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Discovery of gravitational waves: a new chapter in black hole studies

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Contents

Abstract. **With the discovery of gravitational waves, a new space information channel has become available to scientists, and a new field of science, nonlinear dynamics of curved space–time (geometrodynamics for short) has been given an observational foundation. The observation of gravitational waves is especially interesting for understanding the nature of black holes. The observation of the ring-down stage of a binary black hole merger can provide a profound opportunity to obtain proof of the presence of an event horizon for a newly formed black hole. The discovery of gravitational waves opens up new possibilities for the massive discovery and investigation of new black holes in highly evolved binaries.**

Keywords: gravitational waves, black holes, binary stars, geometrodynamics, evolution, coalescence of black holes

1. Introduction

On 11 February 2016, at a dedicated press conference, American scientists officially announced the discovery of gravitational waves (GWs) from coalescing black holes (BHs) in a binary system. Gravitational waves were reliably detected by two laser gravitational-wave antennas, H1 and L1, of the American LIGO observatory (Laser Interferometer Gravitational-Wave Observatory), separated by a distance of ≈ 3000 km. One antenna (H1) is located in Hanford (Washington), and the other (L1) in Livingston (Louisiana). Paper [1] reported the discovery. The international list of authors (1200 scientists from 15 countries) includes researchers from the Faculty of Physics of Lomonosov Moscow State University (MSU) — a group headed by V B Braginsky — as well as a group from the Institute of Applied Physics, Russian Academy of Sciences, headed by E A Khazanov.

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The idea to use the optical-laser Michelson interferometer to register gravitational waves was put forward by Gertsenshtein and Pustovoit [2] long before the first experiments by Weber [3] (1968). In Russia, research in this field was initiated by Zeldovich as a reaction to Weber's controversial results [4]. Later, scientists from the Faculty of Physics of MSU (Braginsky, V N Rudenko, A B Manukin, E I Popov, and A A Khorev) conducted experiments using solid resonant antennas [5], which did not confirm Weber's results. Gravitational wave research by Gertsenshtein, Pustovoit, Braginsky, and Rudenko [2, 5–7] was constantly supported and inspired by V L Ginzburg.

The construction of LIGO was initiated by American scientists K Thorne, R Weiss, and R Driver.

On 14 September 2015, both antennas (H1 and L1) registered a gravitational-wave signal lasting about 0.5 s, called LIGO GW150914 (Fig. 1). The signal represents quasi-sinusoidal oscillations with increasing frequency and amplitude, ending with rapid decay. The observed gravitational-wave signal is well described by Einsten's General Relativity (GR) in the model of coalescing BHs in a binary system (see, e.g., [8]).

The corresponding initial BH masses (in the rest frame of the source) are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$ (where $M_\odot$ is the solar mass). The resulting BH mass after the coalescence is $62^{+4}_{-4} M_\odot$; the mass $3.0^{+0.5}_{-0.5} M_\odot$ was emitted in the form of gravitational waves. The dimensionless angular momentum of the newly formed BH after the coalescence is $0.67^{+0.05}_{-0.07}$. The source of gravitational waves is located at a distance of 410^{+160}_{-180} Mpc from Earth, which corresponds to 1.3 bln light years. The corresponding redshift is $z = 0.09^{+0.03}_{-0.04}$. The gravitational-wave signal first impinged the L1 antenna, and after a time delay of $6.9^{+0.5}_{-0.4}$ ms was detected by the H1 antenna. This enabled the authors to conclude that the gravitational-wave signal arrived from a sky region located in the southern celestial hemisphere. Coordinated searches for an electromagnetic counterpart to the GW burst were carried out by 25 groups of observers in the radio, optical, near-infrared, X-ray, and gamma-ray bands using ground-

