Black Holes in Binary Systems and Nuclei of Galaxies

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During last 45 years, a big progress has been achieved in observational investigations of stellar mass black holes in X-ray binary systems and supermassive black holes in galactic nuclei. Masses of several dozens of stellar mass black holes ($M_{BH} = 4 \div 20 M_{\odot}$) as well as many hundreds of supermassive black holes ($M_{BH} = 10^6 \div 10^{10} M_{\odot}$) were measured. Recent discovery of gravitational waves from a binary black hole merger opens new era in investigations of black holes.

1 Introduction

In the last 45 years, following pioneering papers by Ya.B. Zeldovich [1] and E.E. Salpeter [2] in which powerful energy release from non-spherical accretion of matter onto black holes (BH) was predicted, many observational investigations of BHs in the Universe have been carried out. To date, the masses of several dozens stellar-mass BH ($M_{BH} = 4 \div 20 M_{\odot}$) in X-ray binary systems and many hundreds supermassive BH ($M_{BH} = 10^6 \div 10^{10} M_{\odot}$) in galactic nuclei have been measured. The estimated radii of these massive and compact objects do not exceed several gravitational radii.

Observations suggest (taking into account observational selection effects) that the number of stellar-mass BHs ($M = 8 \div 10 M_{\odot}$) in our Galaxy amounts to at least 10^7 or 0.1% of the baryonic matter. A great discovery was made recently by American gravitational wave antennas LIGO1 and LIGO2: gravitational waves were detected from a binary black hole merger GW150914 [3].

Black holes are derived from the collapse of massive objects. According to modern concepts taking into account general relativity effects, if the mass of the stellar core where thermonuclear burning occurs exceeds $3M_{\odot}$ the gravitational core collapse results in the formation of a BH. If the mass of the stellar core is less than $3M_{\odot}$, the stellar evolution ends up with the formation of neutron star or a white dwarf.

A black hole is an object (more precisely, a space-time region) with such a strong gravitational field that no signal, including light, can escape from it to the space infinity. Characteristic dimension of BH is given by the gravitational (Schwarzschild) radius: $r_g = 2GM/c^2$, where M is the mass of the object, G is the Newtonian constant of gravitation, and c is the speed of light in vacuum.

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In this review, we describe the present-day observational status of BHs and discuss further prospects for studies of these extreme objects.

2 Stellar-mass black holes in X-ray binary systems

Black holes can be found in X-ray binary systems ($M_{BH} = 4 \div 20 M_{\odot}$), and in galactic nuclei ($M_{BH} = 10^6 \div 10^{10} M_{\odot}$).

After the great discovery of gravitational waves [3], it is clear that black holes can be found also in BH+BH and BH+NS binary systems (here BH is black hole, NS is neutron star).

An X-ray binary consists of a normal optical star (the donor of matter) and relativistic object, a neutron star or black hole, which accretes matter from its companion. To date, specialized X-ray satellites (Uhuru, Einstein, Rosat, Mir-Kvant, Granat, Ginga, Chandra, XMM-Newton, Integral, etc.) have discovered more than one thousand X-ray binaries, which serve as a powerful tool in the detection and studies of stellar-mass BHs. The theory of disk accretion was developed in 1972–1973 in papers by Shakura and Sunyaev [4], Pringle and Rees [5], Novikov and Thorne [6].

X-ray and optical observations of X-ray binary systems perfectly complement each other. X-ray observations from space vehicles allow one to foresee the presence of a compact object in a binary system, while measurements of rapid X-ray time variability on timescales Δt as short as 10^{-3} s provide an estimate the characteristic size of a compact star: $r \leq c\Delta t$. These estimates imply that the sizes of compact X-ray sources never exceed several gravitational radii. At the same time, spectral and photometric observations by ground-based optical telescopes enable us to study the motion of the normal star in an X-ray binary system and to deduce using the star as a "test body", the mass of BH or neutron star from Newton's law of gravitation. A great contribution to the theory of absorption and emission lines formation in the stellar atmospheres was done by Sobolev [7]. If the measured mass of an X-ray source exceeds $3M_{\odot}$, it can be considered as a BH candidate. Just this determines the strategy of searching for stellar-mass BHs in binary systems.

