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Triumph of black holes

Anatol M. Cherepashchuk*

P.K. Sternberg Astronomical Institute, M.V. Lomonosov Moscow University, Moscow 119992, Russia

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This review describes the history of observational search for black holes in the Universe and of their studies which has already lasted for more than 60 years. We present results of observations in the optical, X-ray, radio ranges and in the gravitational wave channel.

The data of observations taken together are convincing evidence that black holes, objects extremal to the highest degree, really exist in the Universe. Currently, it is accepted that black holes have received their deserved "citizenship" among classical objects of the Universe: stars, galaxies, etc.

Keywords: Earthquake precursors, radon, GPS TEC, relative air humidity

1 Introduction

Black holes (BHs) are a prediction of A. Einstein's General Relativity. Hard-fought battles among scientists concerning the possibility of actual existence of BHs in the Universe lasted for many decades. Properties of these most extreme objects are so unusual that it was difficult to believe in their existence. Nevertheless, thanks to the achievements of multi-channel astronomy as well as of astronomy of super-high angular resolution, current research provides us with convincing observational evidence for the existence of BHs.

In this review, we attempt to briefly describe the thorny pathway of searches for BHs, their discoveries and studies, as well as to summarize some results in this very interesting field of relativistic astrophysics. Among other reasons, this review was stimulated by the 60th anniversary of X-ray astronomy celebrated in 2023; thanks to its development, the search for BHs and studies of BHs acquired, for the first time, a solid observational basis.

In 1962, a team of scientists headed by Professor Riccardo Giacconi, a future Nobel Prize winner, used the Aerobee meteorological rocket to discover the first X-ray source located outside the Solar System (Giacconi et al., 1962). This compact X-ray source got the name Scorpius X-1 (after the constellation Scorpius where it had been found) and it turned out to be a low-mass X-ray binary system consisting

*Email: cherepashchuk@gmail.com

of a low-mass, solar-type optical star, a donor of matter, and an accreting relativistic object – a neutron star (NS).

Later, X-ray astronomy and astronomy of binary star systems were just where a breakthrough happened in the field of search for massive compact objects, BH candidates. And the 2015 discovery of gravitational waves from merging of BHs in binary systems, together with imaging of the closest neighborhood of supermassive BHs in the nucleus of the galaxy M87 (2019) and in the center of our Galaxy (2022) provided a final proof for the actual existence of BHs. As a result of current research, BHs have won "citizenship" among classical astronomical objects: stars, galaxies, clusters of galaxies, etc.

It should be noted that the advent and development of X-ray astronomy made the topic of studies of close binary systems, earlier a quite classical field of astronomy, one of the frontal problems of modern astrophysics.

2 A short historical discourse

The term "BH" means a region of spacetime with the gravitational field so strong that no signal, even light, is able to retire from it to space infinity of the future (Novikov & Frolov, 1986, 2021).

First speculations about dark stars that do not let out even light appeared after the universal gravitation law had been published by I. Newton in 1687. Mitchell in 1783 and Laplace in 1798 derived a formula for the critical radius of the black body, $R_{\rm crit}$, using classical formulas for the potential and kinetic energy, their zero sum determining the escape velocity. Substituting, for the escape velocity, the velocity of light c, already known at that time from observations of Jupiter's satellites, Mitchell and Laplace found the critical radius of the dark body:

$$R_{\rm crit} = 2GM/c^2, \tag{1}$$

where M is the mass of the body and G, Newton's gravitation constant. If a body with mass M has a radius not exceeding $R_{\rm crit}$, the body should be dark, invisible, since photons from it cannot escape to spatial infinity. For the Earth, if we neglect its rotation, $R_{\rm crit} = 9$ mm; it is 3 km for the Sun.

These considerations are not quite rigorous because the formulas of classical mechanics are not applicable for velocities close to that of light. However, if we proceed quite correctly and use relativistic formulas, we will obtain exactly the same expression for $R_{\rm crit}$ as that derived by Mitchell and Laplace. Remarkably, errors in the two formulas applied by these authors exactly compensated each other, so that the correct result was found.

It is important to emphasize that Mitchell remarked in his 1783 paper that the dark body, though invisible, could be detected from the motion of the second, normal optical, star in a binary system. Just this method is currently used to discover BHs (!).

Einstein published his paper on General Relativity in 1915, and in 1916 K.Schwarzschild obtained the exact General Relativity solution for spherically symmetrical gravitation field of a point source. In this case, the expression for squared interval ds between two events,

$$ds^2 = (1 - \frac{r_g}{r})d\tau^2 - (1 - \frac{r_g}{r})^{-1}dr^2 - r^2(d\vartheta^2 + \sin^2\vartheta\ d\varphi^2), \tag{2}$$

contains the quantity

$$r_g = \frac{2GM}{c^2}, \tag{3}$$

usually called gravitation (Schwarzschild) radius.

For the distance to the source $r = r_g$, the squared ds interval becomes infinity. However, this singularity is not physical but related to the choice of the reference frame because, in this case, components of the Riemann tensor remain finite. The singularity can be avoided by special choice of the reference frame. For example, singularities at $r = r_g$ disappear in the reference frame connected with a body in free fall onto the central source (the Lemaître reference frame).

The physical singularity is in the center of the BH where components of the Riemann tensor become infinite.

Figure 1 presents a schematic view of a non-rotating (Schwarzschild) BH in the imaginary Euclid space (on the assumption that trajectories of light rays are straight lines).

In the center of the BH, there is a singularity to which, in the comoving frame, matter that forms the BH has collapsed. The density of matter here is probably close to Planck density, $\sim 10^{93}$ g cm^{-2}. For such incredible density, known laws of physics are, to all probability, already invalid. Here apparently unknown laws of quantum gravitation rule, although quantum gravitation theory has not been developed yet.

The rigorous scientific justification of unavoidable formation of a singularity during relativistic collapse for a general case, in the absence of spherical symmetry of the collapse, was presented in 1965 by Roger Penrose, Nobel Prize Laureate of 2020 (Penrose, 1965). Before that, many physicists, Einstein among them, were very sceptical of the idea that a singularity was formed during relativistic collapse of matter. Singularity was believed to be a consequence of a strict spherical symmetry of the collapse, which virtually never happens in the Nature.