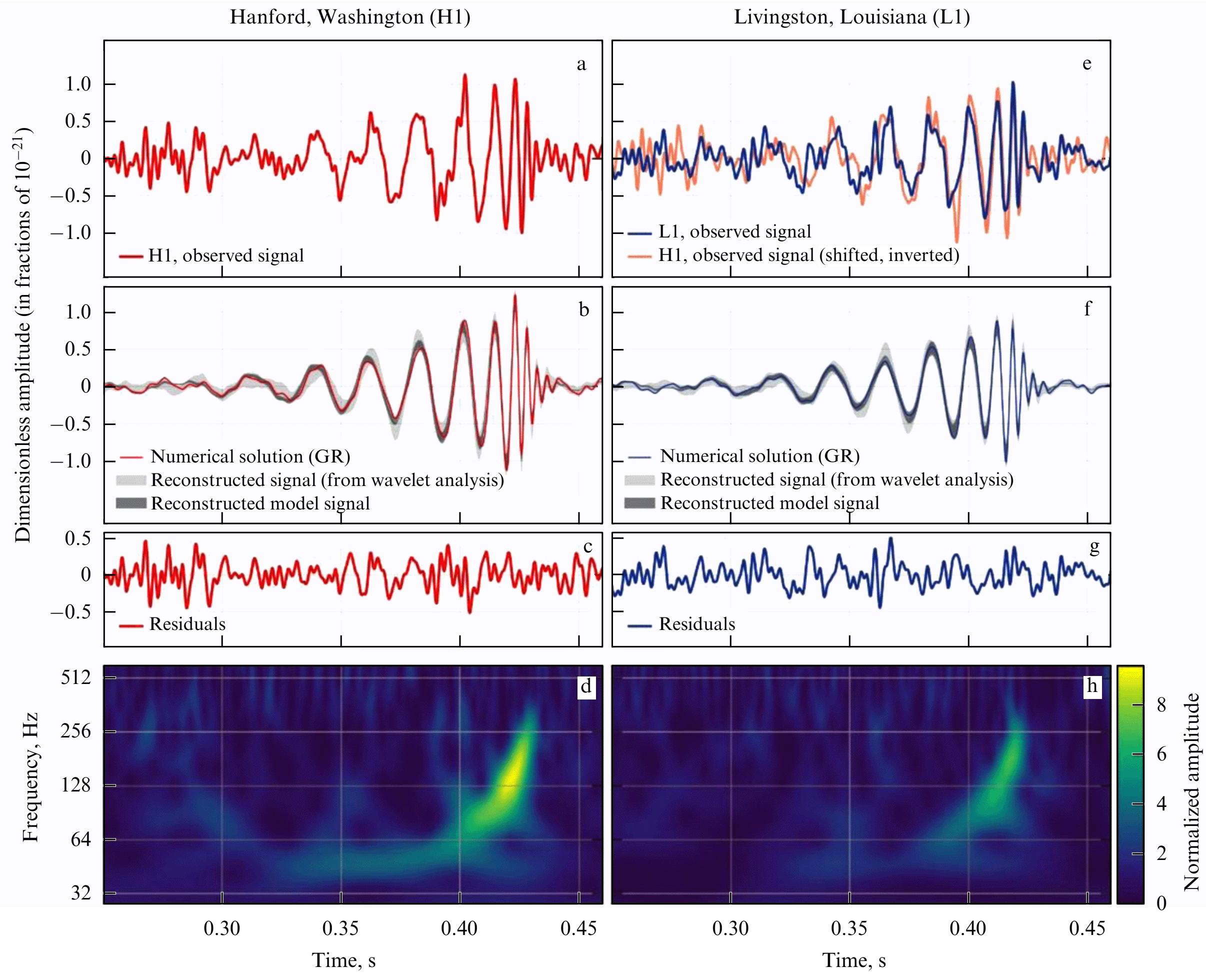

Figure 1. Gravitational wave signal from the coalescence of two black holes detected on 14 September 2015 by two gravitational-wave detectors: (a–d) H1 and (e–h) L1. In e–h, signals from two antennas H1 and L1 are superimposed. (b, f): smoothed signals with superimposed theoretical waveforms; (c, g): the residuals. (d, h): The results of the frequency data analysis are presented. (From [1].)

based and space telescopes [9]. From the Sternberg Astronomical Institute (SAI) of MSU, a group led by V M Lipunov participated in these searches. The MASTER network of robotic telescopes was used.

No possible electromagnetic counterparts were registered except with gamma rays. The Fermi gamma-ray space observatory detected a weak (at a significance level of around 3σ) hard X-ray burst 0.4 s after LIGO GW150914 [10].

The scientific meaning of the discovery of gravitational waves is enormous. A new information channel has been opened, which, in line with electromagnetic, neutrino, and cosmic-ray channels, enables observations of different catastrophic events in the Universe, including the coalescence of double white dwarfs, neutron stars and black holes, supernova explosions, and possibly new phenomena that we are totally unaware of (for example, related to cosmic strings, domain walls, white holes, or wormholes). A further increase in the sensitivity of GW detectors will allow studying GW backgrounds including very long-wavelength GWs (with $\lambda \gtrsim 1$ Mpc) forming at the transitional stages of expansion of the Universe, as well as GW emission from coalescences of supermassive BHs in galactic nuclei (see, e.g., [11]). For instance, superlong gravitational waves could be formed at the end of the inflation stage (when the age of the universe was $\sim 10^{-36}$ s), in the epoch of scalar field decay and the formation of matter particles [12]. Such a GW background radiation carrying information on the very early universe was predicted in 1974 by the SAI researcher Grishchuk [13], who considered a parametric (superadiabatic) mechanism of GW amplification in the expanding universe. The spectrum of the primordial (relic) GW radiation produced prior to the beginning of the classical Friedmann expansion stage (the de Sitter stage) was calculated in 1979 by Starobinsky [14].

The discovery of gravitational waves provided solid observational grounds for a new science, geometrodynamics, which was initiated in the late 1950s–early 1960s by Wheeler [15], Thorne (see review [8]), Zeldovich and Novikov [16], and others. Geometrodynamics studies the nonlinear dynamics of a curved space–time. Gravitational-wave astronomy offers a unique possibility of studying not only material bodies, such as stars and galaxies, but also empty space–time, which can be considered to be one of the material species, whose properties (e.g., curvature) can actually be probed by gravitational-wave telescopes.

The properties of space–time are most prominent during coalescences of black holes in binary systems [8, 11, 17]. Therefore, the discovery of a GW signal from coalescing binary BHs (the LIGO GW150914 event) [1] brings BH studies to a qualitatively new level. If in previous BH research we could only observe the X-ray 'glow' around them caused by accretion of matter from the companion (a normal star) and from the motion of this star to determine the BH masses, now from LIGO GW150914-like events we can study BHs, for example, by observing different decaying oscillation modes of the newly formed massive BH. This provides a profound opportunity to obtain the ultimate experimental proof of the presence of the event horizon in BHs. Therefore, scientists from all around the world congratulate the LIGO collaboration on its grandiose success and very much look forward to new discoveries in the field of gravitational-wave astronomy.

2. Binary stars as sources of gravitational waves

From the very beginning of gravitational-wave studies, binary stars have been considered the most suitable objects for searches for and exploration of gravitational waves.

In 1965, Mironovskii [18] calculated the total emission from binary stars of the Galaxy and showed that short-period close WUMa binaries composed of two contacting stars with masses of $(1-3)M_{\odot}$ with short orbital periods $P \approx 0.3-0.6$ days (see, e.g., [19]) should mostly contribute to the total galactic GW emission.

