General Theory of Relativity (GTR). A characteristic size of a black hole is defined by the Schwarzschild radius (gravitational radius), $r_g = 2GM/c^2$, where M is a mass of the object, c is the speed of light, $G = 6.67 \cdot 10^{-8}\text{dyn} \cdot \text{cm}^2\text{g}^{-2}$ is the gravitational constant.

The gravitational radius is equal to

$$r_g = \begin{cases} 9 & \text{mm} & \text{for} & \text{the Earth} & (M = 6 \cdot 10^{27}\,\text{g}) \\ 30 & \text{km} & \text{for} & 10M_\odot & (M = 2 \cdot 10^{34}\,\text{g}) \\ 40 & \text{AU} & \text{for} & M = 2 \cdot 10^9 M_\odot & (M = 4 \cdot 10^{42}\,\text{g}), \end{cases}$$

where $\odot$ is a symbol for the Sun, 1 Astronomical Unit (AU) is the Earth's average distance from the Sun, $1.5 \cdot 10^{13}$ cm.

The boundary of a black hole is identified with the event horizon where time is stopped for a distant observer. Therefore, all the events occuring under the event horizon are beyond the reach of the observer. The radius of the event horizon is equal to the gravitational radius for a non-rotating (Schwarzschild) black hole and is less than the gravitational radius for a rotating black hole. In this case the event horizon is located inside the black hole's ergosphere where the vortical gravitational field is created. It is John Wheeler who called these objects "black holes" (BH) in 1968.

Properties of BH are described, for example, in [1] as well as in a recent review by the same authors [2]. It is worth mentioning that the event horizon is not a solid observable surface. It can be removed with the use of a proper reference frame. For example, there is no event horizon at all for an observer freely falling onto a BH. Such an observer could get into the BH and see the central singularity which contains all the compressed matter but he could transmit no information outward. Because of extraordinary properties of BH their existence in the Universe is doubted and has been debated for some decades. Some versions of the gravitational theory deny BH (see, e.g., [3]), the problem of searching for them getting more intriguing and interesting. Moreover, because of relativistic effect of time retardation near the event horizon, "contemporary" BH do not seem to have the event horizons completely formed. Astronomers consider these objects to be "virtual" BH with "virtual" event horizons.

In 1964 a pioneering work by Ya.B.Zel'dovich [4] and E.E.Salpeter [5] appeared where the possibility to observe black holes was predicted due to the powerful energy release in the process of non-spherical accretion of matter to the BH. In [6, 7, 8] a theory of disk accretion to neutron stars (NS) and BH was developed which was very helpful in understanding the nature of compact X-ray sources discovered aboard UHURU satellite [9] and identifying them as accreting NS and BH in stellar binary systems. Optical investigations of X-ray binary systems [10, 11, 12] stimulated development of reliable methods for determining NS and BH masses [13]. 3D gasdynamic models of gas flow in binary systems made mechanisms of accretion disk formation more clear [14]. Models of advection-dominated disks around BH proposed in [15, 16] account for anomalously low luminosity of accreting BH in nuclei of normal galaxies and low-mass X-ray binary systems. Searching for stellar-mass BH being rather succesful, a certain progress is likely to have appeared recently in researching super-mass BH in galactic nuclei. The most convincing evidence for super-mass compact objects has been obtained recently while investigating "quiescent" galactic nuclei (see, for example, the recent Symposium results [17] and the review [18]), although quasars and nuclei of active galaxies were considered to be the first super-mass BH candidates [5, 19, 20].

## 2 Methods for Searching Black Holes

Three types of BH are suggested to exist:

1. Stellar mass BH, $M = (3 - 50)M_\odot$, which are formed at advanced stages of massive star evolution. If an evolved stellar core has got a mass $M_c \leq (1.2 - 1.4)M_\odot$ it yields a white dwarf, if its final mass is $M_c < 3M_\odot$ it produces a neutron star, and if the mass is $M_c \geq 3M_\odot$ a BH is likely to be the final object.

2. Super-mass BH in galactic nuclei, $M = 10^6 - 10^9 M_\odot$.

3. Primary BH formed at early stages of the evolution of the Universe.

As to intermediate-mass BH with masses $M = (10^2 - 10^4)M_\odot$, their existence is still debated. Whether or not they can appear is not clear yet. Actually a number of stellar mass BH has been found to be nearly 20, and a number of super-mass BH in galactic nuclei around 200.

Two main problems are to be solved in the process of searching for BH:

1. Looking for massive, $M > 3M_\odot$, compact objects as possible BH candidates.

2. Looking for sufficient observational criteria for them being real BH.

Astronomical observations of BH are possible owing to X-ray halos around them occuring in non-spherical accretion of matter [4, 5, 6, 7, 8]. But terrestrial atmosphere is opaque for X-rays. It is in 1962 that the first X-ray source beyond the solar system, Sco X-1, was discovered aboard an American Aerobee rocket in an experiment leaded by Riccardo Giacconi who was awarded the Nobel Prize in 2002.

Astronomical observations of BH involve three steps.

1. Analysing motions of "trial bodies" (stars, gas clouds, gas disks) in the BH gravitational fields provides estimates of BH masses. Characteristic distances being much greater than gravitational radii, Newton law may be used to make such estimates.

2. BH radii are measured by indirect approaches: through analyses of fast X-ray variability, X-ray line profiles, etc.

3. The most challenging problem is to look for observational evidence of the event horizon.

A final proof whether or not an object is a BH can be obtained if a reliable event horizon or an ergosphere is revealed (for a rotating BH). Special groundbased and space projects are planned to solve this significant problem. The main observational criteria of an accreting stellar mass BH are great mass, powerful X-ray radiation, and absence of X-ray pulses or 1st type X-ray bursts. Pulses or bursts are peculiar to accreting NS which have got observable surface and fast rotation. In a strong magnetic field ( $10^{12}$ Gs) matter from the inner parts of the NS accretion disk is tunnelled via magnetic lines of force to the NS magnetic poles and, after having been collided with the NS surface, is heated up to temperatures over 10 million degrees, up to some hundred million degrees. Hot spots are formed in the areas of collision. Since the rotational axis is not coincident with the magnetic dipole axis, these hot X-ray spots on the NS surface are alternately visible to an Earth observer or shielded by the NS body ("lighthouse effect"). Thus a phenomenon of X-ray pulsar appears when a strictly periodic X-ray radiation comes out, periods lying between less than a second and some minutes (Fig. 1).

If the NS magnetic field is rather small (less than $10^8$ Gs) matter from the inner parts of the accretion disk is spreaded about and accumulated on the NS surface resulting in nuclear explosion of accumulated matter. Thus a phenomenon of the 1st type X-ray burster appears, i.e. short (for some seconds) and powerful X-ray bursts. So, X-ray pulses and the 1st type X-ray bursts are considered to justify that an accreting relativistic object has got the observable surface. Another evidence of such observable surface is when a relativistic object displays pulses in radio occuring due to ejection of charged relativistic particles in a strong magnetic field of a fast rotating NS. In this case, short (between milliseconds and seconds) and strictly periodic pulses of radio emission come out from the NS.

X-ray pulses, radio pulses or the 1st type X-ray bursts are not likely to occur on an accreting BH. What may be expected, however, is just X-ray irregular variability on time scales $r_g/c \cong 10^3 - 10^4$ Fig. 2.

Sometimes NS may be observed which display neither X-ray pulses, radio pulses, nor the 1st type X-ray bursts. Hence, their absence is a necessary but insufficient condition to identify a compact object with a real BH.