The central singularity is surrounded with the event horizon. From the point of view of a distant observer, the pace of time at the event horizon slows down infinitely. In order to notice any change at the event horizon, a distant observer will have to wait for all the infinitely long existence time of the outer Universe. No signal, even

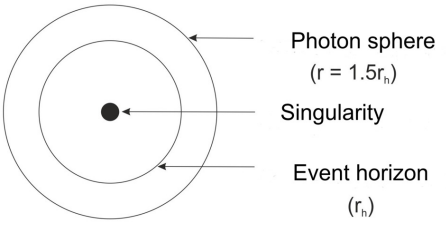


Figure 1 A schematic image of a non-rotating Schwarzschild black hole in the imaginable Euclid space (actually, the space near the black hole is strongly curved, and the light rays follow not straight but strongly curved trajectories). In the center, there is a singularity; in the comoving reference frame, the initial matter has condensed to it. The singularity is surrounded with a spherical event horizon; its radius is equal to the gravitation radius, $r_g = 2GM/c^2$. At this radius, time stops from the point of view of a distant observer. Still further, there is a photon sphere, its radius in the Euclid space being $1.5r_g$. Here captured photons can rotate around the black hole.

light, can travel from the event horizon to space infinity. Nothing happening below the event horizon can be detected by a remote observer. A body in the comoving reference frame that happened to be under the event horizon will unavoidably fall into the singularity, reach it in a finite proper time, and be destroyed by increasing tidal forces. A body, like any signal, cannot escape from under the event horizon. The radius of the event horizon r_h coincides with the gravitation radius r_g in the case of a non-rotating BH, it is smaller than r_g for a rotating BH. For an extremely rapidly rotating (Kerr) BH, $r_g = \frac{1}{2} r_g = \frac{GM}{c^2}$. Sometimes, the term "gravitation radius" is used for the quantity $\frac{GM}{c^2}$, the radius of the event horizon for an extremely rapidly rotating BH.

As already mentioned when discussing the critical radius $R_{\rm crit}$, the Schwarzschild radius is 9 mm for the Earth, 3 km for the Sun, and 40 astronomical units (the distance between the Sun and Pluto) for a mass of 2 billion solar masses (such high-mass BHs are observed in galactic nuclei).

A rotating BH also possesses an ergosphere, with rotating spacetime inside it. A body that happened inside the ergosphere will be permanently rotating. The energy of a rotating BH can be extracted from its ergosphere, and very effectively (Penrose process).

Besides the event horizon, an important feature of a BH is the presence of a photon sphere, whose radius r_p in the imagined Euclid space is $1.5 r_g$. Inside the photon sphere, rays of light can move along closed trajectories.

Note that the space of a BH is actually not Euclidean; it is strongly curved, rays of light follow curved, not straight trajectories here. Thus, the relation between the observed photon-sphere radius and that of the event horizon is different: $r_p \cong 2.6 r_h$. A BH has an action of a multiplying gravitation lens for itself, in the case of a distant observer (see Fig. 2).

We have already mentioned that, from the very beginning, because of the extreme properties of BHs described above, the idea of BHs met rejection by many physicists.

For example, the famous Einstein wrote in 1939: "The essential result of this study is a clear understanding as to why the "Schwarzschild singularities" do not exist in physical reality". A negative attitude to BHs also prevailed among astrophysicists. Thus, the outstanding English astrophysicist Arthur Eddington, the author of the theory of stellar internal structure and evolution, was also a dedicated opponent to possible existence of BHs. During a meeting of the Royal Astronomical Society in 1930s, after S. Chandrasekhar's talk on the existence of a limiting mass for a white dwarf, which implied the possibility of NS and BH formation, Eddington, admitting correctness of the results by Chandrasekhar, nevertheless noted that, in his opinion, there should exist a Law of Nature not permitting the evolution of a star to proceed in a way that absurd.

An especially acute discussion on the validity of Einstein's General Relativity occurred in mid-1970s with the participation of outstanding Soviet scientists: Moscow University rector A.A. Logunov and his opponents, Ya.B. Zeldovich and L.P. Grishchuk, both affiliated to the University. Their discussions were held during meetings of a scientific seminar at the Faculty of Physics of the M.V. Lomonosov Moscow University, they were reflected in several scientific publications in the leading USSR physics journal, Physics–Uspekhi (Advances in Physical Sciences). A.A. Logunov de-

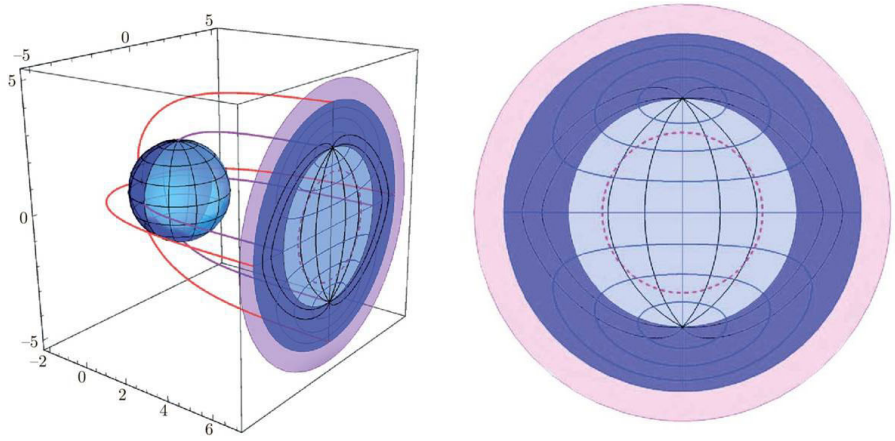


Figure 2 An image of a lensed event horizon of a Schwarzschild black hole inside its "shadow" (the lensed image of the photon sphere, the outmost circle). We consider a black hole in the real, curved spacetime, as a distant observer sees it. Here the dashed circle corresponds to imaginable non-lensed image of the event horizon. The inner solid circle is the gravitationally lensed image of the event horizon's front hemisphere (with corresponding parallels and meridians shown). The outer solid dark circle corresponds to the lensed image of the back hemisphere of the event horizon of the black hole; thus, the distant observer simultaneously sees it from all sides. To the left, trajectories of light in the curved space of the black hole are shown. (From Dokuchaev & Nazarova, 2019.)

veloped a relativistic gravitation theory that treated gravitation as a physical field in a flat spacetime. Ya.B. Zeldovich and L.P. Grishchuk supported the validity of Einstein's General Relativity, where gravitation is identified with the spacetime curvature, the possibility of the existence of BHs following from it.