The first optical identifications of X-ray binary systems and studies of their optical manifestations (ellipticity and reflection effects) were carried out in 1972–1973 and reported in papers [8]–[11]. Based on these studies, reliable methods of estimating the BH masses in X-ray binaries were developed.

Methods of interpreting light curves, line profiles and radial velocity curves of X-ray binaries were developed by assuming that the optical star has an ellipsoidal or pear-like shape in the framework of Roche model with a complex surface temperature distribution due to gravitational darkening and X-ray heating effects [12]. To date, some scientific groups (from USA, the UK, Germany, Netherlands, France, Russia and some other countries) have measured the masses of 26 stellar-mass BHs ($M_{BH} = 4 \div 20 M_{\odot}$), as well as the masses of $\sim$70 neutron stars ($M_{NS} \approx 1 \div 2 M_{\odot}$) in binary systems (see Fig. 1).

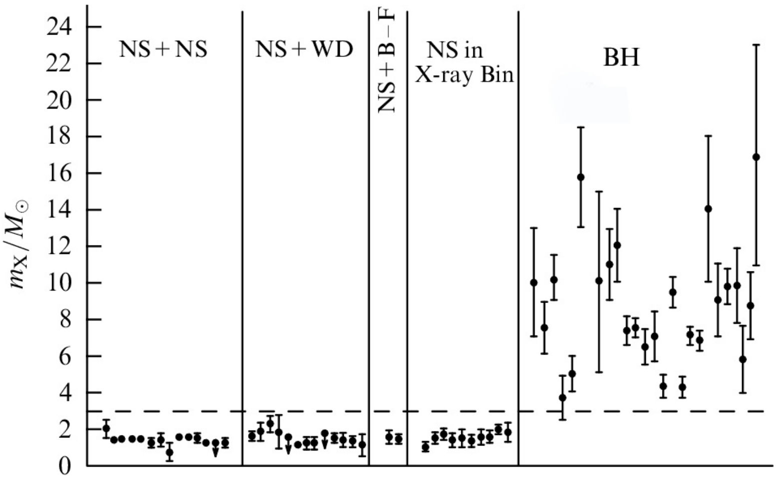

Figure 1: Measured masses of neutron stars and black holes in binary stellar systems: NS+NS – binary radio pulsars with neutron stars, NS+WD – binary radio pulsars with white dwarfs, NS+B–F – binary radio pulsars with an optical non-degenerate stars of the B–F spectral class, NS in X-ray Bin – binary X-ray pulsars. The dashed horizontal line shuts off the value of $3M_\odot$ being the absolute upper limit of neutron star mass predicted by GR.

The measured masses of neutron stars lie within the range of $1 \div 2M_\odot$, with the mean mass being $\sim 1.4M_\odot$. Fine differences in various types of neutron stars have already been found. For example, the masses of rapidly rotating old neutron stars (spin period of about several ms) which have been recycled by accretion in close binary systems [13], are on average $\sim 0.15M_\odot$ higher than the masses of slowly rotating neutron stars (spin periods about several s) [14]. This inference is consistent with theoretical predictions [15].

All neutron stars with measured masses demonstrate clear signatures of their observable surfaces – they are either radio pulsars, X-ray pulsars or type I X-ray bursters.

Thus, in all $\sim$70 cases where a compact object demonstrates clear signatures of an observable surface, its measured mass ranges $1 \div 2M_\odot$ and does not exceed $3M_\odot$, in full agreement with the GR prediction of the existence of an upper mass limit $3M_\odot$ for neutron stars.

The measured masses of 26 BH candidates fall within the range ($M_{BH} = 4 \div 20M_\odot$) with the mean mass being of order $9M_\odot$. As BHs have no observable surface, they should not show up as a radio pulsar, X-ray pulsar, or type I X-ray burster. This is indeed the case for 26 BH candidates: none (!) of these massive ($M > 3M_\odot$), compact (radii do not exceed a few r_g) X-ray sources has shown evidence of radio pulsar, X-ray pulsar, or type I X-ray burster.