There are no so far sufficient observational criteria to select a BH. It is worthwhile mentioning, however, that all the necessary criteria taking into account GR-effects are fullfilled for all known BH candidates (200). So modern astronomers, with a kind of forced argumentation, call the BH candidates "black holes".

## 3 Stellar mass Black Holes

There are two types of X-ray binary systems which can contain BH (see the Catalog [21]):

1. Quasistationary X-ray binaries with massive hot companion stars.

2. Transient (flashing) X-ray binaries, i.e. X-ray novae, with low-mass cool companion stars.

About a thousand X-ray binary systems in the Milky Way and near galaxies have been discovered so far owing to specialized X-ray observatories launched into orbits around the Earth. Noticeable contribution into discovery and researches of X-ray binary systems was made by the Soviet and Russian Mir Kvant and Granat X-ray observatories under R.A.Sunyaev (see, for example, [22],[23] Successful observations of BH candidates in a hard X-ray spectrum that is the most appropriate range to search for BHs [24] have been carried out by the international X-ray and gamma observatory INTEGRAl launched by a Russian Proton carrier rocket in October 2002 [24]. The Russian scientific co-leader of the project is R.A.Sunyaev.

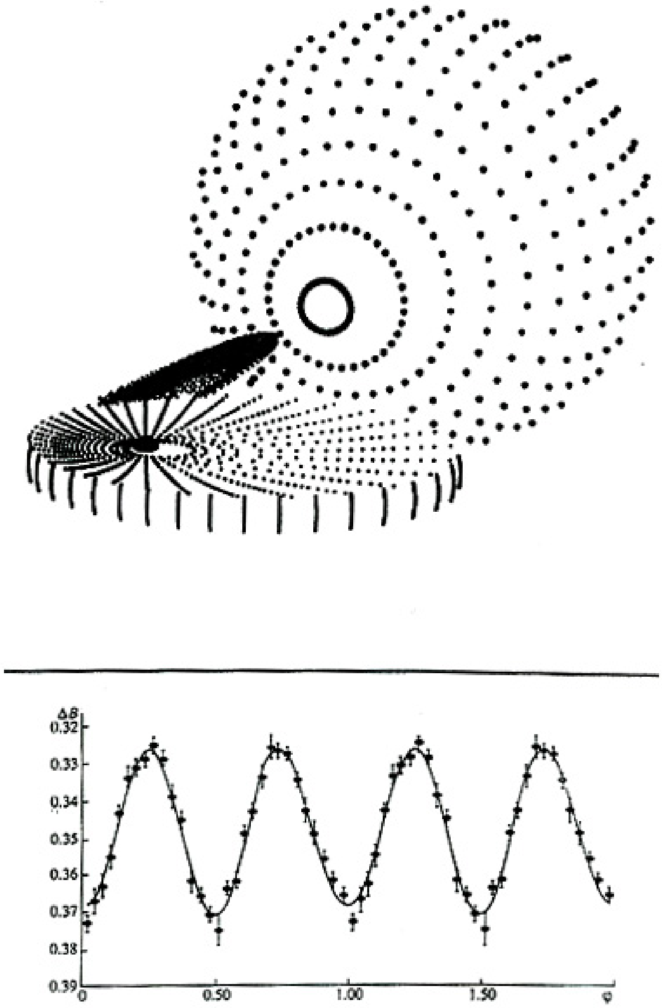


Fig. 1. Accretion of matter onto NS or BH in the inner parts of the accretion disk. A model of an X-ray binary system is shown at the top (**sight from above**). Accretion onto a fast rotating NS with strong magnetic field results in X-ray pulsar phenomenon (shown in the middle of **Fig.1**). The X-ray pulse period ($p = 1.24$ s) and the pulsation phases of the Her X-1 pulsar remain stable over the period of 30 years. This indicates that the NS has a solid observable surface. In the case of accretion onto a BH (at the bottom of the **Fig.1**), X-ray pulses are not observed since there is no any observable surface. Only irregular variability of X-ray radiation is present at time scales up to $t_{min} \sim r_g/c \sim 10^{-3} \div 10^{-4}$ s.

A 3D gas-dynamic model of an X-ray binary system elaborated by A.A.Boyarchuk's team [14] is displayed in Fig. 2. Powerful X-ray radiation is produced in the inner parts of the accretion disk close to a BH.

Spectrum of optical radiation of X-ray Nova Oph1997 in a quiescent state [25] is shown in Fig. 3.

Measuring the doppler shifts of numerous metallic absorption lines that correspond to a K-type star yields the radial velocity curve representing projected orbital velocity of the star on the line of sight. The radial velocity semi-amplitude of the optical star is about 400 km/s. Since radial velocities are measured within 1-3 km/s error, the radial velocity curve is highly reliable. While interpreting it, however, one should take into account that the optical star is not a material point, it has got considerable size and is pear-shaped, temperature distribution over its surface being rather complicated. A mathematical technique has been elaborated so far which allows for these effects to be taken into consideration [18].