These mutually exclusive points of view on BHs in 1970s made the problem of a search for BHs especially intriguing and interesting. They additionally stimulated intense observational astronomical studies in this field of relativistic astrophysics.

3 First observations of black holes

In the pioneering papers by Zeldovich (1964) and Salpeter (1964), we find the first claims that it could be possible to observe BHs. It was demonstrated that non-spherical accretion of matter onto a BH should cause a powerful energy release in the hard spectral range, with an effectiveness exceeding by dozens of times that reached in thermonuclear reactions.

Later on, following Mitchell's ideas, scientists concentrated their effort on searching for BHs in binary systems. The theory of disk accretion of matter onto BHs in binary systems was developed by Shakura (1972), Shakura & Sunyaev (1973), Pringle & Rees (1972), Novikov & Thorne (1973). An optical star in a binary system with a BH, on one hand, is a source of matter whose accretion onto the BH results in the appearance of a strong compact X-ray source. On the other hand, studying the

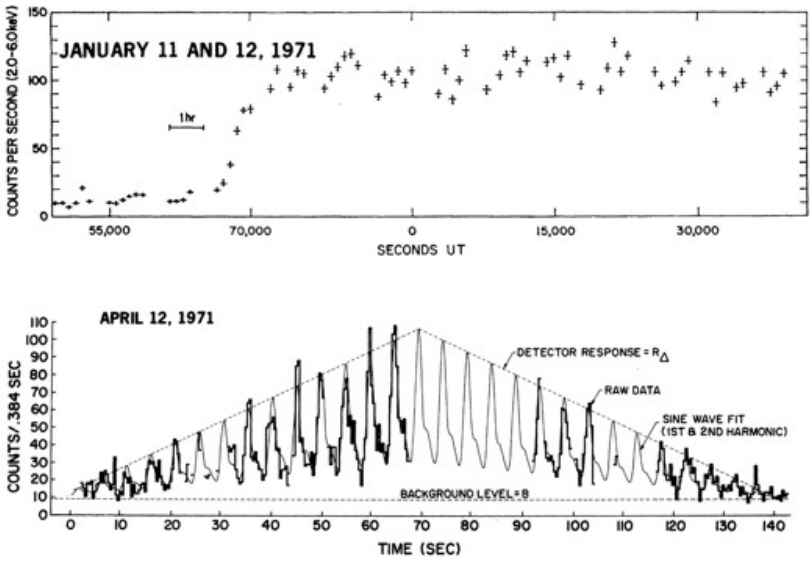


Figure 3 The light curve of an X-ray eclipse (top) and of X-ray pulsations (bottom) for the system Cen X-3 (from Giacconi et al., 1971). The time dependence of the X-ray pulsation amplitude is related to the influence of the detector's radiation pattern.

motion of the optical star by means of spectroscopic and photometric observations, it is possible to determine the mass of the BH.

According to current views, with effects of General Relativity taken into account, if the mass of the stellar core where thermonuclear reactions take place exceeds $3M_{\odot}$, relativistic core collapse occurs towards the end of this massive star's evolution, and a BH is formed. But if the star's core mass is lower than $3M_{\odot}$, a NS or a white dwarf appear at the end of its evolution. The possibility to derive the mass of the relativistic object (a BH or a NS) from the motion of the optical star and to estimate the degree of its being compact from its intense X-ray radiation makes close binary systems (CBSs) a powerful tool in the search for BHs and of their studies.

Paczynski (1967), Tutukov & Yungelson (1973), van den Heuvel (1976) developed the theory of evolution in CBSs with mass exchange, till the latest stages when a close pair of relativistic objects should be formed.

The era of systematic X-ray observations of the sky commenced in 1971, with observations of the specialized American X-ray mission UHURU. This mission discovered about three hundred compact X-ray sources, most of them turned out to be X-ray binary systems. An X-ray binary consists of a normal optical star and a relativistic object whose surroundings are a strong source of X-rays generated during accretion of the matter from the star. In early 1970s, UHURU discovered the first eclipsing X-ray binary systems Cen X-3 (Giacconi et al., 1971) and Her X-1 (Tananbaum et al., 1972) that contain X-ray pulsars, rapidly rotating, strongly magnetic neutron stars in the accretion mode, see Figs. 3, 4. The "No. 1 black hole candidate", X-ray source Cyg X-1 was discovered during rocket experiments and confirmed with UHURU observations (Tananbaum et al., 1971).

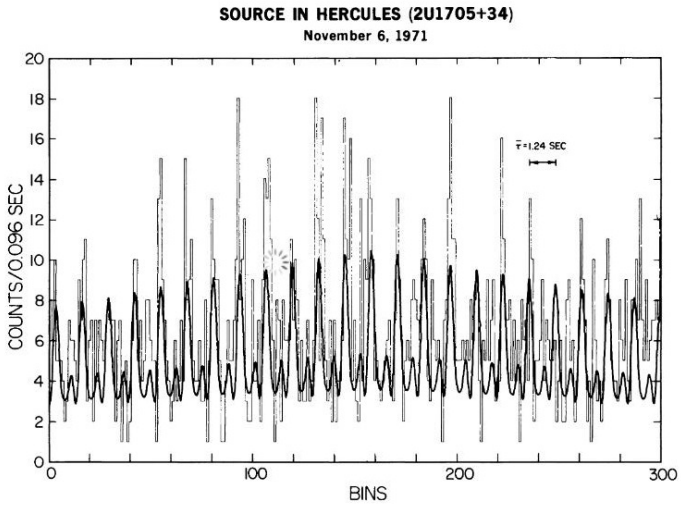


Figure 4 The light curve of X-ray pulsations for Her X-1 (from Tananbaum et al., 1972).

