

CONFERENCES AND SYMPOSIA

PACS numbers: 01.10.Fv, **04.20.–q**, **11.27.+d**, 89.60.Gg, 96.30.Cw, 96.30.Ys, 97.60.Jd, 97.60.Lf, **97.80.–d**, **97.82.–j**, 98.62.Sb, 98.80.Es

Astrophysics and astronomy
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 26 January 2011)

DOI: 10.3367/UFNe.0181.201110c.1097

An Astrophysics and Astronomy scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held in the Conference Hall of the P N Lebedev Physical Institute, RAS, on 26 January 2011.

The following reports were put on the session's agenda posted on the web site www.gpad.ac.ru of the Physical Sciences Division, RAS:

(1) **Cherepashchuk A M** (Sternberg Astronomical Institute, Moscow State University, Moscow) "Investigation of X-ray sources";

(2) **Shustov B M** (Institute of Astronomy, Russian Academy of Sciences, Moscow) "Asteroid and comet hazards: physical and other aspects";

(3) **Sazhin M V** (Sternberg Astronomical Institute, Moscow State University, Moscow) "Search for cosmic strings";

(4) **Zakharov A F** (Russian Federation State Scientific Center 'A I Alikhanov Institute for Theoretical and Experimental Physics', Moscow) "Exoplanet search using gravitational microlensing".

Papers written on the basis of the reports are published below.

Uspekhi Fizicheskikh Nauk 181 (10) 1097 – 1122 (2011)
DOI: 10.3367/UFNr.0181.201110c.1097
Translated by E N Ragozin, E G Strel'chenko, K A Postnov; edited by A Radzig

PACS numbers: 97.60.Jd, 97.60.Lf, **97.80.–d**
DOI: 10.3367/UFNe.0181.201110d.1097

Optical investigations of X-ray binary systems

A M Cherepashchuk

1. Introduction

Observations in the optical range of the spectrum are critically important in the investigation of X-ray binary systems. X-ray binary systems contain relativistic objects (neutron stars and black holes) which accrete a substance of a satellite — a normal star. Optical investigations permit studying the motion of 'probe bodies' (stars, gas disks, etc.) in the gravitational field of a relativistic object, and thereby make it possible to measure the masses of neutron stars (NSs) and black holes (BHs). Mass is the most important parameter determining whether the relativistic object belongs to either the class of NSs or the class of BHs.

According to modern notions [1], with general relativity (GR) effects taken into account, when the core mass of a star which underwent chemical evolution due to thermonuclear reactions exceeds a value of $3M_\odot$, it eventually evolves into a BH; when the mass of the stellar core is less than $3M_\odot$, the stellar evolution results in the formation of a white dwarf or a neutron star. The possibility of measuring the masses of relativistic objects makes X-ray binary systems a powerful tool in the quest for BH stellar masses.

This year will observe the 40th anniversary of the launch of American dedicated X-ray satellite Uhuru into a circumterrestrial orbit, which opened up the era of systematic sky observations in the X-ray region and marked the beginning of observational BH research. In this paper, we describe the results of the 40-year-long quest for and investigations of BHs in X-ray binary systems by means of optical astronomy techniques. It should be noted that it is quite sufficient to apply Newton's law of gravitation when determining BH masses by optical techniques, because the dimensions of the orbits of X-ray binary systems are far greater than the BH gravitational (Schwarzschild) radius $r_g = 2GM/c^2$; for a BH of mass $M = 10M_\odot$, this radius is equal to 30 km.

We emphasize that, since the masses of BHs in X-ray binary systems are determined using Newton's theory of gravitation, BH masses evaluated in this way are independent of the type of the relativistic theory of gravitation, because all of these theories, including those that are alternatives to GR, cross over to Newton's theory at the distance from the gravitating center.

2. Possibility of observation of black holes

According to modern concepts [1–3], a BH comprises a spacetime domain wherein the gravitational field is so strong that no signal from this domain, not even light, can escape it and turn to spatial infinity. The physical boundary of a BH is the horizon of events at which, from the viewpoint of a distant

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Uspekhi Fizicheskikh Nauk 181 (10) 1097 – 1104 (2011)
DOI: 10.3367/UFNr.0181.201110d.1097
Translated by E N Ragozin; edited by A Radzig

observer, the running of time comes to a halt. For a nonrotating BH, the event horizon radius r_h is equal to the gravitational (Schwarzschild) radius $r_g = 2GM/c^2$. For a rotating BH, the event horizon is submerged in the ergosphere with a vortex gravitational field and the horizon radius $r_h < r_g$.

The possibility of BH observation was first pointed out by Zel'dovich [4] and Salpeter [5] in 1964. As they noted, great energy, on the order of 10% of the rest energy of the substance, may be liberated in the nonspherical accretion of a substance on a BH. The theory of the disk accretion of a substance onto relativistic objects was elaborated in Refs [6–8].