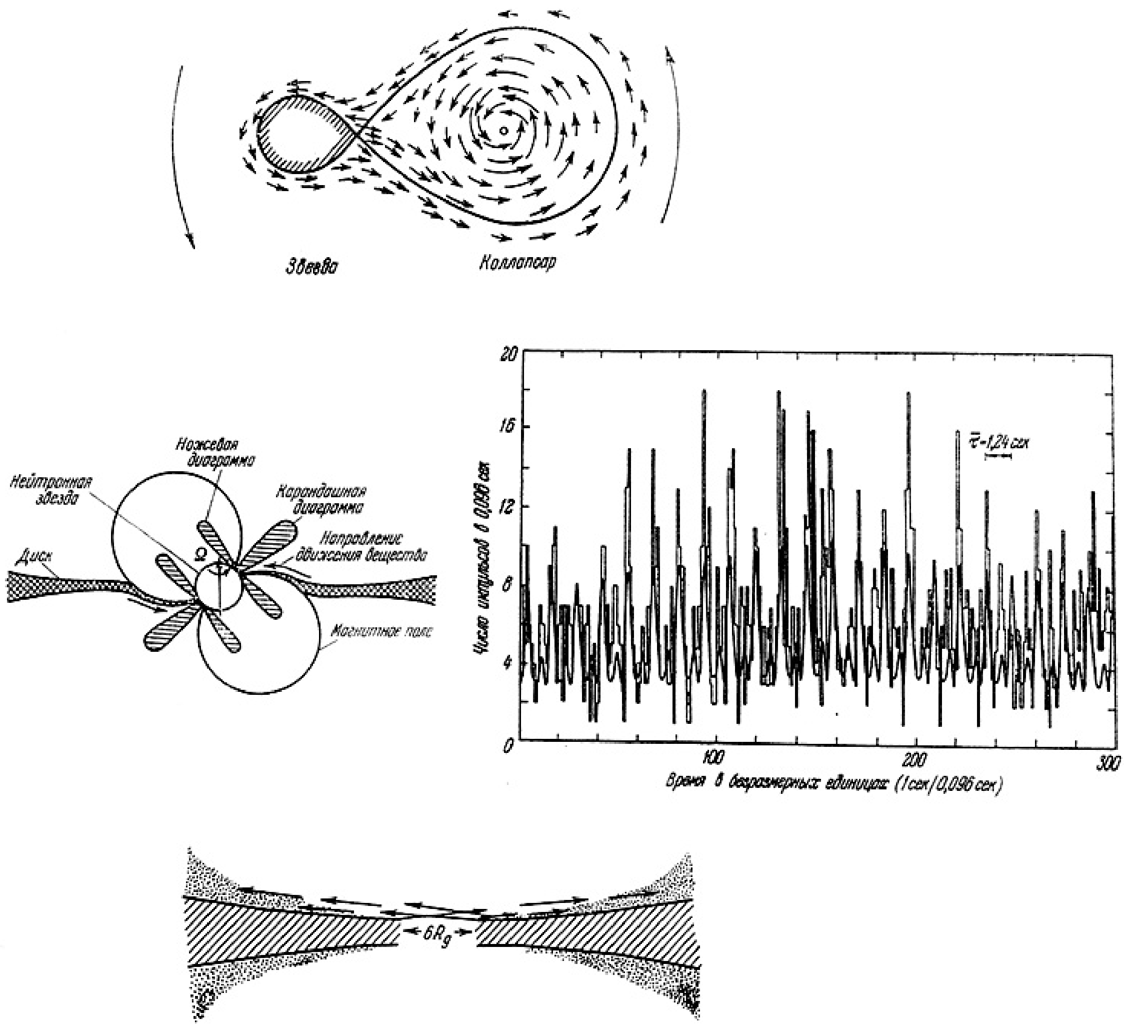


Fig. 2. Mathematical model of an X-ray binary system consisting of an optical star and an accreting NS or BH. The optical light curve of the Cyg X-1 X-ray binary is given below [12]. Light variations are due to pear shape of the optical star and its orbital motion (ellipticity effect). Orbital inclination, $i$, of the binary system towards the picture plane is estimated using the amplitude of light variations in the light curve.

Optical investigations of X-ray binary systems and measurements of BH masses were carried out by American, Canadian and British scientists (Charles, Cowley, Murdin, Hutchings, McClintock, Remillard, Hynes, Martin, Casares, Orosz, Bailyn, Filippenko, Shahbaz, Greiner, et al.) as well as Soviet and Russian researches (Pavlenko, Lyuty, Sokolov, Fabrika, Goransky, Kurochkin, Shugarov, et al.). The optical light curve of the X-ray binary system Cyg X-1, the most plausible candidate for BH, first obtained by Lyuty, Sunyaev and Cherepashchuk [12] is shown in Fig. 1. The amplitude of optical variability due to optical star ellipticity effect gave inclination angle, i, between the orbital plane and the picture plane and allowed one of the earliest estimates of the BH mass to be obtained in Cyg X-1 system. A BH mass is calculated using the formula $m_{BH} = f_{opt}(m)(1 + q^{-1})^2 \sin^{-3} i$ where $q = m_{BH}/m_{opt}$ is a ratio of the BH and optical star masses, $f_{opt}(m)$ is the mass function of the optical star determined over its radial velocity curve ($m_{BH} > f_{opt}(m)$). Parameters q and i are found from additional information: optical light curve analyses, rotational Doppler broadening of lines in the spectrum of the optical star, distance to the binary system, duration of an X-ray eclipse. The technique available is used to determine reliable BH masses having spectral and photometric observations of X-ray binary systems.

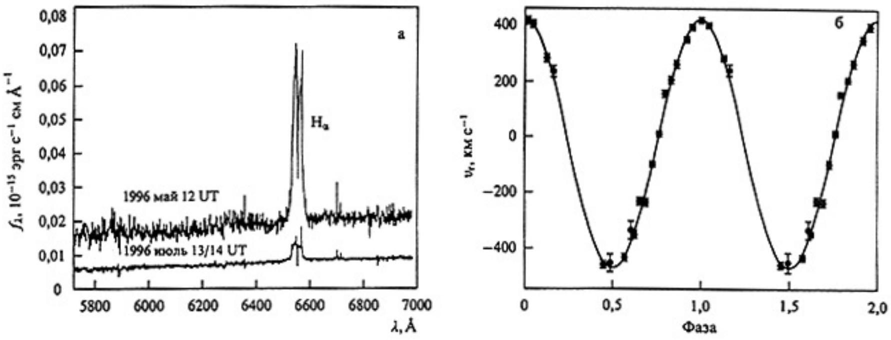


Fig. 3. Optical spectrum of the X-ray Nova – the binary system with a BH, Nova Oph1977 (H1705-250), in a quiet state of radiation observed by Filippenko et al. [25]. Numerous metallic absorption lines are seen in the spectrum of K5V companion. Their Doppler shifts were used to construct a radial velocity curve (shown right). There is also $H_\alpha$ emission line of hydrogen displaying two-hump structure formed in the accretion disk rotating around the BH.

Parameters for 18 X-ray binary systems with measured BH masses are given in Table 1.

Fig. 4 displays masses of relativistic objects (NS and BH) versus companion masses in the binaries.

Companions of X-ray pulsars, 1st type X-ray bursters, and BH in binary systems are O-M type optical stars. Companions of radiopulsars are non-active NS, white dwarfs, and massive type B stars (we do not consider here radiopulsars with planets as companions). Radiopulsar masses are determined at a high level of accuracy taking into account relativistic effects in their orbital motions. Fig. 4 indicates that masses of relativistic objects do not depend on masses of their companions: both NS and BH can belong to binary systems with massive and low-mass companions. Orbital periods of X-ray binaries with BH are shown to lie in wide intervals between 0.17 days and 33.5 days. About a half of the systems have the mass function of the optical star more than $3M_\odot$, i.e. the absolute upper limit for a BH mass predicted by General Relativity. In these cases relativistic objects may be considered to be BH candidates, their masses being over $3M_\odot$. The mathematical technique available allows one to find BH and NS masses, together with their errors, from the mass function of the optical star (see Table 1). Masses of 19 NS are in the interval $M_{NS} = (1-2)M_\odot$, a mean value of their mass being $(1.35 \pm 0.15)M_\odot$. Masses of 18 BH have been measured to lie in the interval $M_{BH} = (4-16)M_\odot$, a mean value of their mass being $(8-10)M_\odot$.

The more numerous a number of relativistic objects with measured masses becomes (19 NS and 18 BH in the Table 1), the stronger is the conviction that there is a systematic difference both in NS and BH masses and in their observational manifestations according to Einstein's GR theory. For all objects with clearly observed surface (radiopulsars, X-ray pulsars, or 1st type X-ray bursters) their masses (of NS) do not exceed $3M_\odot$ what is in full accordance with GR. At the same time, among 18 massive ($M > 3M_\odot$) binary X-ray sources studied (BH candidates) there are neither radiopulsars nor X-ray pulsars, nor 1st type X-ray bursters. Hence, in full accordance with GR predictions, massive ($M > 3M_\odot$) X-ray sources, BH candidates, do not reveal any observable surface. A great number of relativistic objects with measured masses (37) makes the conclusion rather reliable. It is an argument, though not a final proof, that 18 BH candidates with measured masses are real BH in the sense of GR. Thus, presense or absence of pulses or bursts is an observational manifestation crucial while defining whether or not an accreting object is a NS or a BH. Moreover, there are finer spectral distinctions (in the range 1-10 KeV) which indicate that NS have got surfaces observed whereas BH have not got [18].