In order to determine masses of relativistic objects, optical identifications of X-ray binaries are needed. The first optical identifications of X-ray binaries (cf. Fig. 5) and distinguishing main types of their optical variations (the star's X-ray heating and its ellipsoidal shape) were suggested by Cherepashchuk et al. (1972), Bahcall & Bahcall (1972), Lyutyi et al. (1973). The paper by Lyutyi et al. (1973) contains one of the first estimates of the mass of "BH candidate No. 1" in the X-ray binary Cygnus X-1 ($M_x > 5.6_\odot$), see Fig. 6.

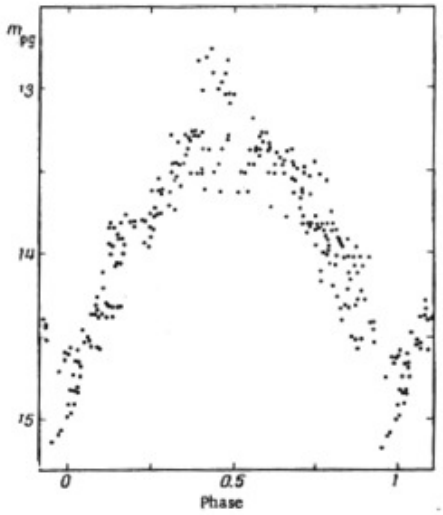


Figure 5 The optical light curve of the X-ray binary Her X-1, due to X-ray heating of the optical star (from Cherepashchuk et al., 1972).

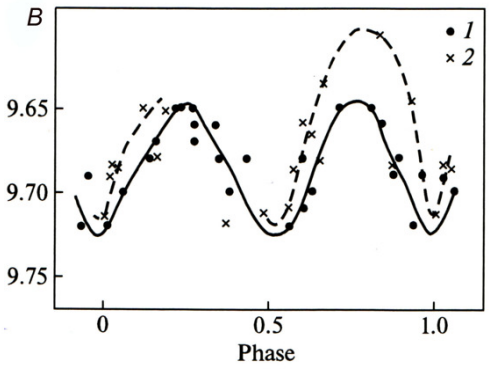


Figure 6 The optical light curve of the X-ray binary Cyg X-1, due to the ellipsoidal shape of the optical star (from Lyutyi et al., 1973).

Studies of optical manifestations of X-ray binaries made it possible to develop effective methods for estimating masses of X-ray sources, accreting BHs among them (see, for instance, Close Binary Stars by Cherepashchuk, 2013, where all necessary references can be found). Note the studies of N.G. Bochkarev's group (Bochkarev et al., 1975; Bochkarev et al., 1985) who were developing techniques of interpretation of light curves and of curves of polarization changes in the light from X-ray binaries.

The fact that one of the first discovered compact X-ray sources turned out to be an accreting BH made scientists optimistic. There was hope that many high-mass X-ray sources, BH candidates, would be discovered soon. In real life, everything was much more complicated. For as long as 11 years, the object Cyg X-1 remained the only known BH candidate. The vast majority of compact X-ray sources discovered in the UHURU project were found to be accreting NSs. As a result, many researchers began to feel doubts: maybe BHs really do not exist in the Universe? The doubts became stronger when B. Paczynski's group had published a model of Cyg X-1 as a triple system (Bahcall et al., 1974). They assumed that the system Cyg X-1 consisted of two high-mass normal stars and a neutron star with a mass about 1.5 $M_{\odot}$. The observed large mass function of the system reflects the combined mass of the two optical stars possessing a large mass difference. The X-ray radiation we observe is formed due to accretion of matter from normal stars onto the NS. As the percentage of triple systems among stars is not low, the model clearly had a right to exist. This is why the number of optimists in the program of searching for BHs began to decrease, and just during these years (1970–80s), adepts of gravitation theories alternative to General Relativity were especially active (as an example, see above about A.A. Logunov's discussion with Ya.B. Zeldovich and L.P. Grishchuk).

Only in 1983, the Canadian scientist Anne Cowley, with collaborators, were able to discover the second BH candidate in the X-ray binary system LMC X-3 and to estimate its mass as $8M_{\odot}$ (Cowley et al., 1983).

Optical stars, matter donors in the systems Cyg X-1 and LMC X-3, are high-mass stars of O–B spectral types, with masses in the range from 6 to $20_{\odot}$. At first, researchers tried to search for BHs just in such systems (called high-mass X-ray binaries). It was believed at that time that binaries are most usually formed as pairs of stars with similar masses (with the mass ratio of components close to unity).

BHs being formed in the core collapse of massive stars, scientists specially selected high-mass X-ray binaries when searching for BHs. This was a miscalculation! Further studies revealed that the distribution of close binary stars over the components' mass ratio was very broad, and the mass ratio close to unity is by no means special. It is especially important, however, that the nuclear evolution time of a high-mass star is shorter than the evolution time of a low-mass star by a factor of thousands. Thus, the stage of accretion and of an X-ray source in a binary with a high-mass O–B star is shorter, by thousands of times, than the stage of an X-ray source in a low-mass X-ray binary, with the optical star's mass of the order of $1M_{\odot}$. Consequently, it is much less probable to find a BH in a high-mass X-ray binary compared to a low-mass one. This is just the explanation of initially very modest results of searches for BHs in high-mass X-ray binary systems.

The first BH in a low-mass X-ray binary A0620-00 was discovered by American scientists (McClintock & Remillard, 1986). The mass of the optical star in this system is $0.7M_{\odot}$, while the mass of the BH is $8M_{\odot}$. While the high-mass X-ray binaries Cyg X-1 and LMC X-3 are quasi-stationary, the low-mass system A0620-00 belongs to the class of transient X-ray binaries, X-ray Novae. After the discovery of a BH in the system A0620-00, scientists began to specially study low-mass X-ray binary systems more actively, and the number of discovered BHs began a rapid increase. While a single BH candidate, Cyg X-1, was discovered during the first 11 years of systematic X-ray observations of the sky, the number of known BH candidates increased to 18 during the next 20 years. By now, the number of BH candidates with reliably measured masses exceeds thirty. We should also note the discovery of microquasar SS433, the first X-ray binary in the super-critical accretion regime with a precessing disk and relativistic jets (Margon, 1984; Cherepashchuk, 1981). The super-critical accretion regime was predicted by Shakura & Sunyaev (1973).

