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Triumph of black holes

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Abstract. The properties of black holes are so extreme that it is hard to believe in their existence. Sixty years ago, in 1964, the seminal works of Ya.B. Zeldovich and E.E. Salpeter on the nonspherical accretion of matter onto black holes were published and it was shown that accreting black holes can be observed in the hard range of electromagnetic radiation. The review describes the 60-year history of observational studies of black holes. The results of observations of black holes in the X-ray and optical ranges, in the gravitational wave range, as well as in the short-wave radio range with ultra-high angular resolution (Event Horizon Telescope program) are briefly summarized. It can be concluded that by now black holes have won the "citizenship rights" among the classical objects of the Universe, and the existence of these highly peculiar objects can be considered proven.

Keywords: black holes; gravitational waves; X-ray binaries

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1 Introduction

Black holes are a prediction of Einstein's theory of General Relativity (GR). A black hole is understood as a region of space-time whose gravitational field is so strong that no signal, even a light signal, can move away from it to the spatial infinity of the future (Novikov and Frolov 1986). The properties of black holes are so extreme that it is hard to believe in their existence.

For many decades, the idea of a black hole (BH) was purely theoretical. However, in 1964, two outstanding scientists, Ya.B. Zeldovich (1964) and E.E. Salpeter (1964), examined the nonspherical accretion of matter onto a BH and showed that accreting BHs can be observed in the hard range of the electromagnetic spectrum. It can be said that today (2024) is the 60th anniversary of the beginning of observational programs of BH studies.

It is also important that 62 years ago, in 1962, the first X-ray source Sco X-1≡V818 Sco was discovered outside the Solar system (Giacconi et al. 1962). From that time, the era of X-ray astronomy began.

In 1972–73, the theory of disk accretion of matter onto BH in binary systems was developed (Shakura 1973; Shakura and Sunyaev 1973; Pringle and Rees et al. 2021; Novikov and Thorne 1973). About the same years, the theory of evolution of close binary systems (CBS) with mass exchange up to the very late stages of two relativistic objects was developed (Tutukov and Yungelson 1973a,b; van den Heuvel 1976).

According to the modern concepts of stellar evolution taking into account the GR effects, if the mass of the core of the star M_c, where thermonuclear reactions take place, exceeds $3M_\odot$, then at the end of the evolution of the star relativistic collapse of its core occurs and a BH is formed. If the M_c mass is less than $3M_\odot$, a neutron star (NS) or white dwarf (WD) is formed at the end of the star's evolution.

The masses of stars are most reliably determined by the motion and interaction of components in CBS. Therefore, the ability to "weigh" relativistic objects makes close binary systems a powerful tool for the discovery and study of NS and BH. Thus, with the beginning of the era of X-ray astronomy, CBS became very important objects for relativistic astrophysics. The emergence and development of X-ray astronomy brought the problem of CBS studies, previously a purely classical field of astronomy, to the forefront of modern astrophysics.

The launch of the first specialized American X-ray observatory UHURU in 1971 marked the beginning of systematic observations of the sky in X-rays. About 300 X-ray sources were discovered, most of which are X-ray binary systems—CBS, in which a normal optical star—a matter donor—feeds accretion onto a relativistic object (NS or BH). The disk accretion theory (Shakura 1973; Shakura and Sunyaev 1973; Pringle and Rees et al. 2021; Novikov and Thorne 1973) allowed us to quickly understand the nature of compact X-ray sources discovered by the UHURU observatory as accreting relativistic objects in X-ray binary systems.

To determine the masses of relativistic objects, identifications of X-ray binary systems with optical stars were required. The first optical identifications of X-ray binary systems were made in Cherepashchuk et al. (1972), Bahcall and Bahcall (1972). In Cherepashchuk et al. (1972) and Lyutyi et al. (1973) the main types of optical manifestations of X-ray binary systems—reflection and ellipticity effects—were discovered and investigated, which were further widely used for optical identifications of X-ray binary systems and for determining the masses of relativistic objects.

In Margon et al. (1979), Crampton et al. (1980), and Cherepashchuk (1981) the object SS 433 was discovered—the first example of a microquasar with manifestations of supercritical accretion on a relativistic object, predicted in Shakura and Sunyaev (1973).