More than one hundred compact X-ray sources, in most cases X-ray binary systems consisting of an optical star — the substance donor — and a relativistic object residing in accretion mode, were discovered from aboard the Uhuru satellite [9]. To date, several thousand X-ray binary systems have been discovered in our and other galaxies with the aid of new-generation X-ray space observatories.

The theory of disk accretion [6–8] made it possible to promptly explain the nature of the majority of the newly discovered compact X-ray sources as accreting NSs and BHs in binary systems. At the same time, this brought up the burning problem of optical identification of X-ray binary systems and of studying their optical manifestations.

The first identification of the Her X-1 X-ray binary system with the variable optical star HZ Her and the explanation of its optical variability by the 'reflection' effect, more precisely by the X-ray heating of the optical star, was made in Refs [10–12]. Lyutyi et al. [13] discovered the optical variability of the Cyg X-1 X-ray binary system — 'the No. 1 candidate' for a black hole — and interpreted this variability as the ellipsoidality effect of the optical star. Webster and Murdin [14] measured the mass function of the optical star in the Cyg X-1 system, which was indicative of the presence of a BH in this system. The authors of Ref. [13] proposed a method of estimating the orbit inclination i for an X-ray binary system from the observed 'ellipsoidal' variability of an optical star, and made one of the first BH mass estimates on this basis: $m_x > 5.6M_\odot$.

The reflection and ellipsoidality effects turned out to be typical observational manifestations of X-ray binary systems in the visible and near-infrared spectral regions. These effects are widely used for optical identification of X-ray binary systems: coincidence of the periods and phases of optical and X-ray variabilities proves the reliability of identification. Furthermore, the reflection and ellipsoidality effects are much used to estimate the orbit inclinations of X-ray binary systems and determine the masses of relativistic objects (see, for instance, review Refs [15, 16]). The author of Ref. [17] discovered optical eclipses in a unique object, SS 433, with collimated precessing relativistic ejections — jets [18]. This was proof that the SS 433 object comprises a massive X-ray binary system residing at an advanced stage of evolution, which contains an optically bright, supercritical accretion disk around a relativistic object [6], the disk precessing with a period of ~ 162 days. The SS 433 object turned out to be the first representative of the objects of a new class — microquasars; the number of such objects discovered in the Galaxy ranges up to about twenty to date. The study of microquasars sheds light on the nature of quasars and galactic nuclei, in which relativistic jets are also frequently observed, though on scales several million times greater than in microquasars.

3. Methods for determining the masses of black holes in X-ray binary systems

X-ray and optical investigations of X-ray binary systems complement each other nicely. X-ray observations from dedicated satellites permit judging the presence of a compact object in a binary system and estimating — from the fast variability of X-ray emission in a time Δt, down to 10^{-3} s — its characteristic dimensions: $r \leqslant c\Delta t \leqslant 300$ km. Optical (spectral and photometric) ground-based observations provide the possibility of investigating the motion of the optical star and thereby a way of estimating the mass of the compact object. If its measured mass is greater than $3M_\odot$, it may be regarded as a candidate for a BH.

The world of X-ray binary systems is quite rich and diverse in its characteristics and observational manifestations (see *Catalogue* [19]). Here, we enlarge on only one aspect of the problem of X-ray binary systems, involving mass determination for stellar BHs (see, for instance, review [15]).

Doppler lineshifts in the spectrum of a binary system are employed to construct the curve of ray velocities of an optical star, and its mass function is determined in the model of a system containing two point masses in Keplerian orbits:

$$f_v(M) = \frac{M_x^3 \sin^3 i}{(M_x + M_v)^2} = 1.038 \times 10^{-7} K_v^3 P (1 - e^2)^{3/2}, \quad (1)$$

where M_x and M_v are the masses of the relativistic object and the optical star (in solar masses), K_v is the observed half-amplitude of the ray velocity curve of the optical star (in km s^{-1}), P is the orbital period of the system (in days), and e is the eccentricity of the orbit (determined from the departure of the ray velocity curve from a sinusoid). The mass function $f_v(M)$ is an observable quantity and has the dimensionality of mass. It constitutes the lower bound on the mass of the relativistic object. For instance, for the Cyg X-1 system, $f_v(M) \simeq 0.24M_\odot$, and for the GRS $1915+105$ system, $f_v(M) \simeq 9.5M_\odot$ (see review [15]). In the latter case, it can be said with confidence that the GRS $1915+105$ system contains a BH with a mass greater than $9.5M_\odot$.