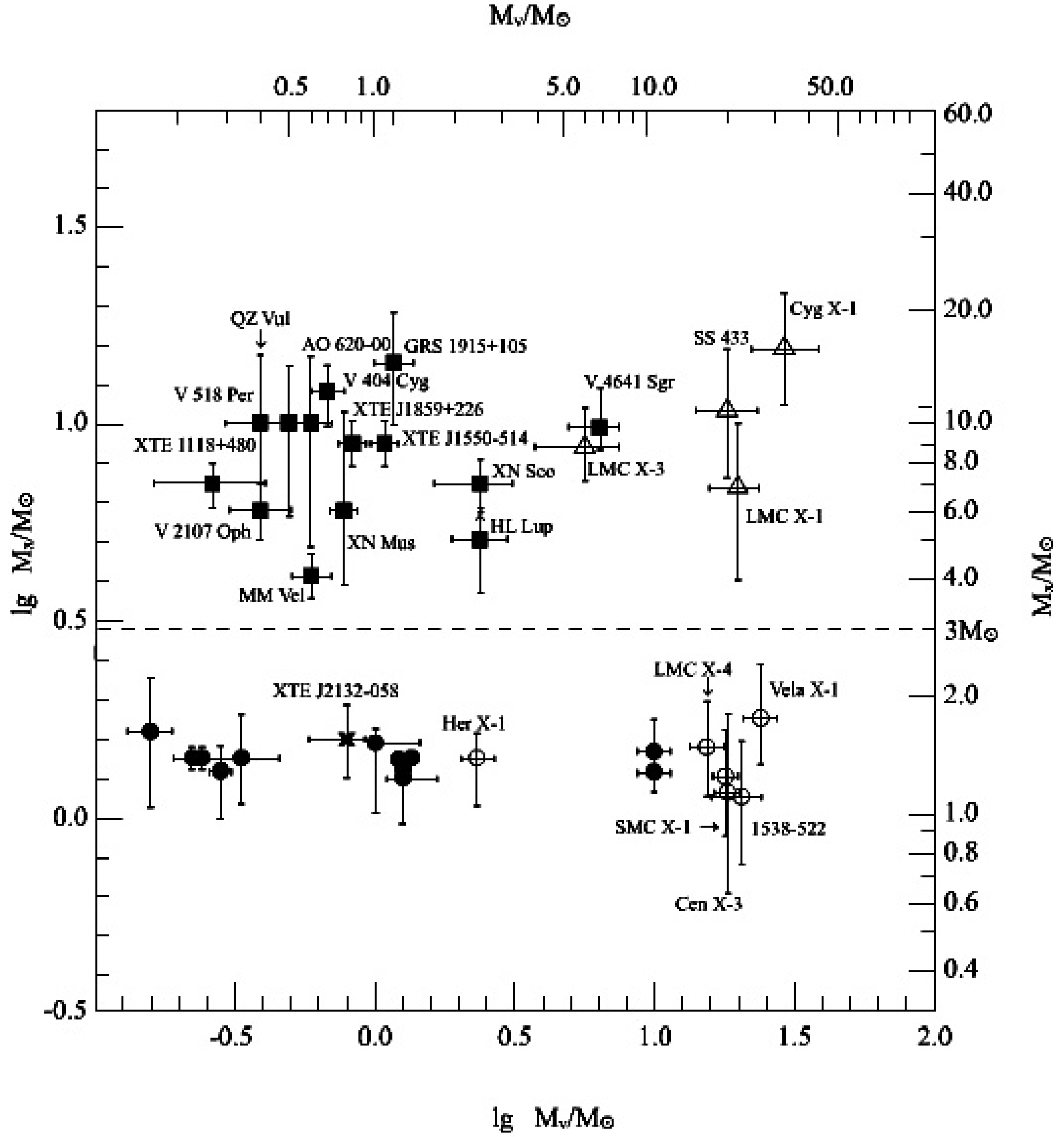


Fig. 4. Masses of NS, $M_x$ (circles and crosses), and of BH (triangles and squares) versus companion masses, $M_v$, in binary systems (in units of solar masses $M_\odot$). Dark circles stand for radiopulsars, light ones for X-ray pulsars, crosses for the 1st type X-ray burster. Dark squares correspond to BH in X-ray Novae, light triangles to BH in quasistationary X-ray binary systems with hot massive optical companions.

Systems GRS1915+105, SAX J1819.3-2525, GRO J1655-40, and 1E1740.7-2942 called microquasars display relativistic collimated jets in X-ray bursts which have velocities $v \geq 0.92$ of the speed of light and plasma cloud motions which have apparent velocities in excess of the speed of light (apparent superluminal motions in the plane of the sky are due to the Special Theory of Relativity effects).

Table 1. **Parameters of Binary Systems with Black Holes**

| System | Opt. Star Spectrum | $P_{orb}$ (days) | $f_{opt}(M)$ ($M_\odot$) | $M_{BH}$ ($M_\odot$) | $M_{opt}$ ($M_\odot$) | $V_{pec}$ (km/s) | Note |
|---|---|---|---|---|---|---|---|
| Cyg X-1 V 1357 Cyg | O 9.7 Iab | 5.6 | 0.24 $\pm$0.01 | 16 $\pm$5 | 33 $\pm$9 | 49 $\pm$14 | stat. |
| LMC X-3 | B3 Ve | 1.7 | 2.3 $\pm$0.3 | 9 $\pm$2 | 6 $\pm$2 | - | stat. |
| LMC X-1 | O(7-9) III | 4.2 | 0.14 $\pm$0.05 | 7 $\pm$3 | 22 $\pm$4 | - | stat. |
| SS 433 | $\sim$ A7 Ib | 13.1 | $\sim$ 1.3 | 11 $\pm$5 | 19 $\pm$7 | - | stat. |
| A0 620-00 (V 616 Mon) | K5 V | 0.3 | 2.91 $\pm$0.08 | 10 $\pm$5 | 0.6 $\pm$0.1 | -15 $\pm$5 | trans. |
| GS 2023+338 (V 444 Cyg) | K0 IV | 6.5 | 6.08 $\pm$0.06 | 12 $\pm$2 | 0.7 $\pm$0.1 | 8.5 $\pm$2.2 | trans. |
| GRS 1124-68 (GU Mus) | K2 V | 0.4 | 3.01 $\pm$0.15 | 6 (+5,-2) | 0.8 $\pm$0.1 | 26 $\pm$5 | trans. |
| GS 2000+25 (QZ Vul) | K5 V | 0.3 | 4.97 $\pm$0.10 | 10 $\pm$4 | 0.5 $\pm$0.1 | - | trans. |
| GRO J0422+32 (V 518 Per) | M2 V | 0.2 | 1.13 $\pm$0.09 | 10 $\pm$5 | 0.4 $\pm$0.1 | - | trans. |
| GRO J1655-40 (XN Sco 1994) | F5 IV | 2.6 | 2.73 $\pm$0.09 | 6.3 $\pm$0.5 | 2.4 $\pm$0.4 | -114 $\pm$19 | trans. |
| H 1705-250 (V 2107 Oph) | K5 V | 0.5 | 4.86 $\pm$0.13 | $6 \pm 1$ | 0.4 $\pm$0.1 | 38 $\pm$20 | trans. |
| 4U 1543-47 (HL Lup) | A2 V | 1.1 | 0.22 $\pm$0.02 | 4.0- 6.7 | $\sim$ 2.5 | - | trans. |
| GRS 1009-45 (MM Vel) | (K6-M0) V | 0.3 | 3.17 $\pm$0.12 | 3.6- 4.7 | 0.5- 0.7 | - | trans. |
| SAX J1819.3-2525 (V 4641 Sgr) | B9 III | 2.8 | 2.74 $\pm$0.12 | 9.61 (+2.08- 0.88) | 6.53 (+1.6- 1.03) | - | trans. |
| XTE 1118+480 | (K7-M0)V | 0.17 | 6.0 -7.7 | | 0.09- 0.5 | 126 | trans. |
| GRS 1915+105 | (K-M)III | 33.5 | 9.5 $\pm$3.0 | $14 \pm 4$ | 1.2 $\pm$0.2 | - | trans. |
| XTE J1550-564 | $\sim K3$ | 1.54 | 6.86 $\pm$0.71 | 8.36- 10.76 | $\sim$ 1 | - | trans. |
| XTE J1859+226 | $\sim K7$ | 0.38 | 7.4 $\pm$1.1 | 7.6- 12.0 | $\sim$ 0.7 | - | trans. |