Later on, it was X-ray astronomy and the astronomy of binary star systems that provided the first breakthrough in the search for and studies of massive compact objects—candidates for BH. The discovery of gravitational waves from mergers of BHs in binary systems in 2015 and the imaging of the nearest neighborhoods of a supermassive BH in the core of the galaxy M 87 in 2019 and in the center of our Galaxy in 2022 allowed us to finally prove the reality of BHs in the Universe. As a result, by now, BHs have won "citizenship rights" among classical objects of astronomy: stars, galaxies, galactic clusters, etc. A new field of astrophysics is successfully developing—demography of BH, that studies the birth, growth of BHs and their connection with classical objects of the Universe.

2 Initial observations of BHs

Studies of the optical manifestations of X-ray binary systems have allowed us to develop efficient methods for estimating the masses of X-ray sources in binary systems, including accreting BHs (see, e.g., the review by Cherepashchuk 2022 and references therein).

In Webster and Murdin et al. (1972), the mass function of the optical star, the supergiant B0Ib, in the X-ray binary system Cyg X-1 $f_v(M) \cong 0.2M_\odot$ was measured. In Lyutyi et al. (1973) the effect of ellipticity of the optical star in the Cyg X-1 system was discovered and from the analysis of this effect an estimate of the orbital inclination in this system was made and one of the first estimates of the black hole mass $M_x > 5.6M_\odot$ was obtained. In Paczynski (1974), constraints were placed on the mass of a BH in the Cyg X-1 system, taking into account the known distance to this system. The fact that one of the first discovered compact X-ray sources turned out to be an accreting BH, gave scientists optimism and hope that in the near future many massive X-ray sources, candidates for BH, would be discovered. But in practice, everything turned out to be much more complicated. For 11 years, the Cyg X-1 object was the only known candidate for a BH. And the vast majority of compact X-ray sources discovered by the UHURU program turned out to be accreting NS. In this regard, many researchers had doubts: maybe there are really no BHs in the Universe? These doubts were reinforced after the publication by Paczynski's group (Bahcall et al. 1974) in which Cyg X-1 model was represented as a triple system consisting of two optical stars with significant mass differences and an accreting NS.

Since the percentage of triple systems among stars is not small, this model had a right to exist. After that the number of optimists in the program of search for BH went down and exactly in these years the supporters of theories of gravitation alternative to GR (for example, the rector of MSU academician A.A. Logunov) were the most active. At scientific seminars at the Physics Department of MSU and on the pages of the journal "Physics-Uspekhi" a sharp discussion between supporters of GR (Ya.B. Zeldovich, L.P. Grishchuk) and opponents of this theory (A.A. Logunov) took place.

Only in 1983 the Canadian scientist Ann Cowley and her coworkers succeeded in discovering a second BH candidate (Cowley et al. 2021) in the X-ray binary system LMC X-3, whose mass was estimated to be $8M_{\odot}$.

In 1986, American scientists McClintok and Remillard discovered the first BH in the low-mass (optical star mass $\sim 1M_{\odot}$) X-ray binary system A0620-00 (McClintock and Remillard 1986). That was a great surprise to scientists, as they had previously searched for BH in massive X-ray binary systems with optical star masses much larger than the solar mass. At the time, it was assumed that binary stars most often formed as pairs of stars with similar masses. Since BHs are formed when the nuclei of massive stars collapse, scientists chose massive X-ray binary systems to search for BH. And they miscalculated. In further studies it, turned out that the distribution of CBS on the ratio of component masses is very wide, and the ratio of masses close to unity is not emphasised in any way. But the main thing is that the time of nuclear evolution of a massive star is thousands of times shorter than the time of evolution of a low-mass star.

Therefore, the accretion and X-ray source stage in a binary system with a massive optical star is thousands of times shorter than the accretion and X-ray source stage in a low-mass X-ray binary system. Therefore, it is much less likely to detect a BH in a massive X-ray binary system than in a low-mass one. This explains the fact that the successes of the discovery of BH in massive X-ray binary systems at first were very modest. To date, more than 30 candidates for BH in X-ray binaries have been discovered, and more than two-thirds of them are observed in low-mass X-ray binary systems.