From Eqn (1) follows an expression for the mass of a BH:

$$M_x = f_v(M) \left(1 + \frac{1}{q}\right)^2 \frac{1}{\sin^3 i}, \quad (2)$$

where $q = M_x/M_v$ is the BH-to-optical star mass ratio. Therefore, despite the fact that the X-ray binary system components are not seen separately, by using formula (2) and the values of parameters q, i determined from additional data, it is possible to evaluate the BH mass.

As noted above, orbit inclination i is determined by analyzing the optical light curve of an X-ray binary system caused primarily by the ellipsoidality effect of the optical star [13]. This method, which was proposed for X-ray binary systems in Ref. [13], is currently the only reliable method for estimating parameter i in the case where there are no X-ray eclipses in the system.

The mass ratio q is estimated from the rotational line broadening in the spectrum of the optical star: for a fixed angular velocity of orbiting, the linear velocity of stellar rotation at the equator increases with stellar radius; in X-ray binary systems, this radius is close to that of the critical Roche cavity of the optical star. Since this radius depends on the mass ratio q, we obtain the following formula for estimating the q parameter:

$$v_{\mathrm{rot}} \sin i = 0.462\, K_{\mathrm{v}} \, \frac{1}{q^{1/3}} \left(1 + \frac{1}{q}\right)^{2/3}, \tag{3}$$

where v_{rot} is the equatorial velocity of stellar rotation (the value of $v_{\mathrm{rot}} \sin i$ is determined from the line profile observed).

Therefore, the use of formulas (1)–(3) in the simplest model of two point masses enables determining the mass of the BH in a binary system. Modern methods of determining the masses of BHs in X-ray binary systems are given at greater length in review [15].

When the mass ratio $q \gg 1$, a material point model may be applied to the optical star as a satisfactory approximation, because the Roche cavity dimensions for the star are relatively small. However, at $q \approx 1$, and even more so for $q < 1$, the application of the material point model to the optical star in an X-ray binary system is not quite correct, because for $q < 1$ the center of mass of the binary system lies within the bulk of the optical star. The parts of the optical star located on different sides of the center of mass of the binary system move in different directions in their orbital motion, resulting in a strong distortion of the line profile in the stellar spectrum and, accordingly, in a distortion of the ray velocity curve. That is why taking into account the real figure of the optical star in the analysis of ray velocity curves for X-ray binary systems is critical for the correct determination of the masses of relativistic objects.

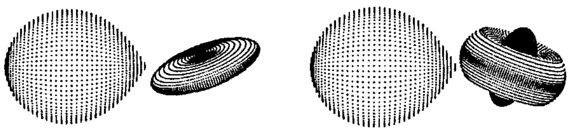

Figure 1. Mathematical models of an X-ray binary system with an accretion disk precessing around the relativistic object.

In our group, we have developed methods for interpreting the light curves, spectral line profiles, and ray velocity curves of X-ray binary systems with the inclusion of the tidal-rotational deformation of the optical star and its heating by the X-ray radiation of the accreting relativistic object, as well as with the inclusion of the presence of an accretion disk around the object [20–22] (Fig. 1). In the calculation of local line profiles in the spectrum of the optical star, advantage is taken of the methods and results of analysis of the spectra of stellar atmospheres developed by N A Sakhibullin [23]. The stellar surface is divided into several thousand elementary areas. By way of solution of the radiation transfer equation with nonzero external boundary conditions, the intensity of radiation emanating from every surface area in the direction of a terrestrial observer is calculated as a function of wavelength; included next are the Doppler shifts of the local line profiles and the mutual eclipses of the components. Summing up the contributions from all surface areas seen by the observer permits calculating the theoretical light curve for a star with a complex shape, the integral profiles of absorption lines in its spectrum, and, accordingly, the theoretical ray velocity curve (Fig. 2). Since the optical star in an X-ray binary system has a pear-like shape with a complex temperature distribution over the surface, the line profiles in its spectrum vary appreciably with the phase of the orbital period, resulting in the consequential distortion of the ray velocity curve in comparison with that in the model of two point masses. It is precisely this distorted theoretical ray velocity curve that should be compared with the observational data in the determination of the BH mass in an X-ray binary system (see Fig. 2).

