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Progress in investigations of highly evolved close binary systems

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The discovery by LIGO observatory of gravitational waves from merging black holes in binary systems stimulated intensive investigations of highly evolved close binary systems. In this review recent results obtained during last years about highly evolved close binary systems are summarized and discussed.

Keywords: Evolution, binary stars, neutron stars, white dwarfs, black holes, X-rays, gravitational waves, mass exchange, Roche lobes, Wolf–Rayet stars

1 Introduction

New important progress in the investigations of highly evolved close binary systems (HECBS) has been achieved by the recent discovery by LIGO and Virgo observatories of gravitational waves from the merging of black holes (BHs) and neutron stars (NSs) in binary systems (Abbott et al., 2016, 2017).

In this review we will summarize recent new results obtained in this important field of astrophysics. Analysis of the HECBS problem for the time before the GW era has been done in our review (Cherepashchuk, 2007).

Highly evolved close binary systems are systems at the evolutionary stage after the initial mass exchange. After the initial rapid mass exchanges are completed, HECBS may contain a WR star, a white dwarf, a neutron star or a black hole as peculiar components.

The first catalogue of HECBS (Cherepashchuk et al., 1996) contains about 650 systems of this type. To date, the number of known HECBS has reached several thousands. Investigations of HECBS are very important for astrophysics and basic physics (see review of Cherepashchuk, 2007 for details). The late stages of evolution of CBS have been investigated in the pioneering works of Tutukov and Yungelson (1973) and van den Heuvel (1976). The theory of accretion of matter onto NSs and BHs in binary systems has been developed by Shakura and Sunyaev (1973), Pringle and Rees (1972) and Novikov and Thorne (1973).

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2 HECBS in X-ray astronomy era

Many types of HECBS were described and analyzed in the catalogue (Cherepashchuk et al., 1996) and in our review (Cherepashchuk, 2007; see also the book: Cherepashchuk, 2013).

I. Massive HECBS.

1. WR+OB systems (like V444Cyg, CXCepetc).
2. "Quiet" X-ray binaries (like system containing massive B-star and radiopulsar PSRJ0045-7319).
3. Massive transient X-ray binaries with B-star (Be/X-ray transients).
4. Persistent massive X-ray binaries (like CygX-1, CenX-3 etc).
5. Binary WR+C systems, containing relativistic object and WR star (like CygX-3, IC10X 1, NGC300X-1 etc).

II. Low-mass HECBS.

1. X-ray novae (like AO620-00, GRS1915+105, GS2023+338 etc).
2. Bright X-ray binaries of Galactic bulge (like Sco X-1, Cyg X-2 etc).
3. X-ray bursters.
4. Cataclysmic binaries, containing accreting white dwarfs.
5. Symbiotic binaries (like CI Cyg, RS Oph, AG Peg etc).
6. Ultrasoft X-ray binaries (like CAL83/4U0543-682).
7. LBV objects.
8. Binary radio pulsars (like PSR 1913+16, 70737-3039AB etc).

The X-ray era in astronomy, which began in 1970 by the launch of the special X-ray satellite UHURU allowed us to discover hundreds of X-ray binaries. To date, the number of discovered X-ray binary systems has reached several thousands. These discoveries stimulated active developments of CBS investigations up to the late stage of their evolution: binary BHs or NSs etc. Relativistic astrophysics in this epoch gained a strong observational basis. Up to now about 30 BH X-ray binary systems as well as about 80 NSs in binary systems have been discovered, weighed and investigated. It was shown that NSs and BHs are different from each other not only by masses, but also by many other observational appearances in full agreement with the prediction of Einstein's General Relativity (GR). In particular, in all cases when a relativistic object shows the appearances of a solid observable surface (X-ray pulsar, radio pulsar, X-ray burster of the first kind), the mass of this object does not exceed $3M_\odot$ in full agreement with GR prediction. On the other hand, if the mass of a relativistic object exceeds $3M_\odot$, no appearances of a solid observable surface are observed for such a massive object.

These important observational facts can be considered as nondirect evidences of the existence of the event horizon for massive ($M > 3M_\odot$) relativistic objects (BH candidates).

Unfortunately no final proof of the real existence of stellar mass BHs in binary systems from investigations in the electromagnetic range (optical and X-ray) has been obtained until now. It is caused by the fact that not only BH candidates, but some neutron stars may not show any evidence for the existence of solid observable surfaces. For example, if the magnetic dipole of a neutron star coincides with its rotational axis,

the phenomenon of an X-ray pulsar during the accretion of matter cannot be observed. In this case BHs may be confused with heavy NSs.

The development of GW astronomy allowed us to obtain new strong evidence for the real existence of stellar mass BHs in the Universe.

3 HECBS in gravitational-wave astronomy era

The outstanding discovery by the LIGO and Virgo observatories of gravitational waves generated by the merger of BH and NS in binary systems (Abbott et al., 2016, 2017) provided new opportunities for investigating the origin of binary relativistic objects in the evolution of massive CBS. New strong evidences for the real existence of stellar mass BH in the Universe have been obtained. By analogy with X-ray binary systems that have been discovered by observing the X-ray radiation formed during the accretion of matter onto a relativistic object, it is natural to refer to the close binary systems detected using gravitational-wave radiation as gravitational-wave binary systems.

The discovery of a burst of electromagnetic radiation from merging NS (in gamma-ray, X-ray and optical range) allowed us to measure the velocity with which gravitational waves propagate in space; it was found to coincide with the speed of light to within $\sim 10^{-15}$.