Since the mid-1970s, many specialized space X-ray observatories have been launched, including the Soviet and Russian Mir/Kvant (1987–1996) and Granat (1989–1998) observatories. Much work is being done by Russian scientists at the international space gamma-ray observatory Integral, as well as at the space X-ray observatory Spectrum-X-Ray-Gamma-ray. The initiator and scientific leader of all these Russian X-ray experiments is R.A. Syunyaev and his remarkable scientific team at Space Research Institute. These investigations were supported by Ya.B. Zeldovich.

To date, many thousands of X-ray binary systems have been discovered and studied. The masses of many dozens of stellar-mass black holes and about a hundred neutron stars have been measured so far.

A very beautiful result is revealed: NS and BH differ not only on masses, but also on observational manifestations in full agreement with the predictions of GR. In all about 100 cases when the relativistic object shows signs of observable surface (phenomenon of X-ray pulsar, radio pulsar, X-ray burster of the 1st type) its mass does not exceed $3M_\odot$ in full agreement with the prediction of GR about existence of the upper limit of mass of NS in $3M_\odot$. At the same time, none of more than 30 massive ($M > 3M_\odot$) X-ray sources shows signs of an observable surface (is neither an X-ray nor a radio pulsar nor an X-ray burster of the 1st type) in full agreement with the prediction of GR about the existence of an event horizon in the BH.

This remarkable result, obtained for 60-year period of investigation of relativistic objects, is an indirect evidence of presence of an event horizon at BH. Unfortunately, this result cannot serve as a final proof of existence of BHs, since there are also NS, which also do not show signs of an observable surface. For example, if the axis of rotation of an NS coincides with the axis of a magnetic dipole, the X-ray pulsar phenomenon will not be observed, and a heavy NS can be confused with a BH. In addition, it is obvious that one cannot make a final judgment about the nature of an object based on the absence of any features.

3 Observations of supermassive BHs in galactic nuclei

In the early 1990s, the determination of the masses of supermassive BHs (SMBHs) in the nuclei of galaxies began. The first estimates of the masses of SMBHs in the nuclei of very active galaxies—quasars—were made back in 1964 by Ya.B. Zeldovich and I.D. Novikov (1965) under the condition of equality of the quasar luminosity and the critical Eddington luminosity. These masses turned out to be very large—of about

$10^8 M_\odot$. Systematic determinations of the masses of supermassive compact objects (BH) in the nuclei of Seyfert galaxies were carried out in the 1980s by E.A. Dibai (1984). To determine the mass of an object, it is sufficient to know the velocity of a "test body" (star, gas cloud, gas disk) rotating around it under the action of gravitational attraction and the distance of this body to the central object under study.

According to the width of powerful and broad emission lines of hydrogen and other chemical elements in the spectrum of the galactic nucleus, E.A. Dibai determined the characteristic velocity of gas clouds rotating around the central supermassive object, and according to the full intensity of these lines, using the photoionization model of the galactic nucleus, the characteristic volume of radiating gas was found and, as a consequence, the characteristic distance of gas clouds from the central supermassive compact object was estimated on the order of magnitude. The estimates of the masses of supermassive compact objects in the nuclei of Seyfert galaxies obtained in this way were of the order of magnitude $10^8 M_\odot$.

In 1973, A.M. Cherepashchuk and V.M. Lyutyi discovered the effect of delayed variability of emission lines in the spectra of active galactic nuclei relative to the continuum variability (Cherepashchuk and Lyutyi 1973). This allowed us to estimate the characteristic distance of gas clouds from the central SMBH not on the order of magnitude, but much more precisely. By measuring the lag time, it is possible to give a reliable estimate of the distance of gas clouds—"test bodies" radiating in the line from the central BH. At known velocity of gas clouds, determined by the widths of emission lines, it is possible to determine the mass of a supermassive BH in this way.