The application of the more realistic X-ray binary system model and modern statistical criteria for substantiating the adequacy of the model to observed data [24] makes it possible

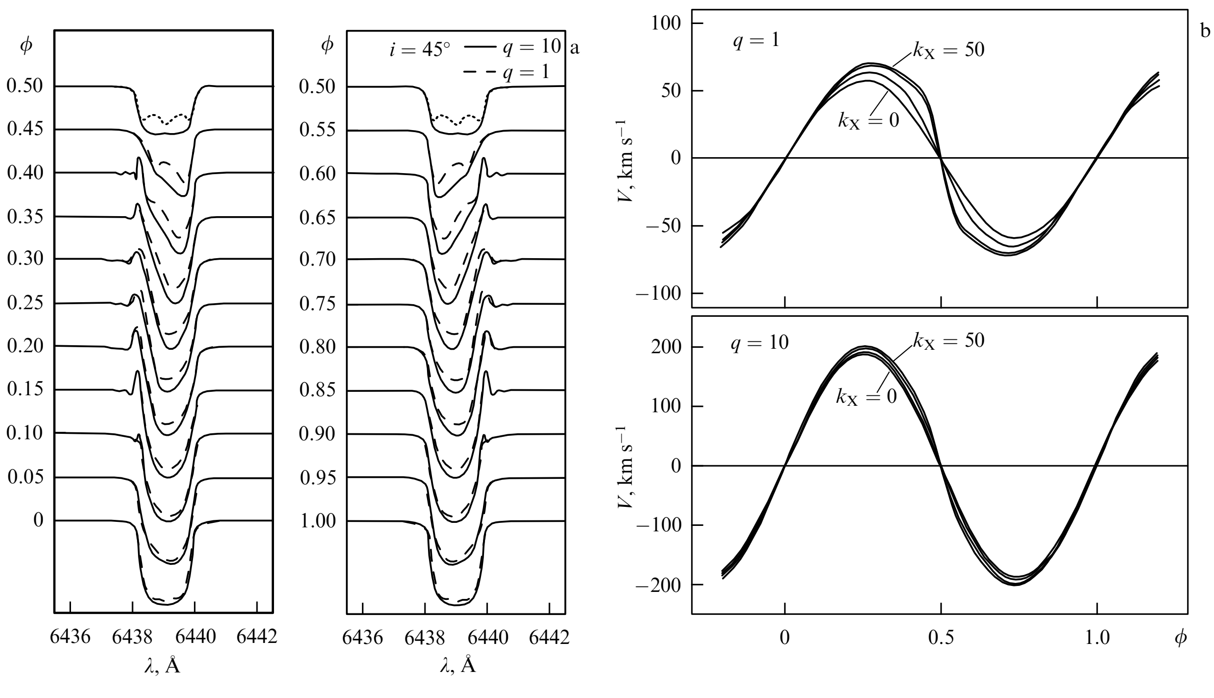

Figure 2. (a) Variation of the CaI absorption line profile in the optical spectrum of an X-ray binary system associated with a variation of optical period phase ϕ, which arises from the tidal deformation of the star and the heating of its surface by X-ray radiation of the accreting relativistic object. For the sake of convenience in comparing the profiles, Doppler line shifts caused by orbital motion are eliminated. (b) Appropriate ray velocity curves for different values of component mass ratio q and X-ray heating parameter k_{X}. The orbit of the system is circular.

to obtain the most reliable parameter values and their confidence intervals (errors).

Let us give several examples of the efficient use of our methods. We showed in Ref. [25] that the masses of X-ray pulsars in binaries with OB supergiant satellites, determined in the framework of the simplest model of the system as a system of two point masses, are underrated by 5–10%. This result is important for improving the equation of state of a neutron substance.

From the analysis of the high-precision ray velocity curve of the Cyg X-1 X-ray binary system, which encompassed the observational data over 502 nights, we were able to estimate the orbit inclination of the system: $i < 45°$, and provide an independent estimate of the BH mass: $M_x = (8.5-13.6)\,M_\odot$ [26].

The inclusion of strong X-ray heating of the optical star in the 2S0921-63 X-ray binary system led to a substantial lowering of the relativistic object mass, and this object was shown to be an NS rather than a low-mass BH [27].

It is pertinent to note that the profiles of absorption lines in the optical spectra of X-ray binary systems are calculated in our model both under the assumption of local thermodynamic equilibrium and neglecting this hypothesis, when a system of equations for the stationary populations of several hundred atomic and ionic energy levels is solved to construct the corresponding source functions.

4. Masses of black holes in X-ray binary systems

During the past four decades, owing to the vigorous investigations carried out by teams of Russian and foreign researchers in both the X-ray and optical spectral regions, it has been possible to accumulate valuable data about the masses of a wealth of BHs and NSs. A new realm of astrophysics has come into existence — the demography of BHs — which studies the origin and growth of BHs, and the association of these extreme objects with other objects in the Universe: stars, galaxies, etc. (see, for instance, review [15]).

The masses of 24 stellar BHs and the masses of about 50 NSs have been measured in binary systems to date (Fig. 3).