At approximately the same time, the nature of cataclysmic variables, including nova and nova-like stars demonstrating optical outbursts, were clarified. It turned out that these outbursts are related to the interaction of stars in close binary systems. Matter from a red dwarf star filling its Roche lobe in a close binary system is transferred onto another binary component — a degenerate white dwarf — around which a bright accretion disk is formed. Instabilities in this accretion disk lead to its turbulization, increasing the matter viscosity and increasing the matter accretion rate onto the white dwarf, which leads to an outburst. Remarkably, the mass transfer in cataclysmic binaries occurs from the less massive red dwarf star to the more massive white dwarf. In this case, the distance between the binary components (the radius of the relative orbit) must increase with time. But then, why do we observe in cataclysmic binaries a bright accretion disk and a bright interaction region of the gas stream from the Roche lobe filling the star with the accretion disk? It turns out that the tendency to increase the distance between the components in cataclysmic binaries is compensated by the distance decrease due to the loss of the orbital angular momentum carried away by the magnetized stellar wind from the red dwarf star [20] and by gravitational waves [21]. The emission of gravitational waves dominates in binaries with orbital periods shorter than 3 h [21–23]. Therefore, the presence of bright accretion disks in cataclysmic binaries with short orbital periods ($P < 3$ h) is an observational consequence of gravitational wave emission.

With the discovery of the binary radio pulsar PSR 1913+16 [24], direct astronomical indications favoring the existence of gravitational waves have been obtained: the orbital period of this binary system decreases in strict agreement with the quadrupole Einstein formula for gravitational wave radiation (see, e.g., [25]). To date, similar results have been obtained for three more binary radio pulsars: J0737-3039AB (a double pulsar binary [26]), PSR 1534+12 (a radio pulsar paired with an inactive neutron star [27]), and PSR J0348+0432 (a radio pulsar paired with a white dwarf [28]).

With the development of the theory of evolution of close binaries (see, e.g., [29]), the evolution of these systems has

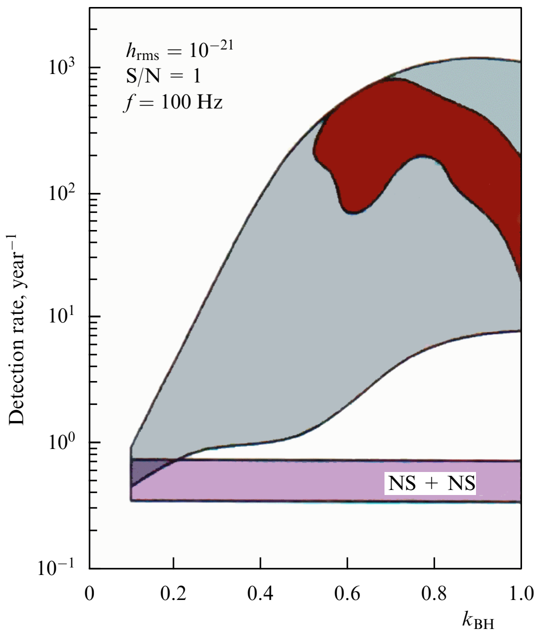

Figure 2. Detection rate of gravitational wave bursts from coalescing neutron stars and black holes in binary systems calculated by Lipunov, Postnov, and Prokhorov using the Scenario Machine code [34]. k_{BH} is the fraction of stellar mass falling under the event horizon during the BH formation.

been understood up to the very late stages — the primary and secondary mass-transfer stages between the binary system components with the formation of white dwarfs, neutron stars, and black holes (depending on the mass of the stars) [30, 31]. Further development of evolutionary scenarios of close binary evolution gave rise to a new method of statistical studies of the evolution of binary stars: population synthesis, which consists in computer simulations of populations of objects with a complex evolutionary history [32, 33]. In [34], Lipunov, Postnov, and Prokhorov calculated binary evolutionary tracks using the original Scenario Machine code to theoretically predict that the LIGO observatory should first discover coalescing binary black holes and not neutron stars. Although the binary BH coalescence rate is significantly lower ($\sim 10^{-6}$ per standard galaxy a year) than the binary neutron star coalescence rate ($\sim 10^{-4}$ per galaxy a year), much more energy is emitted during a binary BH coalescence in the form of gravitational waves. This enables gravitational wave detection from much longer distances than from coalescing binary neutron stars. Because the volume of space available for GW detection is proportional to the cube of the distance, the number of coalescing binary BHs increases and, correspondingly, the probability of their detection by gravitational-wave antennas increases (Fig. 2). Here, clearly, in view of observational selection effects, more massive coalescing binary BHs must be preferentially detected, which was actually observed [1].

3. 'Classical' binary systems consisting of massive stars

Black-hole masses in the LIGO GW150914 system were fairly large: $36M_{\odot}$ and $29M_{\odot}$. Most likely, such massive BHs were formed from very massive stars with masses of $\sim (80-100)M_{\odot}$, although there are grounds to believe that the mass of the end product of the evolution of a massive star,