**Note**: $P_{orb}$ stands here for an orbital period, $f_{opt}(M) = \frac{M_{BH}^3 \sin^3 i}{(M_{BH}+M_{opt})^2}$ is a mass function of an optical star, $M_{BH}$, $M_{opt}$ are masses of black holes and optical companions, respectively, $V_{pec}$ is a peculiar velocity of the center of gravity of a binary system.

Recently interesting results have been obtained concerning rotation of stellar-mass BH. If an accretion disk around the BH rotates in the same direction as the BH itself, such a rotating disk penetrates much closer to the BH than it would in the case of a non-rotating BH. This is due to the fact that the radius of the final stable orbit for a rotating BH is less than for a non-rotating BH, $3r_g$. Hence, luminosity and temperature of the thermal component of X-rays emitted by rotating accreting BH are enhanced because of more powerful release of energy in the process of accretion. As a matter of fact, two transient X-ray binary systems with BH, microquasars GRS1915+105 and GRO J1655-40, display such enhanced characteristics and are likely to contain fast rotating BH.

Radii of stellar-mass BH may be restricted while analyzing observational results on fast variability of X-ray radiation. For example, system Cyg X-1 displays fast irregular X-ray intensity variability on a typical time scale $\Delta t$ up to $10^{-3}$ s. A typical size of the region near a BH emitting X-rays is, therefore, no more than $r = c\Delta t \cong 300$ km/s $\cong 10r_g$. Observations of binary systems with BH have exhibited wide-ranging quasiperiodic oscillations (QPOs).

Detailed findings on QPOs in X-ray binary systems with BH are given in the recent review [26]. If high-frequency QPOs (typical frequencies between 41 Hz and 450 Hz) are associated with orbital motions of plasma condensations near a BH, the corresponding distancies are not more than some gravitational radii. High-frequency QPOs may be also connected with seismic oscillations of inner parts of the accretion disk as the GR theory predicts or they may be caused by relativistic dragging of the inertial reference frame near a fast rotating BH.

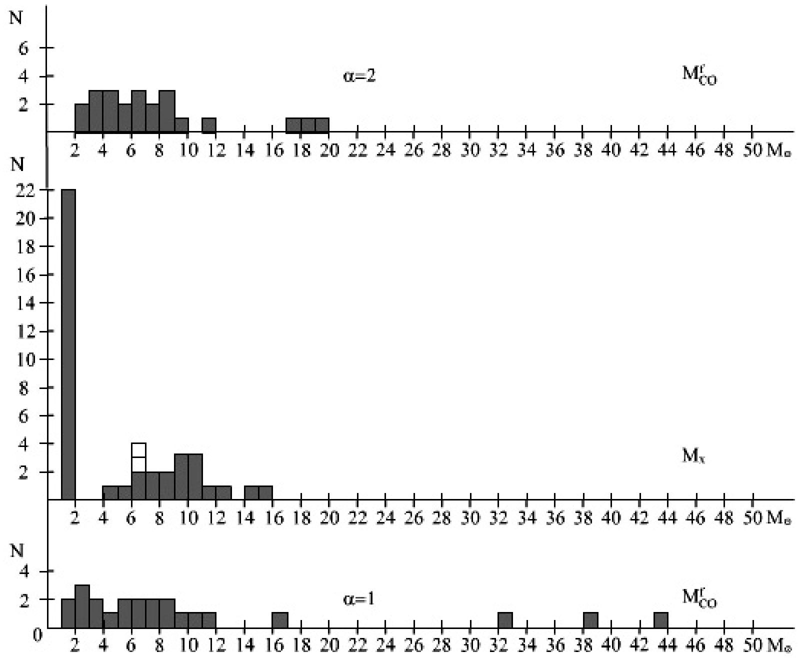


Fig. 5. Observable mass distribution of relativistic objects, $M_x$, in binary systems is displayed in the middle. NS are concentrated in a narrow mass interval, $M_x = (1-2)M_\odot$, while BH masses are restricted by limits $4-16M_\odot$. Masses of isolated BH determined with the use of the microlensing effect are marked by light squares. Mass distributions for the cores of WR stars, $M^f_{CO}$, at the end of their evolution are shown at the bottom and the top ($\alpha = 1$ and $\alpha = 2$ correspond to different models of matter outflow from the star via stellar wind). $M_x$ distribution is bimodal with the gap in the region $M_x = (2-4)M_\odot$, whereas $M^f_{CO}$ distribution is continuous. Hence, the two mass distributions, those for relativistic objects and for CO cores of massive stars at the end of evolution, are of dramatically distinctive character.

Fig. 5 displays NS and BH masses versus mass distributions, $M^f_{CO}$, of CO cores at the end of massive star evolution (Wolf-Rayet stars).

Different models of stellar wind flowing from WR are designated by parameters $\alpha = 1$ and $\alpha = 2$. Distribution of $M^f_{CO}$ in the interval $(1 - 12)M_\odot$ is seen to be continuous while mass distribution of NS and BH resulting from the collapse of massive stellar CO-cores is bimodal with two maxima and a dip in the interval $2 - 4M_\odot$. It seems like there is a deep reason which would prevent the formation of massive NS with $M > 2M_\odot$ and low-mass BH with $M < 4M_\odot$ in binary systems. Such an "avoidance zone" for relativistic objects may be shown to be due to other reasons than observational selection. If the conclusion is confirmed with more observational data, a more serious interpretation will be needed.

## 4 Supermassive BH in Galactic Nuclei

Most galaxies have got compact condensations of stars and gas in their centers which are called "nuclei". Usually the cores are well visible in spiral galaxies and hardly discernible in irregular ones. Among all galaxies a relatively small group may be singled out ( 1 per cent) which involves galaxies with active nuclei: Seyfert galaxies, radio galaxies, BL Lac galaxies, and quasars. The quasars are the most powerful sources of stationary radiation in the Universe. Their total luminosity reaches $10^{47}$ erg/s, which is three orders of magnitude more than that of a host galaxy. Intense non-stationary processes occuring in active nuclei result in variability of optical radiation on time scales of days to many years. Spectra of these active nuclei exhibit strong and often wide emission lines of hydrogen, helium and other elements. Many nuclei of active galaxies are observed to have strongly collimated jets of matter moving with relativistic velocities. A galactic nucleus is currently considered to be a supermassive BH with accretion of stellar matter and gas [15].

To determine BH masses in galactic nuclei a hypothesis is used according to which the gravitational field of a central object controls the motion of gas and stars near the nucleus [27]. As was mentioned above, Newton's law can be used since $r > r_g$. In this case the velocity $v$ of a star or a gas cloud depends on the distance $r$ to the center of a galaxy as $v^2 \sim r^{-1}$. Hence the BH mass in the nucleus can be estimated as $M_{BH} = \eta v^2$ r/G, where $\eta = 1 - 3$ depending on a kinematic model of body motion around the galactic center (for circular motion, $\eta = 1$).