The masses of NSs lie in the (1–2) $M_\odot$ range, the average NS mass being $\sim 1.4 M_\odot$. All of these 50 objects exhibit clear evidences of an observable surface: radio pulsars, X-ray pulsars, or type-I X-ray bursters. Recall that the phenomenon of a radio pulsar is associated with the fast axial rotation of an NS (with a period between 1 and 10^{-3} s) and the strong magnetic field ($\sim 10^{12}$ G) of the NS 'attached' to its surface. The phenomenon of an X-ray pulsar reflects the presence of hot X-ray regions (shock waves) near the magnetic poles of a fast-rotating strongly magnetized NS, while the type-I X-ray burster phenomenon is due to thermonuclear explosions of the substance accumulated in the course of accretion on the surface of an NS with a weak magnetic field. The X-ray pulsar, type-I X-ray burster, and radio pulsar phenomena would be impossible if the NSs did not possess observable surfaces. We emphasize that the fast axial rotation and the strong magnetic field are the natural consequences of compression of the stellar nucleus to the very small size ($\sim$ 10 km) of a compact relativistic object at the end of evolution.

Therefore, whenever a compact object shows evidences of an observable surface (a radio pulsar, X-ray pulsar, or type-I X-ray burster phenomenon), its measured mass does not

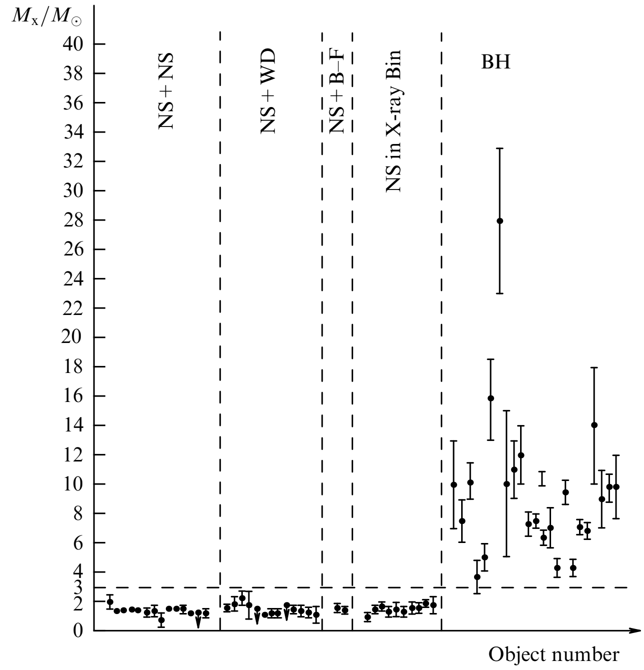

Figure 3. Measured masses of neutron stars (NSs) and black holes (BHs) in binary systems: NS + NS — a radio pulsar in combination with a neutron star; NS + WD — a radio pulsar in combination with a white dwarf; NS + B-F — a radio pulsar in combination with a nondegenerate star of the B-F spectral class, and NS in X-ray Bin — an X-ray pulsar in a binary system. The dashed horizontal line intercepts a mass value of $3M_\odot$ — the absolute upper bound on the mass of a neutron star predicted by GR.

exceed $3M_\odot$, which is in perfect agreement with the predictions of GR (!). We are reminded that the number of measured masses is quite high in this case, amounting to fifty.

The masses of 24 BHs lie in the (4–25) $M_\odot$ range. The average BH mass equals $\sim 9M_\odot$. According to the predictions of GR, a BH should not possess an observable surface, but only an event horizon — a light surface in spacetime. That is why, according to GR, a BH should not exhibit the properties of a radio pulsar, an X-ray pulsar, or a type-I X-ray burster (type II bursters, which are associated with instabilities developing in the inner parts of the accretion disk, may be observed — they are easily distinguished from type I bursters). Such is indeed the case with the 24 BHs studied: none of these massive ($M > 3M_\odot$) compact objects is a radio pulsar, an X-ray pulsar, or a type-I X-ray burster (!). These massive ($M > 3M_\odot$) compact objects — candidates for a BH — exhibit only an irregular or quasiperiodic (but not strictly periodic) variability of X-ray emission over time periods from ~ 0.1 to ~ 0.001 s, which permits estimating the characteristic dimensions of these objects, as discussed in the foregoing. In the model of oscillations of the inner parts of an accretion disk or the orbital motion of hot spots, it is possible to show that so fast an X-ray variability of the known candidates for BHs is due to their very small dimensions which do not exceed several gravitational radii r_g.

Therefore, as data on the masses of relativistic objects accumulate, the following result is taking shape: NSs and BHs differ not only by mass, but also by their observational manifestations, in perfect quantitative agreement with GR; a discontinuity in the observational manifestations of relativistic objects makes itself evident in the vicinity of the theoretically predicted mass value of $3M_\odot$ (the upper bound on the mass of an NS). Objects having masses greater than $3M_\odot$ (i.e., BHs) exhibit no clear signs of an observable surface; meanwhile, when a compact object shows clear indications of an observable surface, its measured mass does not exceed $3M_\odot$.