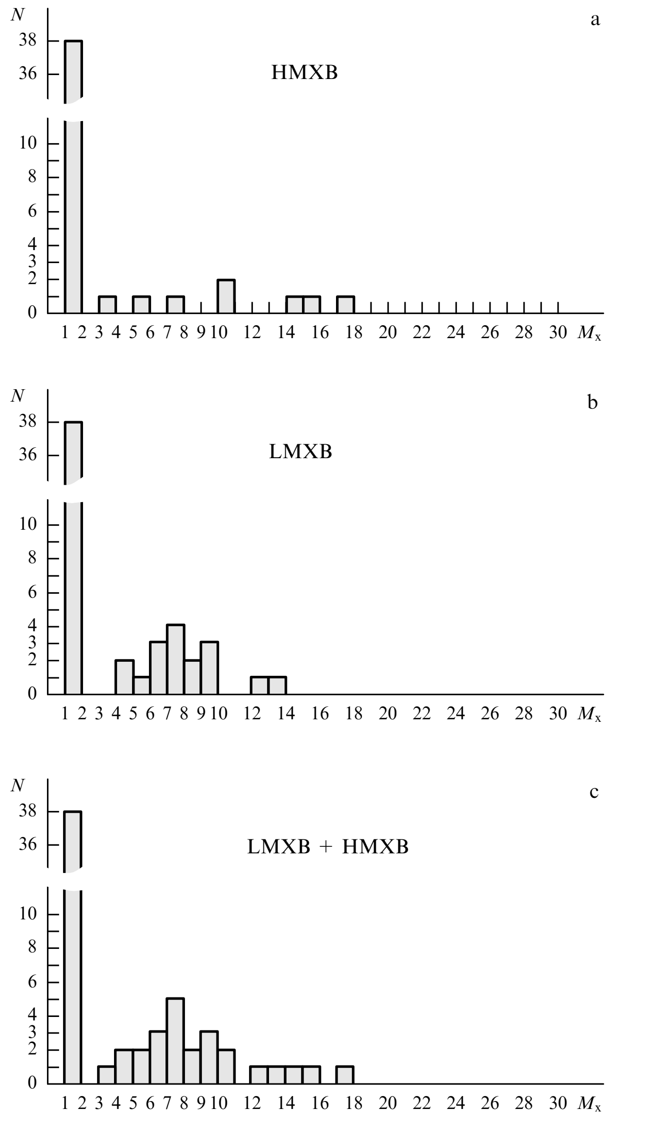

Figure 3. Distribution of masses of neutron stars (the high peak to the left in Figs a–c) and of black holes in X-ray binary systems. HMXB — high-mass X-ray binaries, LMXB — low-mass X-ray binaries.

a BH, is determined not only by the initial mass of the progenitor star but possibly by other parameters, including the stellar wind mass loss rate, the magnetic field of the stellar 'core', its rotation, and different instabilities during the collapse of the iron stellar core. That the BH mass is not uniquely related to the progenitor star mass is suggested by the observed BH mass distribution in X-ray binaries [35], which is approximately flat (Fig. 3). The number of BHs with measured masses in X-ray binaries, on average, does not increase with decreasing the BH mass. At the same time, the number of stars in the Galaxy significantly increases (as M^{-5}) with decreasing the stellar mass. If there were a unique relation between the BH mass and the initial mass of the progenitor star, then, upon decreasing the BH mass from $10M_{\odot}$ to $5M_{\odot}$, the number of BHs would increase by $2^5 = 32$ times, which is not observed (see Fig. 3). It can be shown (see the discussion in [19]) that the flat BH mass distribution in X-ray binaries is not greatly affected by the observational selection. Therefore, the observed flat BH mass distribution shown in Fig. 3 deserves special theoretical investigation.

Table 1. Binary systems.

Notation *	Spectral class of components	Masses of components **
V1036 Sco	O6V + O7V	$32M_{\odot} + 32M_{\odot}$
V3903 Sgr	O7V + O9V	$27.3M_{\odot} + 19.0M_{\odot}$
HD166734	O7.5If + O9I	$> 29M_{\odot} + > 31M_{\odot}$
V1182 Aql	O8V + B1V	$37.8M_{\odot} + 13.5M_{\odot}$
HD47129	O7.5I + O6I	$> 41M_{\odot} + > 48M_{\odot}$
V448 Cyg	O9.5V + B1 II-Ib	$25.2M_{\odot} + 14.0M_{\odot}$
HDE311884	WN6 + O5V	$51M_{\odot} + 60M_{\odot}$
HD193793	WC7 + O4-5	$27M_{\odot} + 60M_{\odot}$
HD193928	WN5 + O5V-III	$45M_{\odot} + 30M_{\odot}$
WR20a	WN6h + WN6a	$83M_{\odot} + 82M_{\odot}$
HD92740	WN7h + O9 III-V	$55M_{\odot} + 21M_{\odot}$
HD186943	WN3 + O9.5V	$17M_{\odot} + 36M_{\odot}$
CX Cep	WN4 + O5V	$20.0M_{\odot} + 28.3M_{\odot}$
CQ Cep	WN6 + O9 II-Ib	$24M_{\odot} + 30M_{\odot}$
WR21a	O3f/WN6ha + O4	$> 87M_{\odot} + > 53M_{\odot}$
NGC3603-A1	WN6a + WN6	$116M_{\odot} + 89M_{\odot}$
R145 (LMC)	WN6h + O	$> 116M_{\odot} + > 48M_{\odot}$
ST1-98 (LMC)	O4 + O4	$> 45M_{\odot} + > 45M_{\odot}$
R136-42 (LMC)	O3V + O3V	$40.3M_{\odot} + 32.6M_{\odot}$
SK-67105 (LMC)	O4f + O6V	$47.2M_{\odot} + 29.8M_{\odot}$
R136-38 (LMC)	O3V + O6V	$56M_{\odot} + 30M_{\odot}$
HV2543 (LMC)	O8 + O9	$25.6M_{\odot} + 15.6M_{\odot}$
R136-39 (LMC)	O3V + O5.5V	$> 27.2M_{\odot} + > 20.5M_{\odot}$
HV2241 (LMC)	O7III + B0III	$36.2M_{\odot} + 18.4M_{\odot}$
AzV73 (SMC)	O8.5V + B0III	$25.3M_{\odot} + 22.8M_{\odot}$
HV1620 (SMC)	O9V + O9.5III	$20M_{\odot} + 15M_{\odot}$

* LMC and SMC are Large and Small Magellanic Clouds.
** For systems with unknown binary inclinations, shown are lower mass limits of the components.

Bearing in mind the complex relation between the progenitor stellar mass and the BH mass, we consider the most massive stars in our Galaxy and nearby galaxies (see monograph [19] and review [36]). The masses of stars in these systems (see Table 1) are determined by the most reliable, dynamical, method using the motion of stars in eclipsing binaries.