It is possible in many cases to see the moving gas directly, for our Galaxy even individual stars, near the galactic center owing to modern observational facilities (the Hubble Space Telescope, very large groundbased telescopes provided with techniques for compensation of atmospheric distortions, intercontinental interferometers, etc.). Therefore the BH masses are determined unequivocally using the formula given.

If a disk of gas and dust surrounding the galactic center cannot be seen and its rotation cannot be investigated another method is applied based on statistical researches of stellar kinematics in the central parts of the galaxy which is defined by the BH gravitational influence.

BH masses in active galactic nuclei with observed strong and wide emission lines can be determined using the formula given. Velocities, $v$, of gas clouds near the nucleus which are responsible for a wide component of emission line profiles can be estimated with the help of the Doppler semi-amplitude of this wide line component. The distance, $r$, of gaseous clouds to the nucleus can be estimated by two ways: by means of a photoionization model of the nucleus [27, 28] or by time delay, $\Delta t$, which reveals in the fast variability of a wide emission line component with regard to the variability of the continuous spectrum, $r \approx c \cdot \Delta t$ (so called reverberation mapping). The time delay effect was discovered by Cherepashchuk and Lyutyi in 1973 [29]. It was mentioned there that the time delay of the line variability with regard to the continuous spectrum is equal to the time needed for ionizing radiation to cover the distance from the galactic center to the gaseous clouds emitting in the line. Thus an independent estimate of the distance can be obtained and the mass of an active galaxy nucleus can be reliably determined.

The first method to estimate BH masses in active galactic nuclei suggested that the bolometric luminosity of the nucleus should be close to the Eddington limit [19]. Such estimates give the following values for quasar nuclei masses: $M > 10^8 M_\odot$.

So far there are some dozens of BH masses in active galactic nuclei estimated by means of the time delay effect according to which emission line variability lags behind continuum [18].

"Normal galaxies" have got nuclei which are characterized by rather faint optical activity as compared to their stellar constituent. In such galaxies stars and gas moving near the nucleus can be observed directly what permits the most exact and model-independent mass estimates of supermassive BH to be obtained. Recently disks of gas and dust spanning some dozens or hundreds of parsecs around the nuclei of many galaxies and rotating according to Newton's law were discovered aboard the Hubble space telescope with high angular resolution (see [30] and references therein). To check the validity of the Keplerian rotation law for a disk ($v \sim r^{-1/2}$) and to obtain the inclination angle $i$ between the disk axis and the line of sight Doppler shifts are investigated in emission lines using the projection of the near-nucleus region of the disk onto the picture plane. Then the mass in the volume with radius $r$ is estimated unequivocally. Since the near-nucleus region in the galaxy may be observed directly the mass-to-luminosity ratio, $M(r)/L(r)$, can be estimated and compared with the corresponding value for external parts of the galaxy, $M/L \cong 1 \div 10$, where $M$ and $L$ are the solar mass and luminosity respectively. The first galaxy to have been used for determining the mass of the central BH using the near-nucleus disk of gas and dust with a luminous and stretched jet was M87 [31]. The mass of the central BH is $(3.2 \pm 0.9) \cdot 10^9 M_\odot$, the mass-to-luminosity ratio is $M/L > 110$. If the central mass was due to a dense cluster of ordinary stars rather than a BH, the nucleus of M87 would be dozens of times brighter than what is actually observed. An average density of dark matter in the nucleus of M87 is estimated to be $10^7 M_\odot/\mathrm{pc}^3$ whereas star density in external parts of the galaxy is $0.5 M_\odot/\mathrm{pc}^3$ and in the most dense stellar clusters $10^5 M_\odot/\mathrm{pc}^3$. All these findings allow one to believe with a good reason that there is a supermassive BH in the nucleus of M87 (three billion solar masses) which undergoes accretion of matter causing many aspects of M87 activity including formation of a relativistic jet. A number of mass estimates obtained so far for supermassive BH by means of researching gas and star kinematics near galactic nuclei reaches many dozens (see, for example, review [18]).

Table 2 gives some results on determining BH masses in galactic nuclei.

Outstanding results for estimating BH masses in galactic nuclei have been obtained recently while researching compact maser sources in near-nucleus molecular disks by means of intercontinental radioastronomy (see review by Moran et al. [32] and references therein). Observations of NGC4258 galactic nucleus revealed 17 compact maser sources emitting very narrow $H_2O$ lines and being located in a disk-like envelope with a radius of $10^{17}$ cm which is seen nearly edge-on. Velocities of maser sources are distributed according to the Keplerian law. The mass of a central BH is $3.9 \cdot 10^7 M_\odot$. This method has been used so far to measure masses of about a ten BHs in nuclei of galaxies (see reviews [32, 18] and references therein).

## 5 A Supermassive Black Hole in the Nucleus of Our Galaxy

The most convincing evidence for a supermassive BH have been obtained recently while researching motions of individual stars in the closest surroundings of SgrA* source, the center of our Galaxy. Beginning from the 90s of the past century the motions of individual stars have been investigated in the picture plane near the center of our Galaxy [33]. Observations are carried out in the IR range using special techniques for compensation of atmospheric distortions of the image (the Galactic

Center is hidden from optical view by thick layers of gas and dust). The stars near the Galactic Center are found to shift considerably, their velocities being the higher the closer to the Center. Recently R.Schoedel [34] et al. constructed an orbit of one of the closest stars to the Galactic Center (SO2) (see Fig. 6).

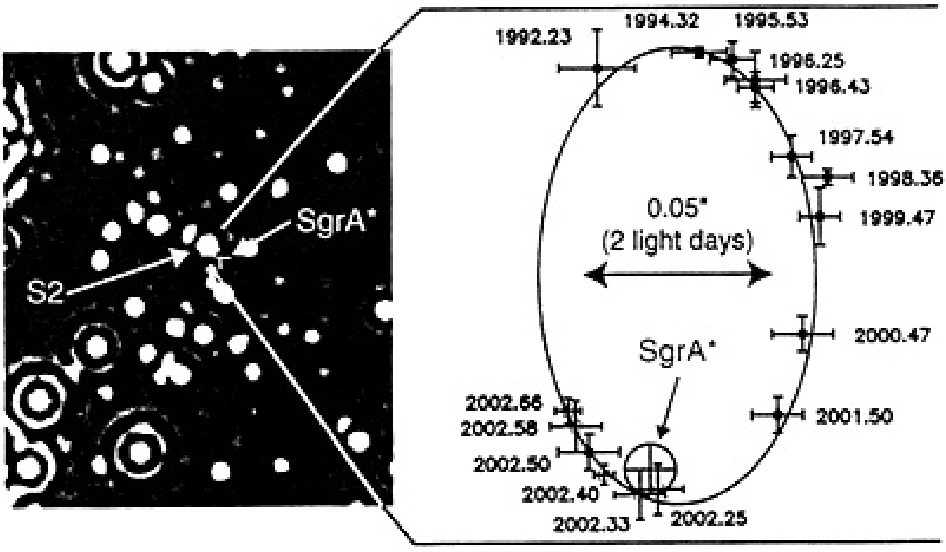


Fig. 6. The orbit of S2 star moving around the supermassive BH in the center of our Galaxy constructed by R.Schoedel et al. [34]. To the left: the sky region in the field of SgrA* source, the center of the Galaxy, which is seen to contain a cluster of stars.