4 Observations of super-massive black holes in galactic nuclei

The early 1990s were the beginning of numerous discoveries of super-high-mass BHs in nuclei of galaxies. The first estimates of masses for super-massive BHs in quasars, nuclei of very active galaxies, were suggested as early as in 1964 by Zeldovich and Novikov (1964) from the condition that the quasar's luminosity should be the same as the critical Eddington luminosity. These masses were found to be very high, $\sim 10^8 M_{\odot}$. Systematic mass determinations for super-high-mass compact objects (BHs) were performed in 1980s by Dibai (1984). To determine an object's mass. it is sufficient to know the velocity of a "test body" (star, gas cloud, gas disk) rotating around it and the distance between this body and the studied object. From the width of strong and broad hydrogen emission lines in the spectrum of a galaxy's nucleus, E.A. Dibai determined characteristic velocities of the motion of gas clouds rotating around the central super-massive object and, from the total intensity of these lines, found the characteristic volume of radiating gas and hence, was able to evaluate, by the order of magnitude, the characteristic distance of the gas clouds from the central super-high-mass compact object. On this basis, E.A. Dibai was able to get mass estimates for super-massive compact objects in the nuclei of several Seyfert galaxies, which were found to be of the order of $10^8 M_{\odot}$.

Cherepashchuk and Lyutyi (1973) discovered the effect of a delay of emission-line variations in the spectra of active galactic nuclei with respect to variations of the continuous spectrum, permitting us to estimate the distance between the central super-massive BH not only by the order of magnitude but with a much better accuracy. By measuring the delay, it is possible to obtain a reliable estimate of the distance between gas clouds emitting in lines – "probe bodies" – and the central BH. The characteristic velocity of the gas clouds being known from spectral-line widths, we can thus find the BH mass. The delay effect became the basis of the method of mass determination for super-massive BHs, the so-called echo mapping method. The first ideas of echo mapping were suggested in the pioneering paper by Antokhin and Bochkarev (1983). The advantage of the method is that here velocities of "probe bodies" and their distances to central BHs are estimated indirectly. Because of this, the echo mapping method can be used for numerous distant galaxies, where telescope resolution is insufficient to directly "see" the "probe bodies". By now, the echo mapping method was used to measure masses for hundreds of super-high-mass BHs in active galactic nuclei.

More recently, Yu.N. Gnedin, V.L. Afanasiev, and their collaborators generalized the echo mapping method for the case of spectropolarimetric observations of active galactic nuclei (Gnedin et al., 2012). Taking into account polarization of light permits us to estimate geometry of the emitting region near the super-massive BH, making possible a better calibration of echo-mapping results.

In the case of sufficiently nearby galaxies, it is possible to apply methods of improving angular resolution of the telescope (adaptive optics, speckle interferometry, use of space telescopes like Hubble, James Webb, etc.) to see "probe bodies" near the BH directly, to measure their velocities and distances from the BH. Thus, we use the method of "resolved kinematics" permitting us to obtain most reliable and accurate mass estimates for super-massive BHs.

The first determination of the mass of a super-massive BH by the resolved kinematics technique was made by a US team (Ford et al., 1994) for the galaxy M87. Using the Hubble Space Telescope, they discovered a disk-like spiral structure: a gas and dust envelope around the center of the galaxy. The radius of the envelope is 73 parsecs. Spectra obtained for different parts of this structure demonstrate that its rotation is Keplerean. This resulted in mass determination for the central super-massive BH, $3.2 \times 10^9 M_\odot$ (the currently accepted value of this mass, based on a study of stellar kinematics in the galaxy's central parts, is $\sim 6.6 \times 10^9 M_\odot$).

J. Moran's team (Moran et al., 1999) used intercontinental radio interferometry with angular resolution of 200 microseconds and spectroscopic resolution of 0.1 km s^{-1} and discovered a disk-shaped envelope around the super-high-mass BH in the nucleus of the galaxy NGC 4258, its radius being $\sim 10^{17}$ cm. From motion of individual condensations in this envelope, the BH mass is reliably estimated as $3.5 \times 10^7 M_\odot$.

In the case of elliptical galaxies, regular rotation velocities are difficult to identify against large random velocities of stars, so statistical methods of stellar dynamics are used to estimate masses of their central super-massive BHs.

Besides the most reliable techniques of echo mapping and resolved kinematics, there exist less direct and less accurate methods for estimating masses of super-high-mass BHs; they are used for quick determinations of BH masses. Usually they are calibrated versus results based on echo mapping.

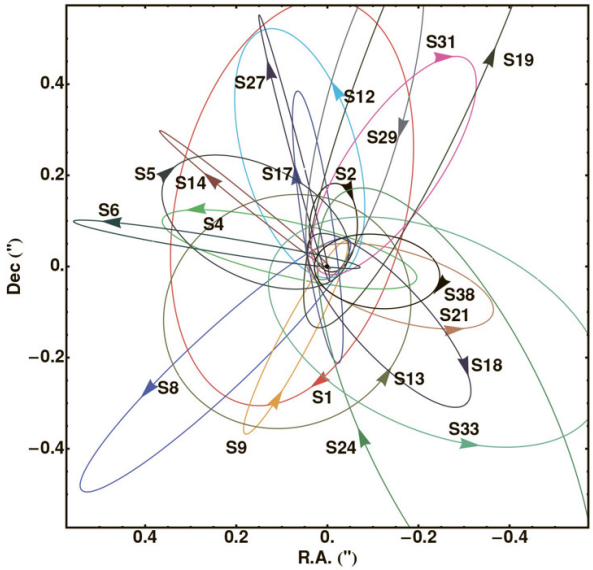


Figure 7 Orbits of 26 stars around the super-high-mass object in the center of our Galaxy, used to determine its mass (from Gillesen et al., 2009).

By now, different scientific teams have measured masses for thousands of super-massive BHs, found to be in the range between 10^6 and $10^{10} M_\odot$. A new science was born: BH demography, it studies the birth and growth of BHs, their relation to classical objects of the Universe: stars, galaxies, etc.

The story of the study of the super-high-mass BH in the center of our Galaxy, at a comparatively low distance from the Earth (~ 8.3 kpc), deserves special discussion.