However, we would do well to bear in mind that some NSs may not show manifestations of an observable surface. For instance, a radio pulsar or an X-ray pulsar phenomenon may not be observed owing to the 'unfortunate' orientation of the magnetic dipole axis relative to the observer or when the NS rotation axis coincides with the axis of the magnetic dipole. That is why the distinctions between the vivid observable manifestations of NSs and BHs noted above are only the necessary, but not the sufficient, criterion that the 24 investigated candidates for BHs are real BHs. Nevertheless, the large number of objects studied (24) gives us confidence that the BHs of stellar masses do exist. This confidence will strengthen with the accumulation of new observational data about the masses of relativistic objects in binary systems. Recently, in connection with the putting into operation of new large 8–10-meter optical telescopes, the possibility has opened up of studying X-ray binary systems in other galaxies, which may lead to a substantial increase in the number of NSs and BHs with measured masses.

In addition to the clear distinctions between the observational manifestations of NSs and BHs described in the foregoing, there are also subtle distinctions between them, which are related to the shape of their X-ray spectra and the character of their X-ray emission intensity variation in time (see, for instance, Ref. [15]). These subtle distinctions also testify that NSs, unlike BHs, possess observable surfaces.

5. Demography of stellar black holes

We describe several findings of the demographic investigations of BH stellar masses.

It turns out that there is no dependence between the mass of a relativistic object and the mass of its satellite in binary systems: both NSs and BHs are found in binary systems, with satellites having both a large mass and a small mass. There is no BH–satellite mass dependence in a binary system, either. In this sense, close binary systems with NSs and BHs are similar to classical close binary systems, in which arbitrary component combinations are found, as repeatedly emphasized by D Ya Martynov [28].

Some interesting features of the mass distribution of NSs and BHs were also brought to light [29, 30]. First, the number of investigated stellar BHs does not increase with decreasing BH mass (Fig. 4). This comes as a surprise, because the stellar mass distribution in the Galaxy is such that the number of stars rises steeply (as M^{-5}) with decreasing stellar mass. Since stellar BHs are formed in the collapses of the iron nuclei of massive stars ($M > 30M_\odot$), one would think that the number of stellar BHs should rise sharply towards smaller masses, but this is not observed. It may be shown [15] that this extraordinary fact is not related to observational selection effects. Second, a dip begins to show itself in the mass distribution of NSs and BHs in the mass range from $2M_\odot$ to $4M_\odot$. In this mass interval, the number of discovered NSs and BHs is close to zero, which is also unlikely to arise from the observational selection effects [15]. If the inference about the presence of a dip in the mass distribution of NSs and BHs in the (2–4) $M_\odot$ interval is confirmed by future observations, it will call for a serious theoretical interpretation.

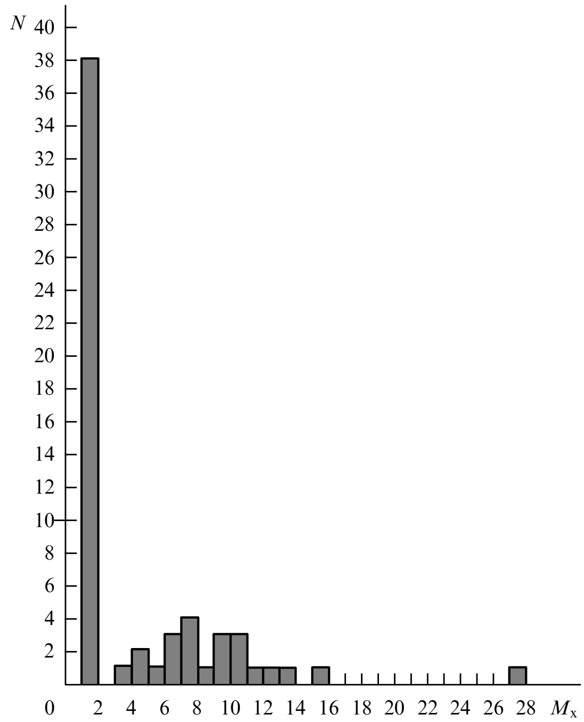

Figure 4. Histogram of the mass distribution of neutron stars and black holes in binary systems. The high peak at the left of the drawing corresponds to neutron stars.