All of them demonstrate only irregular or quasi-periodic (but not strictly periodic) X-ray emission variability down to timescales as short as $\sim 10^{-3}$ s. In the model which takes into account oscillation of the inner parts the accretion disk or the orbital motion of hot spots in the inner parts of the disk, it is possible to show (e.g., [16]) that such a rapid X-ray variability of BH candidates is due to their very small sizes not exceeding several gravitational radii.

Thus, a remarkable result gradually emerges with the increasing bulk of information on the masses of relativistic objects: neutron stars and BH candidates differ not only in masses, but also in other observational manifestations, in full agreement with GR.

New results have recently been obtained in studies of the rotation of stellar-mass BHs. The possibility of determining the angular momentum of a BH stems from the fact that if BH co-rotates with the accretion disk, the inner edge of the disk comes much closer to the BH than in the case of a non-rotating BH, since the radius of the event horizon of a rotating BH is smaller than that of a non-rotating BH.

The measured values of dimensionless angular momentum of stellar mass BH lie within the range

$$a_* = 0.98\,(\text{system GRS1915+105}) \div 0.12\,(\text{system A0620}-00). \tag{1}$$

A remarkable result was recently obtained by Narayan and McClintock [17]. They found a correlation between the observed radio fluxes from collimated jets from accreting BHs, P_{jet}, and the value of dimensionless angular momentum a_* of the BHs: $P_{jet} \sim a_*^2$. This is the first observational evidence that the relativistic jets from accreting stellar-mass BHs can be generated from the conversion of the rotational energy of BH into the kinetic energy of regular bulk motion of matter in collimated relativistic jets with outflow velocities close to the speed of light. Here, the well-known Blandford–Znajek mechanism seems to be operative [18].

Relativistic collimated jets are observed in many X-ray binary systems (most spectacular example is the SS433 binary system, e.g., [19, 20]). Studies of X-ray binaries with relativistic collimated jets, called microquasars, are of special interest, since the physical processes in microquasars are microscopic versions of processes occurring in quasars – very active galactic nuclei, as well as in the nuclei of other galaxies.

3 Supermassive black holes in galactic nuclei

The first estimates of the masses of supermassive BHs (SMBHs) in quasars were made as early as 1964 in the pioneering paper by Zeldovich and Novikov [21] under reasonable assumption that the quasar luminosity is close to the critical Eddington luminosity.

Presently, the masses of SMBHs in galactic nuclei estimated by assuming that the motion of “test bodies” (gas disks, gas clouds, individual stars) near the SMBH is governed by the gravitational field of the central SMBH. In this case the mass of SMBH can be estimated by the formula

$$M_{BH} = \eta V^2 r/G, \tag{2}$$

where V is the velocity of the test body, r is its distance from the center of SMBH, G is the Newtonian constant of gravitation, $\eta \cong 1 \div 3$ is the factor that takes into account the character of test body motions around the central SMBH.

The two most reliable methods of SMBH mass determination in galaxy centers are the resolved kinematics method and reverberation mapping method.

The method of resolved kinematics is based on direct observations of the motion of test bodies (e.g., [22]). It can be applied to nearby galaxies, for which the telescope angular resolution allows "watching" the test bodies residing in the galactic nucleus and direct measurement of their velocities and distances from the central SMBH. For example, there is a SMBH with mass $(4.31 \pm 0.36) \times 10^6 M_\odot$ in the center of our Galaxy. The mass of this SMBH is determined with an accuracy of better than 10% from the motion of 28 stars orbiting it in elliptic orbit [23]. Using very long baseline radio interferometers, by resolved kinematics method the mass of the SMBH in the center of galaxy NGC4257 was reliably determined to be $M_{BH} = 3.9 \times 10^7 M_\odot$ [24]. For more detailed results of SMBH mass estimations by resolved kinematics methods using basically Hubble Space Telescope, see review by Kormendy and Ho [22].

Unfortunately, the angular resolution of telescopes for the most of remote galaxies is insufficient to directly see individual test bodies; in these cases, one has to apply the reverberation mapping method when estimating the mass of SMBHs. In this method, the velocities and distances of test bodies are estimated indirectly. In the case of active galactic nuclei the velocity V is estimated from Doppler width of emission lines formed in gas clouds, rotating around the central SMBH.