Systematic observations of the motion of individual stars near the radio source Sgr A* located in the center of our Galaxy were started in 1992–1995 by two scientific groups, under the leadership of Reinhard Genzel and Andrea Ghez, 2020 Nobel Prize winners for these studies.

The great interstellar extinction towards the Galactic center necessitated observations in the infrared spectral range where gas and dust surrounding the center of the Galaxy were transparent. The angular size of the nearest surroundings of the super-massive BH, where stars of the central cluster experience a strong gravitational influence of the central BH, is less than 1 arcsecond (1 second corresponds to 0.004 parsecs, or 8000 astronomical units), and the authors applied modern methods for improving the angular resolution. R. Genzel observed the Galactic center with the 3.5-m and 8.2-m telescopes of the La Silla and Southern European Observatory using speckle interferometry. A. Ghez observed the Galaxy's center with the 10-m KeckII telescope at Hawaii Islands and used adaptive optics. The methods to improve angular resolution applied by the authors made it possible to achieve accuracy of ~ 0.003 arcseconds in the positions of stars near the Galactic center. As a result, they covered parts of orbits for about 30 stars rotating around the central super-massive BH (see Fig. 7); for one of the stars, S2, it has been possible by now to cover its complete orbit

twice. The orbital period of the star S2 is 15.6 years. Observations of the Galactic center were joined by the GRAVITY collaboration (Gravity Collaboration, Abuter et al., 2020), permitting a considerable improvement of motion parameters for the star S2 (Fig. 8). The mass of the central super-massive BH, determined using the third Kepler law, was found to be $(4.31 \pm 0.36) \times 10^6 M_\odot$ (Giblesen et al., 2009). This is the most accurate (to better than 10%) mass determination for the super-massive BH. Since two orbital periods of S2 have been observed by now, it has been possible to detect the relativistic shift of the periastron of the star's elliptical orbit that is in a good agreement with the theoretical value predicted from Einstein's General Relativity. Further observations of the vicinity of the super-high-mass BH in the Galaxy's center permitted us to discover several stars with still shorter orbital periods: 9.9 years (star S62) and 7.6 years (S4711). Studying the motion of these stars, it will be possible to investigate different relativistic effects as well as to estimate the contribution of dark matter to the total mass of the central super-massive object in the center of our Galaxy.

Recently, the size of this super-high-mass object was estimated by means of the GRAVITY interferometric system (Gravity Collaboration, Abuter et al., 2018) with

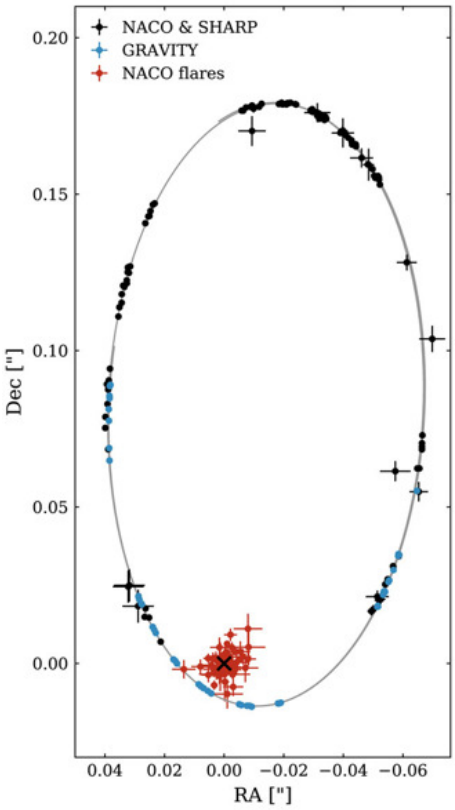


Figure 8 The orbit of the star S2 from observations of 1992–2019. Red pluses inside the ellipse mark the position of the IR source coinciding with the central source, Sgr A* (from GRAVITY collaboration et al., 2020).

angular resolution of the order of 10^{-3} arcseconds. These authors were able to observe rotation of gas clouds around the super-massive BH in the Galactic center at the distance of several Schwarzschild radii.

Thus, by 2000–2015, observations relating to stellar BHs in X-ray binary systems and to super-massive BHs in galactic nuclei have strengthened, as it was luckily formulated by Nobel-prize winner V.L. Ginzburg, our certainty in the actual existence of BHs in the Universe. Unfortunately, the rich observational data on stellar-mass BHs and on super-massive BHs in galactic nuclei do not provide a final proof of the existence of BHs in the Universe.

Though accreting NSs and BHs in X-ray binary systems differ not only by mass but also by observational manifestations in complete agreement with General Relativity predictions, this does not prove the existence of BHs: some accreting NSs, similar to BHs, can lack signatures of observed surface, like phenomena of an X-ray pulsar or an X-ray burster of the first kind. Besides, it is obviously not justified to judge about an object's nature from the absence of certain features (for example, observed manifestations of the existence of a solid surface). As for super-massive BHs, the motion of "probe bodies" around a BH gives a reliable estimate only for the mass of the central super-massive object, while the radius of this object is estimated rather roughly, from indirect evidence (X-ray radiation, its rapid variations, motion of gas clouds at distances of several gravitation radii in the case of the center of our Galaxy, etc.).

The final proof of the existence of BHs came from astronomy of gravitational waves (the LIGO experiment) and from astronomy of super-high angular resolution (the Event Horizon Telescope experiment). Below we give a short description of these outstanding results.

5 Gravitational-wave astronomy and black holes

Bursts of gravitational-wave radiation from merging black holes in binary systems were discovered in 2015 (Abbott et al., 2016).

On February 11, 2016, at a special press conference, American scientists officially announced the discovery of gravitational waves from merging of BHs in a binary system. The reliable detection of gravitational waves (GWs) was achieved with two laser gravitational-wave antennas, H1 and L1, of the American observatory LIGO, separated by the distance of ~ 3000 km.

The international author team included representatives of the group from the Lomonosov Moscow University's Faculty of Physics, headed by V.V. Braginsky, and of the group from the Institute of Applied Physics (Russian Academy of Sciences), headed by E.A. Khazanov.

The idea to use an optical laser Michelson interferometer to detect GWs was suggested by M.E. Gertsenshtein and V.I. Pustovoit in 1962.