The lag effect was the basis for the method of determining the masses of SMBH, called the reverberation mapping method. The first ideas of the reverberation mapping method were expressed in 1983 in the work of I.I. Antokhin and N.G. Bochkarev (Antokhin and Bochkarev 1983). The advantage of this method is that here the velocities of "test bodies" and their distances from the central BH are estimated indirectly. Therefore, the reverberation mapping method can be applied to numerous distant galaxies for which the resolving power of the telescope is insufficient to directly "see" the "test bodies". To date, the masses of hundreds of supermassive BHs in active galactic nuclei have been measured by reverberation mapping.

In recent years, the reverberation mapping method has been generalized in the works of Yu.N. Gnedin and V.L. Afanasiev and collaborators to the case of spectropolarimetric observations of the nuclei of active galaxies (Gnedin et al. 2012). The involvement of the polarization of radiation in the lines makes it possible to estimate the geometry of the emitting region near a supermassive BH, which makes it possible to better calibrate the results obtained by the reverberation mapping method.

In the case of sufficiently close galaxies, using the methods of increasing the angular resolution of the telescope, one can directly “see” “test bodies”, near a SMBH and measure their velocities and distances from the BH. In this way, the method of “resolved kinematics”, is realized, which allows us to obtain the most reliable and accurate estimates of the masses of SMBHs.

For example, the motion of about three dozen stars, including the star S2 with an orbital period of 15.6 years, around a SMBH in the center of our Galaxy has been studied using observations in the IR range and the mass of the central SMBH has been determined with an accuracy better than 10% using Kepler’s third law: $M_{\rm BH} = (4.31 \pm 0.36) \times 10^6 M_\odot$ (Gillessen et al. 2009).

In the case of elliptical galaxy nuclei, where regular galaxy rotation velocities are hardly revealed against the background of large random stellar velocities, the mass of the central SMBH is estimated with the help of the dispersion of stellar velocities using the laws of stellar dynamics.

There are also express, less accurate methods for estimating the masses of supermassive black holes in galactic nuclei based on statistical correlations. As a rule, such methods are calibrated using the results of reverberation mapping and “resolved kinematics” methods.

To date, the masses of thousands of SMBHs have been measured with the help of different methods. These masses lie in the range of $10^6 \div 10^{10} M_\odot$. Estimates of the radii of SMBHs are most often obtained from observations of the rapid variability of galactic nuclei on times up to tens of minutes, which corresponds to values less than 10 gravitational radii.

Thus, by 2000–2015 years the observational data on stellar BHs, as well as on SMBHs in the nuclei of galaxies according to the successful statement of V.L. Ginzburg strengthened our confidence in the real existence of BHs in the Universe.

The definitive evidence for the existence of the BHs came after 2015 from gravitational-wave astronomy (the LIGO[1] experiment and others) and from ultra-high angular resolution astronomy at short radio waves (the Event Horizon Telescope experiment).

4 Gravitational-wave astronomy and black holes

In 2015, bursts of gravitational-wave radiation from mergers of BHs in binary systems were discovered (Abbott et al. 2016). Reliable detection of gravitational waves (GW)

[1] Laser Interferometer Gravitational-Wave Observatory.

was realized at two laser GW antennas of American LIGO laboratories, separated by a distance of approximately 3000 km.

The initiators of LIGO were American scientists K. Thorne, R. Weiss, and R. Driver. The idea to use the Michelson optical laser interferometer for GW registration was suggested by M.E. Gerzenstein and V.I. Pustovoit in 1962 (Gertsenshtein and Pustovoit 1963). The international LIGO Scientific Collaboration included representatives of the Physics Department of Lomonosov Moscow State University, a group of V.B. Braginsky, and a group from the A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences led by E.A. Khazanov.

On September 14, 2015 on both LIGO antennas (H1 in Hanford, Washington and L1 in Louisiana, Livingston) gravitational-wave signal with a duration of about half a second was registered, and it was named LIGO GW150914 (if you read the numbers from right to left, we get 140915—the date of registration of the signal). The signal is a quasi-sinusoidal oscillation with increasing frequency and increasing amplitude followed by a sharp decay (the so-called ring-down stage). The observed GW signal is well described in the framework of GR by the model of merger of two BHs.