The star SO2 has 15.2-year orbit with an eccentricity of 0.87 and a semi-major axis of $4.62{\cdot}10^{-3}$ pc ($20000 r_g$). Kepler's third law yields, for a BH mass, $(3.7 \pm 1) \cdot 10^6 M_\odot$. The dark gravitating matter density in the field measured reaches $10^{17} M_\odot/\mathrm{pc}^3$ while a typical dynamical break-up time of a supposed cluster of individual dark bodies in the galactic nucleus (due to collective collisions) is estimated to be $10^5$ years, the age of the Galaxy being $10^{10}$ years. This argues strongly that the massive compact object in the center of the Galaxy forms a whole dark body rather than a cluster of individual low-mass objects. Moreover, orbits of eight individual stars near the galactic center were measured lately: SO-16, SO-19, SO-20, SO-1, SO-2, SO-3, SO-4, SO-5. The BH mass in the Galactic nucleus is estimated to be $(4 \pm 0.3) \cdot 10^6 M_\odot$, it is situated at the dynamic center of the Galaxy within $\pm 10^{-3}$ arcsec. The BH proper motion is $(0.8 \pm 0.7) \cdot 10^{-3} \mathrm{s} \cdot \mathrm{year}^{-3}$ what is actually zero within the limits of error. These findings argue strongly in favour of Gurevich's idea [35] that supermassive BH form in galactic nuclei due to accretion of baryonic matter which falls into potential wells in the center of galactic halos of dark matter. The SO-16 star approaches the BH as close as 90 AU ($1700 r_g$) while moving in the orbit around.

## 6 Observational Restrictions upon Radii of Black Holes in Galactic Nuclei

According to X-ray image data with resolution $0.''5$ obtained by the Chandra observatory the center of the Galaxy is shown to emit variable X-rays. On the time scale of a year X-ray luminosity changes between $2 \cdot 10^{33}$ and $10^{35}$ erg/s, the galactic nucleus displaying rapid variability (as high as 5 times on the scales $t_{min} \leq 10$ min) [36]. Hence the size of the region emitting in X-rays, $r \leq c t_{min}$, is

$20r_g$. The center of the Galaxy shows large variations in IR flux density, a factor of 2 over 40 min, as was discovered with the W. M. Keck II 10-meter telescope [37]. This variability implies that the size of the IR emitting field does not exceed $80r_g$. IR luminosity of the galactic center is $10^{34}$ erg/s at 3.8 $\mu$m. The variable IR source is coincident with the center of the Galaxy to within $6 \cdot 10^{-3}$ arcsec and does not move, its velocity being at least $v < 300$ km/s, whereas the stars near the galactic center have got constant luminosity and move around the center with velocities of thousands of km/s.

**Table 2. Masses of Supermassive Black Holes in Galactic Nuclei Estimated from Kinematics of Gas and Stars**

| Galaxy | Type | Distance Mps | $M_B$ (bulge) | $\sigma_1$ km/s | $M_{BH}$(max,min) ($M_\odot$) | Method of determination |
|---|---|---|---|---|---|---|
| Milky Way | SBbc | 0.008 | -17.65 | 103 | $1.8 \cdot 10^6$(1.5,2.2) | s,p |
| NGC221 =M32 | E2 | 0.81 | -15.83 | 75 | $2.5 \cdot 10^6$(2.0,3.0) | s,3I |
| NGC224 =M31 | Sb | 0.76 | -19.00 | 160 | $4.5 \cdot 10^7$(2.0,8.5) | s |
| NGC821 | E4 | 24.1 | -20.41 | 209 | $3.7 \cdot 10^7$(2.9,6.1) | s,3I |
| NGC1023 | SB0 | 11.4 | -18.40 | 205 | $4.4 \cdot 10^7$(3.9,4.9) | s,3I |
| NGC1068 | Sb | 15.0 | -18.82 | 151 | $1.5 \cdot 10^7$(1.0,3.0) | m |
| NGC2778 | E2 | 22.9 | -18.59 | 175 | $1.4 \cdot 10^7$(0.5,2.2) | s,3I |
| NGC2787 | SB0 | 7.5 | -17.28 | 140 | $4.1 \cdot 10^7$(3.6,4.5) | g |
| NGC3115 | S0 | 9.7 | -20.21 | 230 | $1.0 \cdot 10^9$(0.4,2.0) | s |
| NGC3245 | S0 | 20.9 | -19.65 | 205 | $2.1 \cdot 10^8$(1.6,2.6) | g |
| NGC3377 | E5 | 11.2 | -19.05 | 145 | $1.0 \cdot 10^8$(0.9,1.9) | s,3I |
| NGC3379 | E1 | 10.6 | -19.94 | 206 | $1.0 \cdot 10^8$(0.5,1.6) | s,3I |
| NGC3384 | S0 | 11.6 | -18.99 | 143 | $1.6 \cdot 10^7$(1.4,1.7) | s,3I |
| NGC3608 | E2 | 22.9 | -19.86 | 182 | $1.9 \cdot 10^8$(1.3,2.9) | s,3I |
| NGC4258 | Sbc | 7.2 | -17.19 | 130 | $3.9 \cdot 10^7$(3.8,4.0) | m,a |
| NGC4261 | E2 | 31.6 | -21.09 | 315 | $5.2 \cdot 10^8$(4.1,6.2) | g |
| NGC4291 | E2 | 26.2 | -19.63 | 242 | $3.1 \cdot 10^8$(0.8,3.9) | s,3I |
| NGC4342 | S0 | 15.3 | -17.04 | 225 | $3.0 \cdot 10^8$(2.0,4.7) | s,3I |
| NGC4459 | S0 | 16.1 | -19.15 | 186 | $7.0 \cdot 10^7$(5.7,8.3) | g |
| NGC4473 | E5 | 15.7 | -19.89 | 190 | $1.1 \cdot 10^8$(0.31,1.5) | s,3I |
| NGC4486 =M87 | E0 | 16.1 | -21.53 | 375 | $3.0 \cdot 10^9$(2.0,4.0) | g |
| NGC4564 | E3 | 15.0 | -18.92 | 162 | $5.6 \cdot 10^7$(4.8,5.9) | s,3I |
| NGC4596 | SB0 | 16.8 | -19.48 | 152 | $7.8 \cdot 10^7$(4.5,12) | g |
| NGC4649 | E1 | 16.8 | -21.30 | 385 | $2.0 \cdot 10^9$(1.4,2.4) | s,3I |
| NGC4697 | E4 | 11.7 | -20.24 | 177 | $1.7 \cdot 10^8$(1.6,1.9) | s,3I |
| NGC4742 | E4 | 15.5 | -18.94 | 90 | $1.4 \cdot 10^7$(0.9,1.8) | s,3I |
| NGC5845 | E3 | 25.9 | -18.72 | 234 | $2.4 \cdot 10^8$(1.0,2.8) | s,3I |
| NGC6251 | E2 | 93.0 | -21.81 | 290 | $5.3 \cdot 10^8$(3.5,7.0) | g |
| NGC7052 | E4 | 58.7 | -21.31 | 266 | $3.3 \cdot 10^8$(2.0,5.6) | g |
| NGC7457 | S0 | 13.2 | -17.69 | 67 | $3.5 \cdot 10^6$(2.1,4.6) | s,3I |
| IC1459 | E3 | 29.2 | -21.39 | 340 | $2.5 \cdot 10^9$(2.1,3.0) | s,3I |

**Note:** $M_B(bulge)$ is here a stellar B magnitude of the galactic bulge, $\sigma_1$, the velocity dispersion of bulge stars, $M_{BH}$, the mass of the central BH in terms of $M_\odot$ (with maximum and minimum BH mass values in brackets corresponding to RMS deviations of mass determination). Designations in the last column stand for different ways of BH mass determination: s – stellar radial velocities, p – stellar proper motions, m – radial velocities of gas clouds estimated over maser emission lines, g – a rotating gas disk observed in emission lines, 3I – axially symmetric dynamical model involving three integrals of the motion.