The creation of the LIGO gravitational wave observatory was initiated by the American scientists K. Thorne, R. Weiss, and R. Drever.

On September 14, 2015, both antennas (H1 in Hanford, Washington and L1 in Livingston, Louisiana) detected a gravitational-wave signal, about half a second in duration, designated LIGO GW150914 (from 2014.09.15, the date of its detection). The

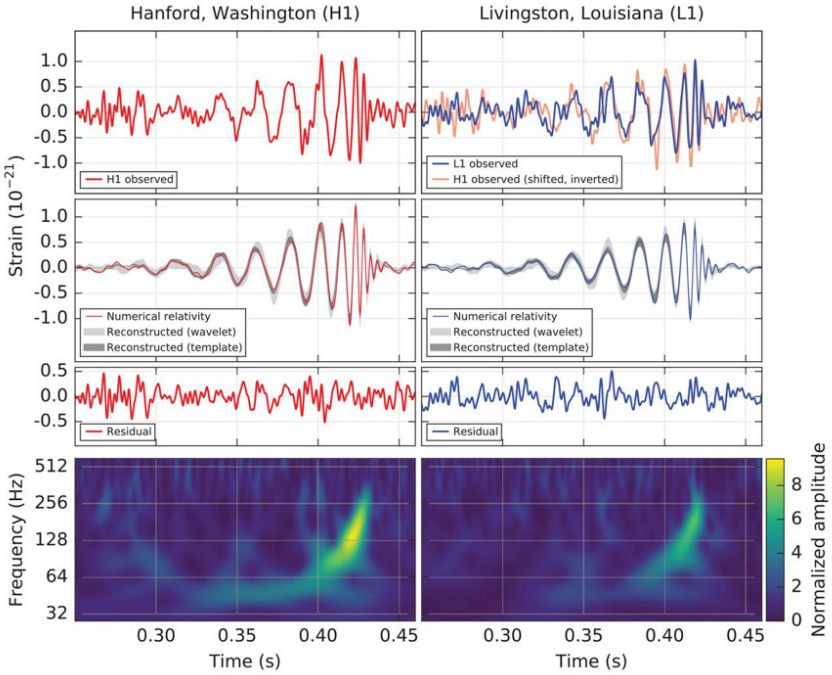


Figure 9 The first gravitation-wave signal from merging black holes in the binary system GW150914, detected by the LIGO observatory (from Abbott et al., 2016).

signal revealed quasi-sinusoidal oscillations with increasing frequency and increasing amplitude, with subsequent abrupt decay (the so-called ring-down stage). The observed GW signal is well described in the frame of General Relativity for the model of two merging BHs (see Fig. 9).

With the discovery of GWs, the new science that began its development in the late 1950s – early 1960s in the studies by J. Wheeler, K. Thorne, I.D. Novikov, Ya.B. Zeldovich and other scientists has gained a solid observational basis. Geometrodynamics is the science studying non-linear dynamics of the curved spacetime. Gravitational wave astronomy provides us with a unique possibility to study not only different material bodies, like stars, galaxies, etc., but also the empty spacetime that can be viewed as one of the forms of matter whose properties, like parameters of curvature and whirls, can be actually studied with GW telescopes.

Properties of spacetime are especially clearly revealed when BHs in binaries merge. Thus, the discovery of GW signals from merging BHs raises the problem of BH studies to a qualitatively new level. Earlier, when studying in the electromagnetic channel, we were only able to passively observe the X-ray "halo" around the BH due to accretion of matter from the companion star and to determine the BH mass from the motion of this companion. Now we can, in a sense, arrange "experiments" with black holes in binary systems, study the process of their merging, formation of a common event horizon, and to investigate different modes of this horizon's decaying oscillations. This means a principal possibility of an experimental existence proof of the event horizon (Cherepashchuk, 2016).

By now, several GW observatories (LIGO, Virgo, KAGRA, etc.) have discovered 90 GW events, mainly related to merging BHs in binary systems (see the catalog in Abbott et al., 2021). Besides, GWs were detected from several merging events of neutron stars in binary systems (Abbott et al., 2017). From the comparison of arrival times of the GW and optical signals, it was possible to show that the GW propagation velocity in space coincides with the velocity of light with a very good accuracy ($\sim 10^{-15}$). Thus, several gravitation theories alternative to General Relativity could be rejected.

The fact that the first discovered GW signals were those from merging BHs rather than NSs was not unexpected by scientists. As early as in 1997, astrophysicists from Sternberg Astronomical Institute (Lomonosov Moscow University) V.M. Lipunov, K.A. Postnov, and M.E. Prokhorov predicted (Lipunov et al., 1997) that the LIGO observatory would first detect the signal from merging BHs rather than NSs. Though the merging frequency of BHs in binaries ($\sim 10^{-5} - 5 \times 10^{-6}$ events per year per one standard galaxy) is considerably lower than that for NSs ($\sim 10^{-4}$), merging BHs release much more energy in the form of GWs. Thus, GWs can be recorded from much larger distances. The volume of space being proportional to the cube of distance, the number of merging BH pairs available for observations increases, in turn, increasing the chance of their detection with GW telescopes.

The problem of parameter determination for a system of two BHs (determination of their masses, angular momenta, etc.) is over-defined (the number of parameters to be determined is much lower than the number of equations describing data points on the curve of the GW signal), GW observations of merging BHs permit us not only to derive BH masses but also to repeatedly check the validity of General Relativity in dynamics, in super-strong, variable gravitational fields. No discrepancies between the General Relativity and GW observations were detected in any cases.

Thus, we have serious reasons to claim that BHs of stellar masses (with masses $\sim$ 4–100 $M_\odot$) have finally been discovered.