In this connection, mention should be made of an interesting opportunity to explain the unusual stellar BH mass distribution. The authors of Ref. [31] came up with the idea that the flat mass distribution of stellar BHs and the dip in this distribution in the (2–4) $M_\odot$ interval may be due to enhanced quantum evaporation of BHs, which follows from several multidimensional gravitation models (see, for instance, Ref. [32]). In these gravitation models, the time τ for the quantum evaporation of a BH is much shorter than the Hawking time [33], and may be estimated by the formula

$$\tau \sim 1.2 \times 10^2 \left(\frac{M}{M_\odot}\right)^3 \left(\frac{1\ \mathrm{mm}}{L}\right)^3, \tag{4}$$

where M is the BH mass, and L is the characteristic scale length of the additional (fourth) spatial dimension. For an average BH mass of $\sim 9M_\odot$ and the expected upper bound on the L quantity of several hundredths of a millimeter, the quantum evaporation time reaches $\sim 10^8$ years, which is much smaller than the age of the Universe and is comparable to the period of nuclear evolution of the stars. Since the rate of quantum evaporation rises steeply with a lowering of BH mass, it is believed that the observed deficit of small-mass BHs is due to the fact that many BHs with small masses managed to evaporate during the lifetime of the Universe. It is remarkable in this model that the known value of the observed average stellar BH mass of $9M_\odot$ permits imposing a constraint on the value of the L parameter, which is consistent with the constraints following from the data of laboratory physical experiments [34].

Furthermore, if the characteristic stellar BH evaporation time is shorter than the age of the Universe ($\sim 1.4\times 10^{10}$ years), a decrease in BH mass in an X-ray binary system should lead to an observable change in its orbital period. The quest for such changes in the orbital periods of X-ray binary systems is currently underway (including in our group). As a result of this research, it has been possible to obtain the upper constraint on the characteristic length scale of the additional spatial dimension: $L < 0.1$ mm [35]. Further accumulation of observational data on the variation of X-ray binary system periods will permit a substantial improvement in this estimate.

There are also other, less exotic, explanations for the anomalous mass distribution of stellar BHs, which are related to the mass loss by massive stars in the form of stellar wind [29], and to the features of the late stages of massive star evolution [36, 37].

It should be emphasized that the existence of a dip in the observable relativistic object mass distribution over the (2–4) $M_\odot$ region (the supposition of its existence was made in Refs [38, 39]) was recently confirmed by a rigorous statistical analysis of the latest observational data on BH masses in X-ray binary systems [40].

Recent years have seen a constant strengthening of the viewpoint that the collapses of the carbon–oxygen nuclei of Wolf-Rayet stars with a fast axial rotation, which give rise to extremely fast rotating (Kerr) BHs in different galaxies, may be the sources of the famous and so far mysterious cosmic gamma-ray bursts whereat an enormous amount of energy is released in several seconds in the gamma-ray range, this energy being comparable to the energy liberated in the annihilation of the entire solar mass. As noted in Ref. [41], the orbital motion of a close satellite in a very close binary system maintains, owing to the tidal mechanism, the fast axial rotation of the star — the precursor of a Kerr BH — despite a substantial loss of the angular momentum of the star's rotation in throwing off its shell during the supernova explosion. Therefore, there are grounds to believe that in the observation of cosmic gamma-ray bursts we directly 'witness' the formation of stellar BHs in very close binary systems.

Two types of quasiperiodic (but not strictly periodic) oscillations (QPOs) of X-ray emission intensity are observed in X-ray binary systems with BHs: low-frequency QPOs (LFQPOs) with frequencies of $\sim 0.1-30$ Hz, and high-frequency QPOs (HFQPOs) whose frequencies lie in the 40–450 Hz range (see, for instance, Refs [42–44]). The low-frequency QPOs may be observable for several days or even months. For the GRS $1915+105$ system with a BH, for instance, QPOs with a frequency of 2.0–4.5 Hz were observed for 6 months in 1996–1997. Furthermore, this system also exhibited high-frequency QPOs with frequencies of 41 and 67 Hz, as well as with frequencies of 113 and 168 Hz.

Attempts to relate low-frequency QPOs to the geometrical and physical characteristics of accretion plasma run into difficulties, because LFQPOs correspond to frequencies which are much lower than those inherent in the orbits in the inner parts of the accretion disk. For a BH with a mass of $10\,M_\odot$, for instance, an orbital frequency of 3 Hz corresponds to a disk radius of $100r_g$, while the assumed radius of the domain of maximum energy liberation in the X-ray region lies in the $(1–10)\,r_g$ range, depending on the BH rotation parameter. Numerous LFQPO models treat this phenomenon in the framework of different oscillation mechanisms of the disk or its structures (see, for instance, Ref. [45]).