Therefore, observations indicate that there is a massive compact object with a mass of $4 \cdot 10^6 M_\odot$ and a radius less than 20 gravitational radii in the center of our Galaxy, the parameters arguing in favour of the object being a supermassive BH.

Direct measuring a supermassive BH radius in the center of the Galaxy (as well as in the centers of nearby galaxies) will be possible after launching space interferometers: an X-ray interferometer with $10^{-7}$ arcsec resolution [38] and the RadioAstron interferometer with $10^{-6}$ arcsec resolution in the radio range. Angular sizes of the supermassive BH in the centers of our Galaxy and the Andromeda Galaxy are $7 \cdot 10^{-6}$ and $3 \cdot 10^{-6}$ arcsec, respectively. Launching these interferometers will allow not only supermassive BH radii to be measured but also physical phenomena to be observed connected with plasma moving near the event horizon. Such experiments are likely to provide sufficient criteria to select BH and to prove, once and for all, their existence in the Universe. Using contemporary intercontinental interferometry techniques made it possible to research, in the millimeter range, the formation of jet in the inner parts of the M87 galaxy as well as to confine directly a value of the supermassive BH radius within $r < 30 - 100$ gravitational radii [39].

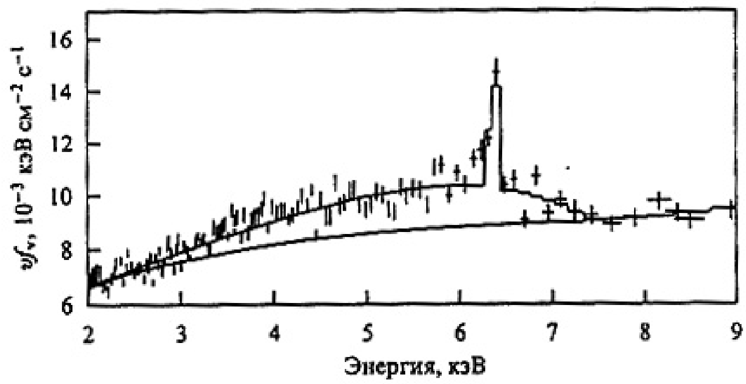


Fig. 7. The profile of Fe X-ray $K_\alpha$ line in the spectrum of the Seyfert galaxy MCG-6-30-15 obtained by the X-ray observatory XMM in the period of low X-ray nucleus luminosity (Wilms J. et al. [40]). Along with a narrow line with the energy close to the laboratory standard, $\sim 6.4$ keV, a very large profile component is observed which is greatly displaced towards the low spectral energies. This indicates that the region of line formation is within three gravitational radii from the central supermassive BH.

In addition, iron $K_\alpha$ emission line profile in X-rays at 6.4 keV in spectra of active galactic nuclei observed aboard X-ray observatories ASCA, CHANDRA, and XMM with high spectral resolution [40] also restricts strongly the values of BH radii. Relativistic effects near the event horizon of the central BH result in the redshift of a spectral line, its specific asymmetric profile and a huge width (up to 100,000 km/s) thus providing bounds on the supermassive BH radius in the center of a galaxy. For instance, in case of MCG-6-30-15 galactic nucleus, analysis of the wide spectral component of Fe XXV X-ray line profile indicates that the inner edge of the accretion disk is located less than $3r_g$ from the central supermassive BH which seems to rotate [40] (see Fig. 7).

## 7 Demography of Supermassive Black Holes

A number of supermassive BH with their masses measured approaches now 200. The radii estimated are available for many of them: $r < (10 - 100)r_g$. Hence a new field in astrophysics is intensively developing now, the demography of BH. The basic results achieved in this field are briefly stated below.

1. Supermassive BH in galactic nuclei have masses correlated with those of galactic bulges, spherical condensations of old low-mass stars near the nucleus with the large dispersion of velocities [41]: $M_{BH} = 0.0012 M_{bulge}^{0.95 \pm 0.05}$.

2. There is the correlation between supermassive BH masses and velocity dispersion of stars, $\sigma$, belonging to the bulge [42]: $M_{BH} \sim \sigma_{bulge}^4$.

3. Masses of supermassive BH are correlated with linear rotation velocities of galaxies in the range of a costant value of the velocity. Since a linear rotation velocity of a galaxy far away from its center is mainly due to the gravitational pull of the galactic halo consisting of dark matter, the mass of the central supermassive BH should be correlated with the mass of the galactic halo [43]: $M_{BH} \sim M_{halo}^{1.27}$.
   The result obtained is an important evidence in favour of Gurevich's model [35].

## 8 Conclusion

The actual state of the problem connected with searching for both stellar-mass BH and supermassive BH in the galactic nuclei has been described. We did not touch upon the problem concerning searches for primary BH because of the lack of observational data and ambiguity revealed in their interpretation. Primary BH may as well exist among isolated stellar-mass BH. It is worthwhile mentioning that, using gravitational microlensing effect [44], the masses of two isolated BH have been measured so far: $m_{BH} \cong 6 M_\odot$ (the brightness of a distant background star being strenghened because of the influence of a foreground object playing a part of a "gravitational lense", the duration of its strengthened brightness is proportional to a square root of the gravitational lense mass). The problem for searching BH of intermediate mass ($m_{BH} = 10^2 \div 10^4 M_\odot$) was not considered either because there were not convincing findings in this field. The review on intermediate mass BH located both in galaxies and in stellar clusters is available in [45].

It is important that the problem with searching for BH is actually supported with a firm observational basis and a number of BH being discovered is gradually increasing (around 200 at the present moment). It should be especially emphasized that all necessary constraints imposed upon BH manifestations by Einstein's General Relativity are fulfilled as it follows from observational data. This strengthens considerably our confidence in actual existence of BH in the Universe.

The main task to be solved in the decade to come is to find sufficient criteria for BH candidates being real BH. The following experiments may be expected to help in solving this problem:

1. Using space interferometers with $10^{-6} - 10^{-7}$ arcsec angular resolution and direct observations of matter moving close to event horizons of supermassive BH in nuclei of our and nearest galaxies.

2. Searches and investigations of gravitational wave bursts from BH coalescence in binary systems with the use of laser gravitational wave interferometry (LIGO, VIRGO, LISA, etc.).

3. Detection and researches of radiopulsar motion in binary systems with BH (among 1000 pulsars one pulsar is anticipated to be paired with a BH, about 1500 pulsars being known so far).

4. Detailed investigations of spectra, intensity, polarization and variability of X-ray and gamma-radiation from accreting BH with the use of new generation orbital observatories.

5. Observations and interpretations of gravitational microlensing effects in galactic nuclei caused by closer galaxies (gravitational lenses).

6. Routine storage of evidence concerning masses of black holes and neutron stars (NS) as well as statistical comparison between observational manifestations of BH and NS.

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