With the discovery of GW, a new science, Geometrodynamics, which began to develop in the late 1950s and early 1960s in the works of J. Wheeler, K. Thorne, I.D. Novikov, Ya.B. Zeldovich and other scientists, was put on a solid observational basis. Geometrodynamics is a science that studies the nonlinear dynamics of curved space-time. Gravitational-wave astronomy gives us a unique opportunity to study not only various material bodies, such as stars, galaxies, etc., but also empty space-time, which can be considered as one of the types of matter, whose properties, such as curvature and curl parameters, can be actually studied with the help of GW telescopes.

Especially brightly space-time properties are revealed at mergers of BHs in binary systems. Therefore, the discovery of GW signals from the merger of BHs takes the problem of BH research to a qualitatively new level. Earlier, at investigations in the electromagnetic channel, we could only passively observe the X-ray "halo" around the BH, caused by accretion of the satellite matter and determine the mass of the BH by the motion of this satellite. Now we can as if "experiment" with black holes in binary systems, study the process of their merger, the formation of a common event horizon, and study different modes of damped oscillations of this horizon. This gives us a fundamental possibility of the final experimental proof of the existence of the event horizon (Cherepashchuk 2016).

To date, a number of GW observatories (LIGO, Virgo, KAGRA, etc.) have discovered about 90 GW events, mostly associated with mergers of BHs in binary systems (see Abbott et al. 2021 catalog). In addition, GW from several neutron star mergers in binary systems have been discovered (Abbott et al. 2017). By comparing the arrival times of the GW and the optical signal from these mergers, the scientists were able to show that the speed of GW propagation in space coincides with the speed of light with great precision ($\sim 10^{-15}$). This allowed them to reject a number of theories of gravitation that are alternative to GR.

The fact that the first GW signals were discovered from the merger of BHs, rather than NSs, was not unexpected for scientists. Back in 1997, astrophysicists from the Sternberg State Astronomical Institute V.M. Lipunov, K.A. Postnov, and M.E. Prokhorov (Lipunov et al. 1997) predicted that the LIGO observatory should register signals from mergers of BHs earlier than from NSs. Although the frequency of BH mergers in binary systems ($\sim 10^{-5} \div 10^{-6}$ mergers per year per standard galaxy) is significantly lower than the frequency of NS mergers ($\sim 10^{-4}$), BH mergers release much more energy in the form of GW. This makes it possible to detect GW emission from much greater distances. Since the volume of space is proportional to the cube of the distance, the number of merging pairs of BHs available for observations increases and, consequently, the probability of their detection by GW telescopes increases as well.

Since the problem of determining the parameters of the system of two BHs (masses, angular momenta, etc.) from the observed GW signal is overdetermined (the number of sought parameters is much smaller than the number of equations describing the observed points on the curve of the GW signal), in GW observations of merging binary BHs it is possible not only to determine the masses of BHs, but also to check many times the validity of the GR equations in the dynamics in superpower variable gravitational fields. In all cases, no inconsistencies between GR and observations of the GW are found.

This allow us to conclude that stellar-mass BHs (with masses of about $4 \div 100\ M_\odot$) are finally discovered.

5 Ultra-high angular resolution astronomy and supermassive black holes (Event Horizon Telescope)

In recent years, scientists have been able to construct images of the nearest neighborhood of SMBHs in the core of the galaxy M 87 (Akiyama et al. 2019) and in the core of our Galaxy (Akiyama et al. 2022). The ground-based intercontinental radio interferometer system Event Horizon Telescope (EHT) was used, which is a global network of submillimeter radio telescopes, including radio telescopes of the USA, Germany, Japan, Chile, Taiwan, and other countries, including the radio telescope located at the South Pole.

It is important that these telescopes operate in the short radio wavelength range ($\lambda\,1.3$ mm). Only in the short-wavelength range it is possible to “break through” to the event horizon of the central SMBH, which is surrounded by a relatively dense magnetized plasma emitting both thermal and non-thermal synchrotron radiation. At long wavelengths, due to scattering of radio emission on plasma inhomogeneities and due to synchrotron self-absorption, the central SMBH is inaccessible for direct observations.