High-frequency QPOs have a direct bearing on the processes occurring near the radius of the last stable orbit around a BH, since the orbital frequency for the last stable orbit is equal to 220 Hz $\times (M/10\,M_\odot)^{-1}$ for a Schwarzschild BH, and to 1615 Hz $\times (M/10\,M_\odot)^{-1}$ for a Kerr BH [44]. Interestingly, the high-frequency QPOs emerge in pairs with frequencies at the ratio of 3:2. Examples of such systems are as follows: GRO J1655-40 (300, 450 Hz), XTE J1550-564 (184, 276 Hz), GRS $1915+105$ (113, 168 Hz), and H1743-322 (165, 241 Hz). Observed in the GRS $1915+105$ system is a second pair of high-frequency QPOs (41, 67 Hz), whose frequencies are not in the ratio of 3:2.

The ratio of 3:2 in high-frequency QPOs constitutes evidence that the HFQPOs are caused by some resonance effects in the oscillations of the inner parts of the accretion disk, which are described in the framework of GR (see, for instance, Refs [46–48]). As noted in Ref. [43], a relationship between the HFQPO frequency and the BH mass in an X-ray binary system is beginning to show up:

$$f_0 \simeq 931 \left(\frac{M_{\rm BH}}{M_\odot} \right)^{-1} \text{Hz}\,,$$

where f_0 is the fundamental frequency of the pair of frequencies, so that the observed frequencies are $2f_0$ and f_0.

In recent years, a close similarity has been established between X-ray binary systems with BHs and galactic nuclei [49]. In particular, a statistical relationship termed the fundamental plane was discovered for supermassive and stellar BHs [50]:

$$\lg L_{\rm R} = (0.60^{+0.11}_{-0.11}) \lg L_{\rm X} + (0.78^{+0.11}_{-0.09}) \lg M_{\rm BH} + 7.33^{+4.05}_{-4.07}\,,$$

where $L_{\rm R}$ is the radio luminosity (caused primarily by the jet's radio emission), $L_{\rm X}$ is the X-ray luminosity (primarily due to the emission of the accretion disk), and $M_{\rm BH}$ is the mass of a BH (supermassive and stellar alike).

It was also established that the variability of active galactic nuclei is similar to the variability of accreting stellar BHs in binary systems, when this variability is normalized according to the BH mass and accretion rate [49]. It is well known that the X-ray variability of active galactic nuclei and BHs in binaries may be described by the variability power spectral density $P(\nu)$, where ν is the frequency ($1/\nu$ is the characteristic time). For long characteristic times, the $P(\nu)$ function may be approximated by a power law: $P(\nu) \sim \nu^{-\alpha}$, where $\alpha \approx 1$. This power law spectrum exhibits a break at shorter characteristic times to assume the form $P(\nu) \sim \nu^{-\alpha}$, where $\alpha \geqslant 2$. The corresponding spectrum break frequency is denoted as $\nu_{\rm B}$, and the characteristic spectrum break time as $T_{\rm B} = 1/\nu_{\rm B}$. Then, when $T_{\rm B}$ and $L_{\rm bol}$ (the luminosity which characterizes the rate of accretion) are determined from observations, the BH mass $M_{\rm BH}$ may be estimated from the relationship

$$\lg T_{\rm B} = 2.1 \lg M_{\rm BH} - 0.981 \lg L_{\rm bol} - 2.32\,.$$

We emphasize that this statistical relationship is true both for stellar BHs and for supermassive BHs in galactic nuclei. The black holes in binaries which are in accretion mode exhibit aperiodic variability of X-ray emission over times ranging from several days to $10^{-2}-10^{-3}$ s. Suchlike variability is also observed in the emission of supermassive BHs, though on longer time scales — from several years to several months and weeks.

Such are the main observational features of the stellar BH demography. Estimates made on the basis of the above observed data (with the inclusion of observational selection effects) show that the total number of stellar BHs in our Galaxy should be of order 10^7. For an average BH mass of (9–10) $M_\odot$, the total mass of stellar BHs amounts to $\sim 10^8 M_\odot$, or about 0.1% of the mass of the visible baryon substance of our Galaxy contained in stars, gas, and dust. It should also be noted that the total mass of stellar BHs in the Galaxy is more than an order of magnitude ($\sim$ 25 times) greater than the mass of the supermassive BH ($4.3 \times 10^6 M_\odot$) located at the galactic center [51].

6. Conclusion

Over the past 40 years, major advances have been made towards the solution to the problem of the quest for and investigation of stellar BHs in X-ray binary systems. This progress is due to the power of ground-based optical telescopes and the unique possibilities furnished by cosmic observations in the X-ray spectral region.

Several dozen massive and extremely compact objects have been discovered, the observed properties of these objects bearing a great resemblance to the properties of BHs predicted by Albert Einstein's GR. The whole set of observational data on these numerous massive and compact objects agrees nicely with the predictions of GR. This, as V L Ginzburg himself expressed one day, strengthens our confidence in the existence of BHs in the Universe.

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