The characteristic distance r of the gas clouds from the central SMBH is determined from the time delay of the emission lines variability relative to that of the continuum spectrum, which is formed in the central parts of the galaxy nucleus.

The time delay between the variability in emission lines relative to the continuum in active galactic nuclei was discovered in 1970–1972 by Cherepashchuk and Lyutyi [25]. It turned out that although due to non-stationary processes in galactic nuclei both the lines and continuum change chaotically, a correlation is revealed between their changes: the line intensity variations repeat those of the continuum intensity with a time delay Δt, which in different galaxies varies from a week to several months. It was noted [25] that a comparatively high gas density in the clouds corresponding to broad components of emission lines implies a short gas recombination time, so the time delay Δt is basically the time of flight of hard emission photons, which are created near the central accreting source to the gas clouds – test bodies emitting spectral lines. Then, the characteristic distance from the test bodies to the central SMBH can be estimated using formula $r \cong c\Delta t$. The SMBH mass can ultimately be estimated from the known characteristic distance r and velocity V using formula (1). The reverberation mapping method for SMBH mass estimates has been widely applied to evaluate SMBH masses in active galactic nuclei.

There are also indirect, less reliable methods of SMBH mass estimates. These include, for instance, the use of widths and absolute intensities of emission lines in active galactic nucleus spectra (e.g., [26]), the empirical relation between SMBH mass and velocity dispersion of stars in the galactic central regions and kink frequency in the power spectra of X-ray irregular variability of galactic nuclei. Such methods enable a quick mass estimation of a large number of SMBHs, which is essential for statistical studies. As a rule, the results obtained with these indirect methods are calibrated by SMBH masses which were reliably measured using resolved kinematics and reverberation mapping methods.

To date, the masses of several hundreds SMBHs have been measured applying resolved kinematics and reverberation mapping methods. They all lie within the range of $10^6 \div 10^{10} M_\odot$. The most reliable mass estimates of SMBH in 44 elliptical and 41 spirals (see the recent review by Kormendy and Ho [22]) span the interval from $(0.94 \div 1.34)\, 10^6 M_\odot$ to $(0.49 \div 3.55)\, 10^{10} M_\odot$. Here, the values in parenthesis stand for the mass determination errors. Reliable values of mass of SMBHs and central star clusters were summarized recently by Zasov and Cherepashchuk [27] for 82 galaxies with known rotational velocities (i.e. with known total galactic masses, including the dark matter halo mass).

Indirect mass evaluations were made for many thousand SMBHs in active galactic nuclei. For example, the targeted spectrophotometric Sloan digital sky survey (SDSS) allowed about 60 000 SMBH mass in centers of quasars to be estimated by indirect method, and statistical dependence of SMBH masses on redshift to be constructed in the redshift range $z = 0.1 \div 4.5$ [28]. It turned out that on average the SMBH mass increases with redshift (i.e. with a decrease in the proper age of a quasar). This effect, if free of a strong observational selection, can hardly be explained in the framework of the model of an SMBH mass increase due to the accretion of circumnuclear matter in quasars.

But the most difficult question to explain relates to the discovery of more than a dozen quasars with very high redshifts $z = 6 \div 8$ (proper age of less than one billion years [29]). How could such massive ($M_{BH} = 10^8 \div 10^{10} M_\odot$) SMBHs be formed in a time of less than 10^9 years? This important observational fact poses a serious theoretical problem.

In recent years (e.g., [30]), the analysis of iron K_α line profiles in X-ray spectra of galactic nuclei has allowed the dimensionless angular momentum $a_* = cj/(GM_{BH}^2)$ to be estimated for some SMBHs. These parameters found to be less than the critical value of $a_* = 0.998$, in agreement with theoretical predictions [31]. The parameter a_* can be estimated also from the kinetic energy flux in relativistic jets from SMBH [32]. These estimates require the magnetic field value in the last stable orbit in the accretion disk or the SMBH event horizon to be known. Spectropolarimetric observations of the nuclei of active galaxies made by Gnedin group [33] allowed the values of parameter a_* to be estimated for a dozen SMBHs. The values found range from $a_* = 0.920 \div 998$ to $a_* = 0.550 \div 0.650$ and do not exceed the theoretical upper limit $a_* = 0.998$.