Paper [1] also mentions the possibility of coalescence of binary BHs not only in isolated binaries but also in systems formed due to collective dynamical interactions of massive stars in dense stellar clusters. Here, we consider isolated massive binary stars only, which are actually observed in galaxies (see Table 1).

Table 1 shows that our Galaxy and other galaxies contain close binaries in which the mass of at least one of the components exceeds $80M_{\odot}$ and which could be progenitors of systems like LIGO GW150914. But such massive binaries are very rare. Taking very strong observational selection effects into account, it is problematic to infer any statistical conclusions from these data.

Importantly, very massive binaries ($M_{1,2} = (80-100)M_{\odot}$), the possible progenitors of LIGO GW150914, are actually observed in our and other galaxies (see Table 1). Binary systems from Table 1 with less massive components ($M_{1,2} = (15-60)M_{\odot}$) could lead to the formation of a coalescing binary BH system with smaller component masses than in LIGO GW150914, as well as to a coalescing binary neutron star or a BH and neutron star binary system.

The masses of some single stars derived from their luminosity reach several hundred $M_\odot$ (see, e.g., [19]). In particular, the masses of stars in the cluster R136 in the LMC (Large Magellanic Cloud) were recently estimated in [37] using the bolometric luminosity, with a record high result $M = (165-320)M_\odot$. However, the estimates of stellar masses derived from the luminosity and not from the motion in binary systems can be unreliable. In addition, so far it is unclear whether such a massive star can form in binaries.

Massive ($M > (30-40)M_\odot$) stars experience strong mass loss due to the stellar wind during their nuclear evolution, which decreases the probability of massive BH formation. Because the stellar wind from a hot massive star is primarily accelerated by radiation pressure, the mass loss rate $\dot{M}$ depends on the metal abundance (metallicity) z in the stellar matter, which determines the stellar matter opacity [38]:

$$\dot{M} \sim z^{0.75}\,, \quad 0.001 \leqslant \frac{z}{z_\odot} \leqslant 10\,.$$

In addition, the high mass loss rate can be stimulated by stellar rotation. The most suitable progenitors of massive binary systems like LIGO GW150914 are massive ($M = (100-1000)M_\odot$) hydrogen–helium population-III stars that were formed at an early stage of the evolution of the Universe. However, the comparatively low redshift (≈ 0.09) of LIGO GW150914 does not allow relating the progenitor of this system to this class of objects.

In the 1980s, it became clear that the stellar wind of Wolf–Rayet (WR) stars has a clumped cloudy structure [39, 40]. Because most information on the stellar wind mass loss of WR stars is obtained from observations of thermal radio emission from their winds, the values of $\dot{M}$ derived from these data are overestimated and should be corrected (decreased by 3–5 times) [41]: the thermal radio emission depends on the electron density nonlinearly (as the second power). Therefore, if there are numerous dense clumps in the stellar wind, the intensity of thermal radio emission under other equal conditions should increase. Thus, interpretation of this intensity by a homogeneous wind overestimates $\dot{M}$. This conclusion is supported by observations of specific binary systems [19]. For example, in the eclipsing binary system V444 Cyg (WN5 + O6), the value of $\dot{M}$ for the WN5 star, inferred from the change in the orbital binary period (which is independent of the wind clumping), is $0.6 \times 10^{-5} M_\odot$ per year, and the value $\dot{M}$ found from observations of thermal radio emission of this system is $2.4 \times 10^{-5} M_\odot$ per year, which is four times as large.

The several-fold decrease in the mass loss significantly weakens the stellar wind mass loss effect, favoring the formation of CO cores in WR stars and hence massive BHs [42].

4. Black holes in X-ray binaries

Of the 26 X-ray binaries with measured BH masses (see review [35]), 9 systems are high-mass X-ray binaries (HMXBs) with massive optical components ($M = (5-70)M_\odot$), and 17 systems are low-mass X-ray binaries (LMXBs) with low-mass optical components ($M \approx (0.3-2)M_\odot$). That BHs are mostly discovered in LMXBs is the observational selection effect: the time of nuclear evolution of a low-mass star is several hundred or thousand times as long as that of a high-mass star. Therefore, when the optical star fills its Roche lobe, the accretion of matter onto a BH from a low-mass star continues several hundred or thousand times as long as from a massive star. Thus, the probability of discovering a BH in a low-mass X-ray binary system is much higher than in a high-mass binary.

In an LMXB with a BH, the mass of the optical star is fairly small, $(0.3-2)M_\odot$, and therefore the end product of the evolution of such a system should be the coalescence of the BH with a white dwarf.

In HMXBs with a BH, the masses of the optical components are high, $(5-70)M_\odot$, and hence the end evolutionary stage of these systems should be the coalescence of two BHs, the coalescence of the BH with a neutron star, and a Thorne–Zhytkow (TZ) object [43], in which a BH or a neutron star spirals in toward the center of the optical star. Recently, a very reliable candidate for TZ objects with an anomalous chemical composition was discovered [44]. If the mass of the optical star in an HMXB with a BH lies close to the low boundary of the interval $(5-70)M_\odot$, the end product of the evolution of such a system can be coalescence of the BH with a white dwarf.

Data on BH masses and optical-star masses in X-ray binaries are presented in reviews [35, 45] and in monograph [19].