At a wavelength of 1.3 mm, the angular resolution of the EHT is 2.3×10^{-5} arcsec, and at a wavelength of 0.9 mm, the angular resolution will be 1.5×10^{-5} arcsec. For SMBHs in the centers of our Galaxy ($M_{\rm BH} = 4.3\times10^6\ M_\odot$) and of the galaxy M 87 ($M_{\rm BH} = 6.6\times10^9\ M_\odot$) at such short radio wavelengths we can directly observe the nearest neighborhood of the BH: the inner part of the accretion disk and the dark shadow in its center, caused by the capture of photons by the photon sphere of the BH. We emphasize that only an extremely strong gravitational field of the BH is able to make photons propagate at a speed of 300 000 km/s moving along circular trajectories near the BH. The gravitational field of a NS is not strong enough to make photons’ trajectories circular (a NS has no photon sphere). Therefore, the detection of a dark shadow in the center of the accretion disk around the central compact supermassive object is a direct evidence that this object is a BH.

In the case of the Schwarzschild BH, the observed linear diameter of the shadow (gravitationally-lensed image of the photon sphere of the BH) is $\sim$2.6 times larger than the Schwarzschild diameter of the BH ($2R_{\rm Schw} = 4GM/c^2$).

For the SMBH in the center of our galaxy ($M_{\rm BH} = 4.3\times10^6\ M_\odot$), which is 8.33 pc away from us, the angular diameter of the shadow is 5.3×10^{-5} arcsec, which exceeds the resolving power of the EHT (2.3×10^{-5} arcsec). For the SMBH at the center of the galaxy M 87 ($M = 6.6\times10^9 M_\odot$), for which the distance is 1.8×10^4 Mpc, the shadow diameter is 3.8×10^{-5} arcsec.

Thus, it is quite realistic to “see” images of dark shadows for the SMBHs in the centers of the M 87 galaxy and our Galaxy with the help of the EHT.

The large and complex work on performing interferometric observations and their mathematical processing has led the EHT science team to a tremendous success (Akiyama et al. 2019, 2022). Shadow images were constructed for the SMBHs in the centers of our Galaxy and the galaxy M 87. The observed sizes of these shadows are in a good agreement with their sizes calculated with the help of the GR formula for those values of BH masses, which are independently determined from the motion of stars near these BHs.

Thus, thanks to the achievements of the EHT scientific team, the existence of SMBHs in the nuclei of galaxies can be considered definitively proven.

6 Conclusion

Many years (more than 60 years) of hard work of scientists from many countries to search for BHs in the Universe to date crowned with convincing evidence that BHs—these highly extreme objects, in the existence of which is hard to believe, really exist in the Universe.

X-ray astronomy provided the first breakthrough in observational studies of accreting BHs. Rich data on many candidates for BHs were accumulated. A new science—relativistic astrophysics was developed. A very beautiful result was obtained. It has appeared that NSs and BHs differ not only on masses, but also on observational manifestations in full agreement with predictions of GR. According to the apt statement of V.L. Ginzburg, it strengthened our confidence in the real existence of BHs in the Universe.

Since 2015, with the advent of gravitational-wave astronomy and ultrahigh angular resolution astronomy, strong evidence has been obtained that both stellar-mass BHs and supermassive BHs really exist in the Universe. By the present time all doubts in the existence of BHs have disappeared, and these objects have won "citizenship rights" among classical objects of the Universe—stars, galaxies, etc. A new science was born—demography of BH, which studies the processes of BH birth and growth, as well as the evolutionary connection between BHs and classical objects of the Universe.

A new aspect of the BH problem has appeared—the study of binary SMBHs. The task of searching for wormholes in the Universe is set. New observational experiments are being planned and developed. Hundreds of thousands of new X-ray binary systems with BH have been discovered by the Spectrum-X-Ray-Gamma-ray Observatory. The planned Russian space experiment Millimetron is supposed to observe SMBHs in the nuclei of galaxies with angular resolution up to 10^{-8} seconds, as well as to search for wormholes. New generations of GW observatories, including space GW observatories, are aimed at detailed studies of stellar-mass and supermassive BHs, including binary SMBHs. The important role of BHs is taken into account in studies of the evolution of the Universe and its structures.

The discovery of BHs means a breakthrough in our understanding of the nature of matter and space-time.

We can conclude that *we are currently experiencing the triumph of BHs.*

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