Limits on the radii of SMBHs are set by observations of fast variability of the optical, infrared and X-ray emission from some galactic nuclei on timescales smaller than tens of minutes. Strong but model-dependent constraints on the SMBH radii can be obtained by analyzing the broad X-ray profiles of the iron K_α emission line at 6.4 keV. The line width of this asymmetric profile corresponds to velocities as high as $\sim 10^5$ km/s. The analysis of this component in the galaxy MCG6–30–15 [34] implies that the inner edge of the accretion disk in this case is located at a distance smaller than $3r_g$ from central SMBH, possibly due to its rapid rotation.

In the last few years, direct measurements of the radii of SMBHs in the center of our Galaxy ($M_{BH} \cong 4.3 \times 10^6 M_\odot$) and galaxy M87 ($M_{BH} = 6 \times 10^6 M_\odot$) have been carried out using VLBI-interferometry at short wavelengths ($\lambda \cong 1.3$ mm) with an angular resolution close to 10^{-5} seconds [35, 36]. It is shown that the dimension of the SMBHs "shadow" at the center of the accretion flow is several gravitational radii ($r_g = 9.1 \times 10^{-6}$ arcseconds for SMBH in our Galaxy and $r_g = 7.8 \times 10^{-6}$ arcseconds for the SMBH in the galaxy M87). A great contribution to the problem of measuring the dimensions of SMBHs will be done by the space radiointerferometers RADIOASTRON and MILLIMETRON.

Accordingly to S.S. Doelman, international effort has been done recently to create an Event Horizon Telescope (EHT) through a millimeter wavelength VLBI network. The EHT is the global effort to carry out the investigations of BH "shadow" and strong gravity effects in the vicinity of the event horizon of SMBH. The Black Hole Cam team, along with groups from Taiwan, Japan, Chile, USA and Germany are all working within the EHT.

New results of measurement on EHT of linear polarization and intensity of radioemission on the scale about 6 gravitational radius for the supermassive black hole in the galaxy M87 have been published recently [37].

Thus, supermassive ($M_{BH} = 10^6 \div 10^{10} M_\odot$) and very compact objects (with sizes not exceeding several gravitational radii) have been discovered to date in the nuclei of many galaxies. All their features most likely suggest that they comprise black holes.

4 Demography of stellar-mass and supermassive black holes

Black hole demography studies the formation and growth of black holes and their evolutionary connection to other astrophysical objects – stars, galaxies, etc.

In the last few years, a close similarity has been established between the observational manifestations of BHs in X-ray binary systems and in galactic nuclei [38]. In particular, the statistical dependence, called the fundamental plane, was discovered for supermassive and stellar-mass BHs [39]

$$\lg L_r = (0.60^{+0.11}_{-0.11}) \lg L_x + (0.78^{+0.11}_{-0.09}) \lg M_{BH} + 7.33^{+4.05}_{-4.07}, \qquad (3)$$

where L_r is the observed radio luminosity (mainly due to relativistic jet radio emission), L_x is the X-ray luminosity (from the accretion disk and the jet base), and M_{BH} is the black hole mass (for both stellar-mass BHs and SMBHs).

The variability of active galactic nuclei containing accreting supermassive BHs was related to be similar to that of accreting stellar-mass BHs in X-ray binary systems if the variability time is normalized depending on the BH mass [38].

In X-ray binaries with BHs, in addition to irregular variability there are two types of quasi-periodic (i.e., not strictly periodic) oscillations (QPO) of an X-ray flux: low frequency QPOs (LFQPOs) with the characteristic frequencies $0.1 \div 30$ Hz, and high-frequency QPOs (HFQPOs) with frequencies falling in the range of $40 \div 450$ Hz.

Quasi-periodic X-ray oscillations were recently discovered from accreting SMBHs in the nuclei of some galaxies. For example, QPOs with the characteristic period of about one hour were observed in the active nucleus of the galaxy REJ1034+396 [40]. With a central SMBH mass of about $10^7 M_\odot$, this quasiperiod corresponds to an orbit radius of about $3r_g$, which yields an upper limit on the size of this very massive and compact object, giving support to its BH nature.