The most massive X-ray binaries (with the most reliably measured BH mass $M_{\rm BH}$ and optical-star mass $M_{\rm V}$) include

$$\text{Cyg X-1} \quad (M_{\rm BH} = 14.81 M_\odot\,,\ M_{\rm V} = 19.16 M_\odot)\,,$$

$$\text{LMC X-1} \quad (M_{\rm BH} = 10.3 M_\odot\,,\ M_{\rm V} = 30.6 M_\odot)\,,$$

$$\text{M33 X-7} \quad (M_{\rm BH} = 15.55 M_\odot\,,\ M_{\rm V} = 70 M_\odot)\,.$$

These systems reside in different galaxies, and their parameters are insufficient to explain the parameters of LIGO GW150914: $M_{\rm BH} = 29 M_\odot$ and $36 M_\odot$. In these systems, the coalescence of two BHs with smaller masses or coalescence of the BH with a neutron star can be realized.

We stress once again that the observational selection effects make the most massive coalescing BHs, like LIGO GW150914, very favorable for detection. Further increases in the sensitivity of gravitational-wave antennas and in the exposure time will enable the detection of BHs with smaller masses, for which the LMC X-1 and M3 X-7 systems are quite suitable progenitors.

5. Formation of binary black holes

In [46, 47], the population synthesis code [33] was used to calculate the evolution of massive binary systems up to the very late evolutionary stages at which BHs are produced. One of the scenarios (Fig. 4) of the formation of the X-ray binary M33 X-7 leads to the appearance of a TZ object. Another scenario (Fig. 5) describes the formation of the binary system IC10 X-1 ($M_{\rm BH} = 28 M_\odot$ (?), $M_{\rm V} = 26 M_\odot$), in which a massive BH was assumed [48], but which has not been confirmed by later observations [49]. Nevertheless, from the methodological standpoint, it is interesting to consider the evolutionary scenario for the formation of a massive BH in the IX10 X-1 binary system. In this case, the evolution of the binary system ends with the formation of two BHs, which coalesce in 4.3×10^9 years to produce a gravitational-wave burst.

We describe the evolution of the M33 X-7 system (see Fig. 4). Initially, the mass of the primary star lies in the range $m_1 = (80-120)M_\odot$, the secondary mass is $m_2 = (40-60)M_\odot$, and the initial major semiaxis of the orbit is $a \lesssim 100 R_\odot$. After

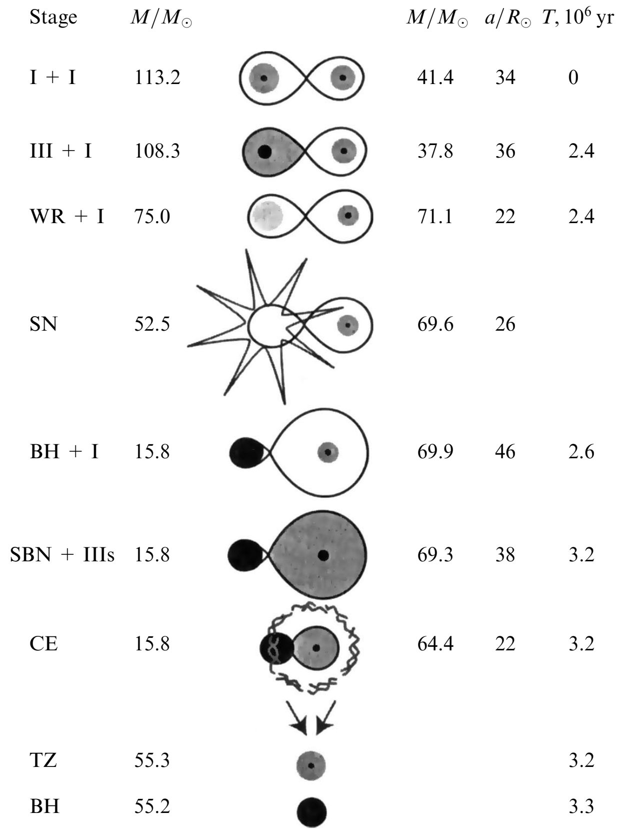

Figure 4. Evolutionary stages for the X-ray binary M33X-7 calculated by the Scenario Machine code. Shown are masses of the components M (in Solar masses), the distance between the components a (in solar radii $R_\odot$), and the time T during which the binary system is at the corresponding evolutionary stage. CE (common envelope) is the common envelope stage.

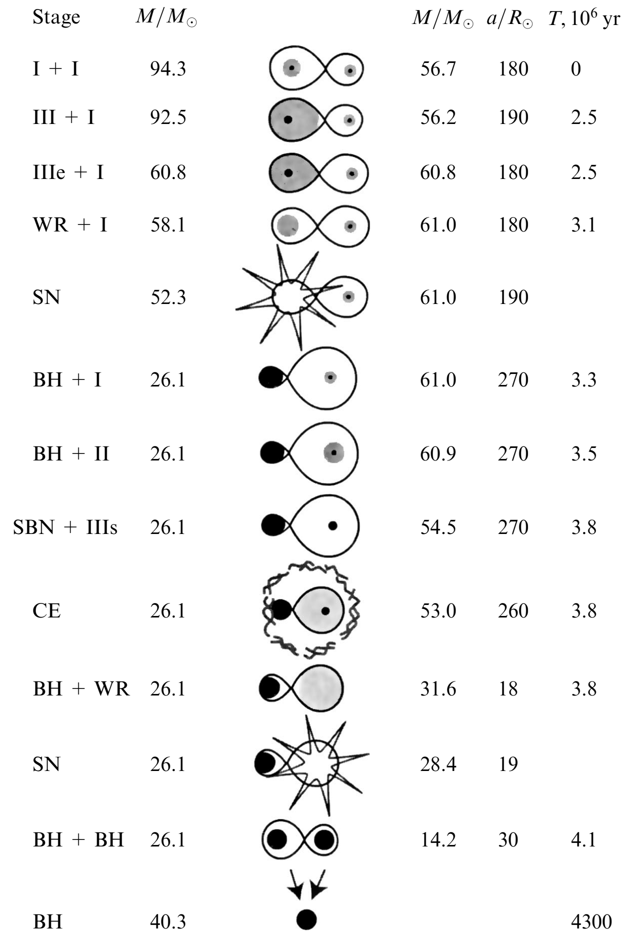

Figure 5. Evolutionary stages for the X-ray binary system IC10X-1 calculated by the Scenario Machine code. The notation is the same as in Fig 4.