6 Astronomy of super-high angular resolution and super-massive black holes (Event Horizon Telescope)

During the recent years, researchers have been able to construct images of the nearest surroungings of super-high-mass BHs in the nucleus of the galaxy M87 (Event Horizon Telescope Collaboration, 2019) and in the nucleus of our Galaxy (Event Horizon Telescope Collaboration, 2022). They used the ground-based intercontinental radio interferometric system Event Horizon Telescope (EHT), which is a global network of sub-millimeter radio telescopes that includes radio telescopes from USA, Germany, Japan, Chile, and other countries, among them a radio telescope at the South Pole. It is important that the radio telescopes work in the range of short radio waves ($\lambda \leq$ 1.3 mm). Only in the short wavelength range, it is possible to "break through" to the event horizon of the central super-massive BH surrounded with comparatively dense magnetized plasma that emits thermal as well as non-thermal, synchrotron radiation. The central super-massive BH is not detectable for direct observations at long waves because of radio wave scattering on plasma inhomogeneities and synchrotron self-absorption.

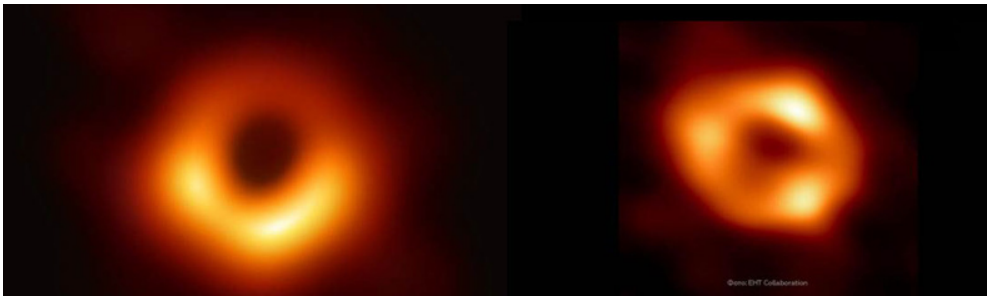


Figure 10 Images of central parts of accretion disks around super-high-mass black holes in the centers of the galaxy M87 and of our Galaxy. In the middle, we see a black "shadow" from the black hole (the gravitation-lens image of the photon sphere) (from Event Horizon Telescope Collaboration, 2019, 2022).

At the wavelength of 1.3 mm, the EHT angular resolution is 2.3×10^{-5} arcseconds, and at the wavelength of 0.9 mm, it will be 1.5×10^{-5} arcseconds. In the case of super-massive BHs in the centers of our Galaxy ($M_{\rm BH}=4.3\times10^6M_\odot$) and the galaxy M87 ($M_{\rm BH}=6.6\times10^9M_\odot$), these short radio waves make possible direct observations of the nearest surroundings of the BH: the inner part of the accretion disk and the dark shadow in its center, due to photon capture by the BH's photon sphere. It should be emphasized that only the extremely strong gravitation field of a BH is able to make photons, propagating with the velocity of 300000 km s^{-1}, to move along circular trajectories around the BH. The gravitation field of a NS is not strong enough to make photon trajectories circular (a NS does not possess a photon sphere). Thus, the detection of a dark shadow in the center of the accretion disk around the central, compact, super-high-mass object is a direct evidence that the object is a BH.

In the case of a Schwarzschild BH, the observed linear diameter of the shadow (gravitationally lensed image of the BH's photon sphere) exceeds the Schwarzschild diameter of the BH ($4GM/c^2$) by a factor ~ 2.6.

For the super-massive BH in the center of our Galaxy ($M_{\rm BH}=4.3\times10^6M_\odot$), at th distance of 8.33 kpc, the angular diameter of the shadow is 5.3×10^{-5} arcseconds, larger than the EHT resolution (2.3×10^{-5} arcseconds). For the super-massive BH in the center of the galaxy M87 ($M_{\rm BH}=6.6\times10^9M_\odot$), at the distance of 1.8×10^4 Mpc, the shadow diameter is 3.8×10^{-5} arcseconds.

Thus, using the EHT, it is quite realistic to "see" images of dark shadows for super-massive BHs in the centers of the galaxy M87 and of our Galaxy.

The large and complex work: interferometric observations and their reductions has led the EHT scientific team to a tremendous success (Event Horizon Telescope Collaboration, 2019, 2022). They obtained images of shadows for the super-massive BHs in the centers of our Galaxy and of the galaxy M87 (cf. Fig. 10).

The observed sizes of these shadows are in a perfect agreement with the sizes computed from the General Relativity formula for those BH masses that were independently determined from the motion of stars near these BHs.

Thanks to the achievements of the EHT science team, we can consider the presence of super-high-mass BHs in galactic nuclei finally proven.

7 Conclusions

The long (more than 60 years) and rather complicated effort of researchers from many countries aimed at the search for BHs in the Universe has resulted, at this time, in convincing evidence that BHs, these quite extreme objects difficult to believe in, actually exist in the Universe.

X-ray astronomy provided the first breakthrough in observational studies of accreting BHs. Rich data of observations were accumulated for many BH candidates. A new science, relativistic astrophysics, was developed and a very beautiful result was obtained. NSs and BHs were found to differ not only by their masses but also by observed phenomena, in complete agreement with General Relativity predictions. As it was luckily formulated by V.L. Ginzburg, it has strengthened our certainty in the actual existence of BHs in the Universe.

Beginning with 2015, thanks to the advent of gravitational-wave astronomy and astronomy of super-high angular resolution, we obtained final proof that stellar-mass BHs as well as super-massive BHs actually exist in the Universe. By now, all doubts concerning the existence of BHs have been removed, these objects have won "citizenship" among classical objects of the Universe: stars, galaxies, etc. A new science, BH demography, was born; it studies processes of BH birth, growth, the evolutionary links between BHs and classical objects of the Universe. There appeared a new aspect of the BH problem: studies of binary super-massive BHs. The problem of the search for wormholes in the Universe is posed. New observational experiments are being planned and developed. Hundreds of thousands of new X-ray binaries with BHs have been discovered on board the "Spectrum-X-ray-Gamma" X-ray observatory. The planned Russian space experiment "Millimetron" is going to observe super-massive BHs in galactic nuclei with the angular resolution as good as 10^{-8} seconds of arc, to search for wormholes. New generations of GW observatories, among them space GW observatories, are aimed at detailed studies of stellar and supermassive BHs, including binary super-massive BHs. The important role of BHs is taken into account in studies of the evolution of the Universe and its structures.

Discovery of BHs is a breakthrough in our understanding of matter and spacetime. We may conclude that we are currently witnessing a triumph of BHs.

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