Interesting results were obtained in studies of the mass distribution of stellar-mass BHs. It turned out that in binary systems there is no dependence of masses of relativistic objects on their companion masses. The neutron star and black hole mass distribution turned out to be unusual as well [41, 42], – see Fig. 2. The number of studied stellar-mass BHs does not increase with decreasing of their masses. This looks strange, since the stellar mass distribution in the Galaxy (the most massive stellar objects are progenitors of the relativistic compact objects) is such that the number of stars very strongly (as M^{-5}) increases with decreasing stellar mass.

In addition, a mass distribution dip between $2M_\odot$ and $4M_\odot$ seems to exist for neutron star and BH masses. In this mass range, no neutron stars or BHs have been observed. The mass dip within the range $(2-4)M_\odot$ for neutron stars and BH mass distributions, if confirmed in further observations (especially from observations of X-ray binaries in other galaxies), will require a serious theoretical elucidation.

Let us briefly discuss the problem of SMBH demography (see the recent review by Kormendy and Ho [22]). As noted above, the formation time of SMBHs in galactic nuclei is relatively short, namely less than 10^9 years. Such a rapid formation of very massive BH is difficult to explain in the model assuming their mass growth due to gas accretion onto a low-mass seed BH that has been formed via the core collapse of a massive ($M = 100 \div 1000 M_\odot$) population III star, even if the mass accretion rate is as high as the Eddington luminosity.

Recently, in addition to SMBHs, the important role of massive stellar clusters located in galaxy center has been revealed [43, 44].

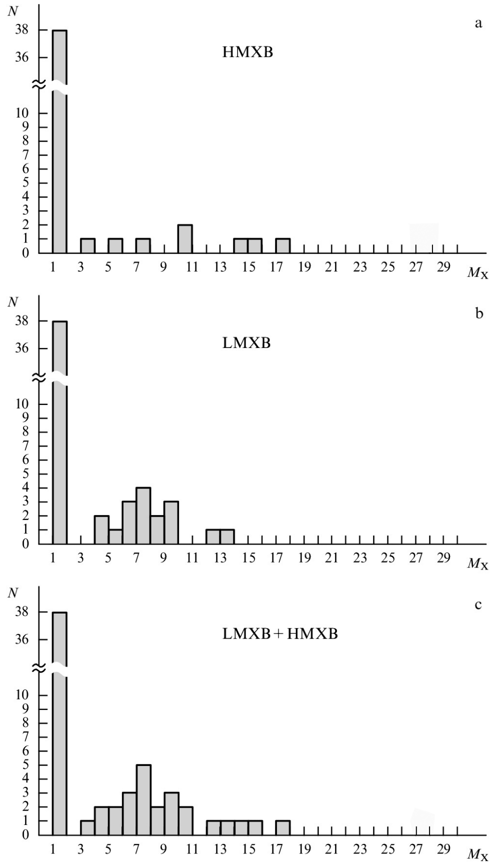

Figure 2: Neutron star and black hole mass distributions in binary systems: (a) black hole masses in high-mass X-ray binaries (HMXB) with massive optical stars of O–B and WR spectral classes; (b) black hole masses in low-mass X-ray binaries (LMXB), and (c) the total black hole and neutron star mass distributions (in low-mass and high-mass X-ray binaries). The high peaks in the left part of the panels (a)–(c) correspond to neutron star masses.

An important correlation is also revealed between SMBH masses, the masses of central star clusters, and parameters of spheroidal galactic components:

$$M \sim \sigma^{\beta},$$

where M is the mass of the SMBH or a stellar cluster, and σ is the star velocity dispersion in the spheroidal component. The index of a power is $\beta = 4 \div 5$ for SMBHs (e.g., [45]), and β falls within the range from 1.57 ± 0.24 [45] to 2.73 ± 0.29.

Although the dispersion of the exponent β for central star clusters is large ($\beta = 1.57 \div 2.73$), the dependence of mass M on the velocity dispersion σ for central star cluster may be considered as weaker compared to SBMHs. This allows us to assume that the formation and evolution of central SMBHs and massive star clusters in galactic nuclei are related to different mechanisms.