the exhaustion of hydrogen in the core, the primary, more massive star expands to fill its Roche lobe. The mass transfer to the secondary component starts, as a rule, at a higher rate than dictated by the nuclear evolution time scale (when the mass transfer occurs from the more massive to the less massive star, the distance between the components decreases). The final stage of the mass transfer can occur on an evolutionary time scale close to the nuclear time (when the mass of the primary star significantly diminishes). After the loss of the hydrogen envelope, the primary star turns into a WR star (the 'naked' helium core of the primary star with a small hydrogen envelope). The WR star explodes as a type-Ib/c supernova to form a BH. The weak stellar wind at the main-sequence stage, as well as the 'correctly' adjusted fraction of the pre-supernova mass falling under the horizon in the course of the BH formation, enables the formation of a BH with the required mass $(15-20)M_\odot$ in a fairly close binary system.

At the first mass transfer stage, a common envelope does not form because the initial mass ratio $q = m_1/m_2 = 0.35$ is higher than the critical value $q = 0.3$ [29]. The secondary star, which increased its mass during the mass transfer, fills its Roche lobe and starts supercritically accreting onto the BH, leading to the formation of a common envelope, and the binary system ends up with the spiraling in of the BH into the optical star center. Thus, a TZ object appears [43]. The end product of the evolution of M33 X-7 is a single massive BH. During the spiraling-in phase at the TZ formation stage, the system can be a powerful source of gravitational waves [50].

We now consider another evolutionary scenario related to the formation of the X-ray binary system IC10 X-1 (see Fig. 5). Initially, the primary mass lies in the range $m_1 = (80-120)M_\odot$, the mass of the secondary star is $m_2 = (15-60)M_\odot$, and the initial orbital separation is large, $a \approx (170-200)R_\odot$. After hydrogen exhaustion in the core, the primary, more massive star expands to fill its Roche lobe. The mass transfer begins on the time scale that is typically much shorter than the nuclear evolution time, and the final stage of the mass transfer occurs on a time scale close to the nuclear one. After the loss of the hydrogen envelope, the primary star becomes a WR star, which explodes as a type-Ib/c supernova to produce the first BH in the system. Next, the secondary star, whose mass increased during the first mass transfer phase, terminates its nuclear evolution in the main sequence and fills its Roche lobe. After the stage of supercritical accretion onto the BH at the stage of the Roche-lobe filling by the secondary star, the common envelope stage occurs, during which the components approach very close to each other but do not coalesce, and a TZ object is not formed, and the envelope of the optical star is dispersed by acquiring kinetic energy from the orbital motion of the components via dynamical friction. This is made possible due to the initially large orbital separation $a \approx (170-200)R_\odot$. Ultimately, a binary system consisting of a WR star and a BH is formed (similar to Cyg X-3 in our Galaxy). Later, the second WR star explodes as a type-Ib/c supernova to produce the second BH in the system. The end product of the evolution of this system is the coalescence of two BHs due to the loss of orbital angular momentum by gravitational waves (because of the large initial orbital separation $a \approx 30R_{\odot}$, the duration of this stage is 4.3 billion years). As a result of the coalescence, a single massive BH is produced. At the final stage of the coalescence, a burst of gravitational wave radiation is generated, like that observed in the LIGO GW151226 event. We stress, however, that the BH masses in this binary ($26.1M_{\odot}$ and $14.2M_{\odot}$) are below those in the GW150914 system ($36M_{\odot}$ and $29M_{\odot}$). Dedicated calculations of the massive binary star evolution aimed at obtaining the final binary BH system with masses $36M_{\odot}$ and $29M_{\odot}$ are currently underway at SAI.

6. Evidence of the absence of observable surfaces in black holes from X-ray binary studies

Long-term research on close binary systems with relativistic components has provided astronomers with information on the masses and observational appearance of about hundred relativistic objects ($\approx$ 70 neutron stars and 26 black holes) (Fig. 6).

It turns out that neutron stars and BHs differ not only by mass, but also by observational appearance, in full agreement with GR predictions. This holds for almost a hundred relativistic objects, which is statistically quite significant.

Figure 6 shows the most reliable values of the masses of neutron stars and black holes. All neutron stars with measured masses exhibit clear signs of observed surfaces — they are radio pulsars, X-ray pulsars, or type-I X-ray bursters.

We recall that the phenomenon of a radio pulsar is related to rapid axial rotation of a neutron star with a strong magnetic field. The phenomenon of an X-ray pulsar is due to accretion of matter onto the magnetic poles of a rapidly rotating strongly magnetized neutron star (the magnetic dipole axis does not coincide with the spin axis of the neutron star). The phenomenon of a type-I X-ray burster is due to thermonuclear explosions of matter accumulated on the surface of a neutron star with a weak magnetic field. Clearly, if neutron stars have no observable surfaces, they would not appear as radio pulsars, X-ray pulsars, or type-I X-ray bursters.

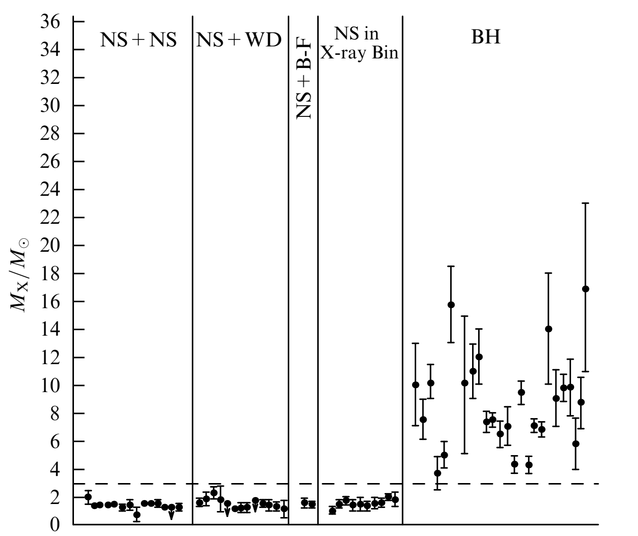

Figure 6. Masses of neutron stars (NS) and black holes (BH) in binary systems. NS + NS are radio pulsars in binary systems with neutron stars, NS + WD are radio pulsars in binary systems with white dwarfs, NS + B-F are radio pulsars in binary systems with nondegenerate stars. The horizontal dashed line cuts the mass $3M_{\odot}$, the absolute mass upper limit of a neutron star predicted by GR.

With the accumulation of observational data on neutron stars and BHs, a remarkable result has gradually emerged. In all 70 cases of 'weighted' neutron stars, the mass of the relativistic object exhibiting the signatures of the observable surface does not exceed $3M_{\odot}$, the absolute upper bound for a neutron star predicted by GR.

At the same time, none (!) of the 26 massive ($M > 3M_{\odot}$) relativistic objects (BH candidates) exhibits signatures of an observable surface (to appear as a radio pulsar, X-ray pulsar, or type-I X-ray burster), in full agreement with GR. According to GR, BHs do not have an observable surface; they have only an event horizon, a light-like surface in space–time. Therefore, a BH should not exhibit strictly periodic pulsations of radio or X-ray emission or thermonuclear explosions from the surface (X-ray bursts). This is indeed observed: heavy ($M > 3M_{\odot}$) accreting relativistic objects demonstrate either irregular variability of X-ray emission on short time scales ($\sim 10^{-3}$ s), or quasiperiodic (but not strictly periodic) variability: quasiperiodic oscillations (QPOs) of X-ray emission.

We note that in addition to the highly distinct features in the observational appearance of neutron stars and BH candidates described above, there are more subtle differences related to the form and time behavior of their X-ray emission (see, e.g., review [51]). These fine differences also suggest that neutron stars have observable surfaces, unlike BH candidates ($M > 3M_{\odot}$).

Unfortunately, these facts do not ultimately prove the absence of observable surfaces in heavy relativistic objects: some neutron stars can also have no signature of the observable surface. For example, if the magnetic dipole axis of a rapidly rotating magnetized neutron star coincides with its spin axis, the phenomenon of an accreting X-ray pulsar would not be observed. In this case, it is difficult to distinguish a heavy ($M > 3M_{\odot}$) neutron star from a BH.

To prove the existence of the event horizon, it is necessary to observe effects specific to BHs. These include different oscillation modes of the event horizon of a newly formed BH from a coalescing binary BH system and the characteristic decay of these oscillations after the coalescence (the so-called ring down phase), which can be observed in gravitational waves using modern and future gravitational wave telescopes.

As noted in [8, 11, 17], the evolution of a close BH binary system can be separated into three phases: the inspiraling of two BHs due to orbital angular momentum loss by gravitational radiation, coalescence, and the final stage (ringdown).

The inspiraling phase of two BHs can be described in the post-Newtonian approximation (see, e.g., [17]). The dynamics of coalescence of two BHs requires full-fledged GR simulations on supercomputers, which have already been done for many model problems [8]. At the final stage, two initial BHs form a new high-mass BH in a strongly perturbed state, and the excitations decay with time. These excitations represent a superposition of quasinormal modes, and the decay of the quasinormal modes produces the characteristic ringdown form of the gravitational-wave signal.

According to [11], gravitational-wave emission at the coalescence and the ringdown stage yields information on the highly nonlinear large-scale dynamics of the space–time curvature. Therefore, detailed study of these gravitational wave signals will enable testing full nonlinear GR equations.

It is quite possible that the final proof of the existence of the BH horizon will be obtained this way.

We now discuss the possibility of registration of a short burst of a hard X-ray counterpart to the LIGO GW150914 event reported by the Fermi gamma-ray observatory [10]. In the case of a coalescence of 'pure' BHs without an electric charge, it is impossible to expect an electromagnetic radiation burst. However, if some amount of gas was left around the system from the preceding mass-transfer stage, the strong deformation of space–time can lead to the formation of shocks and possible electromagnetic radiation.

7. Conclusion

The discovery of gravitational waves opened a new stage in BH studies. Observations of gravitational waves from coalescing binary BHs offer a unique possibility to finally prove the existence of the BH horizon. Scientists are now able not only to observe BHs in X-ray binary systems but also to make experiments with them by exploring the nonlinear dynamics of a highly curved space–time during the formation of the horizon in coalescing binary BH systems. This places BH studies on a qualitatively new level, which should lead to breakthroughs in our understanding of the properties of space–time.

Presently, in Russia there is only one detector of gravitational waves in the kilohertz frequency range, the underground OGRAN detector (Opto-acoustic GRavitational wave ANtenna), constructed by a collaboration including SAI, the Institute of Nuclear Research, RAS, and the Institute of Laser Physics, Siberian Branch, RAS [52]. The sensitivity of the OGRAN detector is so far limited to a distance of 100 kpc, but after cooling to liquid nitrogen temperatures, the distances up to 15 Mpc will become available.

Note added in proof

Recently, the LIGO collaboration reported the detection of the second GW event, GW151226, related to the coalescence of black holes in a binary system [53]. The black hole masses are $14.2^{+8.3}_{-3.7}M_{\odot}$ and $7.5^{+2.3}_{-2.3}M_{\odot}$, which fall within the range of black hole masses in X-ray binary systems, $(4-16)M_{\odot}$.

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