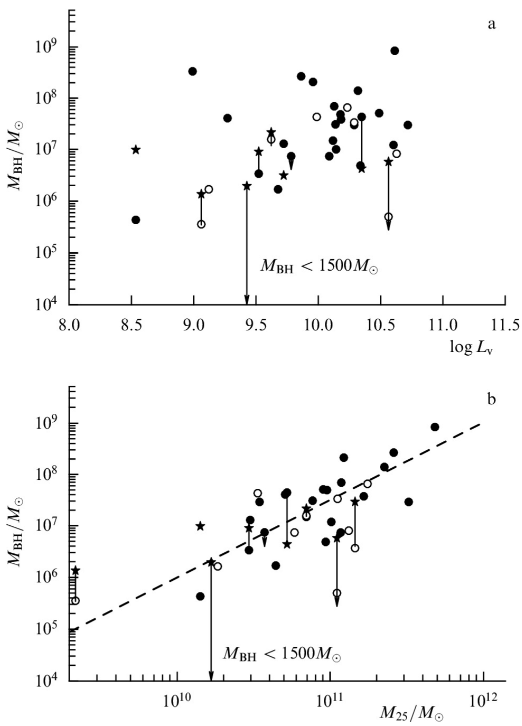

Figure 3: SMBH mass as function: (a) total optical luminosity L_V of the host galaxy characterizing the baryonic mass, and (b) the indicative mass of the galaxy $M_{25} = V_{far}^2 R_{25}/G$, which includes both baryonic and dark-matter masses. The filled "star" symbols correspond to central stellar clusters. Linear segments join circles (BHs) and filled "stars" (clusters). Arrows show the upper limits (taken from paper by Zasov et al. [43]).

Of special interest is the possible association of central SMBHs and massive star clusters with dark matter in galaxies. Our observations of the galactic rotation in galaxies with known heavy central black hole masses are aimed at solving this problem [43, 46, 27]. As shown in studies performed by A.V. Gurevich's group [47], the gravitational instability in proto-galaxy dark matter clumps form sharp and deep minima of gravitational potential (cusps), into which baryonic matter "falls" to produce a stellar population of the forming galaxy.

This process can also stimulate the formation of an SMBH in galaxy nucleus. Therefore, the association of the central SMBH mass with the mass of the galactic halo dominated by dark matter is rather expectable Indeed, due to coalescence of galaxies at early stages of their formation, as well as star formation in galactic centers, this association can be rather indirect. Nevertheless, the search for a correlation between the central SMBH mass and the dark matter-dominated galactic halo mass is a very important observational task.

In Fig. 3 important correlations obtained in our paper [43] are presented. They demonstrate the important role of dark matter in the central SMBH formation in the galactic nucleus. The figure depicts two dependencies: $M_{BH}(L_V)$ and

$M_{BH}(M_{25})$, where L_V is the total optical luminosity of the galaxy, which is a single-valued function of the total baryonic mass of the galaxy, and M_{25} is the so-called indicative mass of the galaxy: $M_{25} = V_{far}^2 R_{25}/G$, where V_{far} is the observed maximum rotational velocity of the galaxy (which tends to a plateau at large distances from the nucleus), and R_{25} is the radius of the galactic region limited by the surface brightness isophot reaching the 25th stellar magnitude per square arcsecond, which determines the boundary of the visible part of the galaxy. Apparently, there is virtually no correlation between the SMBH mass and the total baryonic mass of the whole galaxy. At the same time, if we consider the indicative galactic mass M_{25} for the same galaxies as comprising both baryonic and substantial fraction of dark matter, a good $M_{BH}(M_{25})$ correlation is revealed. This result immediately indicates that the influence of dark matter on central SMBH formation, although indirect, remains quite significant.

The linkage of central SMBH and stellar clusters with the kinematics and color of host galaxies was studied in more detail in the paper by Zasov and Cherepashchuk [27].

5 Conclusions

After 45 years of observational studies of BHs, there are almost no doubts that these extreme objects really exist in the Universe. This is due to the fact that all observations of these massive and very compact objects are in beautiful agreement with GR prediction for black holes.

Recent discovery of gravitational waves from a binary black hole merger GW150914 [3] opens a new era in investigations of black holes.

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