On the other hand, the GW radiation emitted at the stage of merger of two black holes as well as the GW radiation during the ring-down stage provide information about highly nonlinear large-scale dynamics of space-time curvature. Therefore, a detailed study of these GW signals (with a sufficiently high signal-to-noise ratio) allows us to verify the nonlinear equations of General Relativity in all their complexity. It is quite possible that on this path the final evidence will be obtained that the event horizon exists for BH (Cherepashchuk, 2016).

In 2019 the LIGO and Virgo team published the first gravitational-wave transient catalogue of compact binary mergers (GWTC-1) observed by LIGO and Virgo during the first and second observing runs (Abbott et al., 2019). The data of this catalogue are presented in Table 1.

Table 1 shows that the masses of BH prior to the merger fall in the range of 7.6–50.6 $M_\odot$, while after the merger they vary from $17.8M_\odot$ to $80.3M_\odot$. The dimensionless angular momenta of the BH after the merger are in the range of 0.66–0.81, which is less than that for extremely rotating Kerr BH.

Therefore there are grounds to suggest that the angular momenta of the majority of BHs before the merging would be small.

The least massive pairs of merging BHs are GW151226 ($13.7M_\odot + 7.7M_\odot$) and GW170608 ($10.9M_\odot + 7.6M_\odot$). The most massive merging pairs of BH are GW170729 ($50.6M_\odot + 34.3M_\odot$) and GW170823 ($39.6M_\odot + 29.4M_\odot$). Recently one more very massive pair of BH GW190521 has been discovered by the LIGO and Virgo teams: GW190521 ($85M_\odot + 66M_\odot$). The mass of the final BH after merging is $142M_\odot$. The distance is about 5.3Gpc (see Abbott et al., 2020). It is hard to understand the mechanism of the formation of such massive BHs because massive stars with cores more than $40–60M_\odot$ experience pulsational pair instability after carbon burning (see e.g. Yoshida et al., 2016).

Table 1 Parameters of 11 gravitational-wave binary systems from the GWTC-1 catalogue (Abbott et al., 2019).

Event	Type of components	$M_1/M_\odot$	$M_2/M_\odot$	$M_\mathrm{f}/M_\odot$	a_f	d_L/Mpc
GW150914	BH+BH	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	430^{+150}_{-170}
GW151012	BH+BH	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	1060^{+540}_{-480}
GW151226	BH+BH	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	440^{+180}_{-190}
GW170104	BH+BH	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	960^{+430}_{-410}
GW170608	BH+BH	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	320^{+120}_{-110}
GW170729	BH+BH	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	2750^{+1350}_{-1320}
GW170809	BH+BH	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	990^{+320}_{-380}
GW170814	BH+BH	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	580^{+160}_{-210}
GW170817	NS+NS	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	≤ 2.8	≤ 0.89	40^{+10}_{-10}
GW170818	BH+BH	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	1020^{+430}_{-360}
GW170823	BH+BH	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	1850^{+840}_{-840}

The second catalogue of GW bursts (GWTC-2) containing 50 GW transients has been published recently (Abbott et al., 2020a). New data fully confirm General Relativity (Abbott et al., 2020b).

Table 2 contains the masses of some BH in GW binary systems with BH. For comparison, Table 2 also displays the characteristics of the most massive X-ray binary systems with BH (in which only one BH is formed), as well as the parameters of some of the most massive "classical" CBSs in our Galaxy and the Large Magellanic Clouds (LMC). The large masses of BH in the GW binary system that was discovered first, GW150914 ($36M_\odot + 29M_\odot$), are beyond the BH mass range in the well known X-ray binary systems (4–16)$M_\odot$ (see e.g. Cherepashchuk, 2013). This result stimulated a discussion of the mechanisms of formation of close binary BH that are different from the classical scenarios of evolution of isolated massive close binary systems with mass exchange (see e.g. Belczynski et al., 2016; Bogomasov et al., 2018; Tutukov and Cherepashchuk, 2017 and references therein).

However, the discovery by the LIGO observatory of a second GW burst, GW-151226, associated with the merger of BHs with masses of $14M_\odot$ and $7.5M_\odot$, which are consistent with the masses of BHs in X-ray binary systems, (4–16)$M_\odot$, showed that the classical scenario of the evolution of isolated massive CBS (Massevich and Tutukov, 1988) is apparently able to explain the emergence of such close pairs of BH.

As noted in Cherepashchuk (2016), because the BHs with masses of $36M_\odot$ and $29M_\odot$ in the GW150914 system must be formed from very massive stars with masses $\sim 100M_\odot$, whose number is very low in the Galaxy and other nearby galaxies, the formation rate of such massive BHs in the Galaxy and nearby galaxies is also very low. This is why BHs with masses greater than $\sim 30M_\odot$ have not yet been discovered in X-ray binary systems.

Because GW telescopes can detect signals at distances of ∼1Gpc from millions of galaxies, the probability of detecting signals from a merger of the most massive BHs increases significantly.

Because the sensitivity of GW telescopes is limited, GW signals from a merger of the most massive BHs should be the first to be detected, as indeed is the case (see Table 1). Moreover, because GW bursts come from massive binary systems that

Table 2 Comparison of the parameters of gravitational-wave binary systems, massive X-ray binaries, and "classical" massive close binaries.

Gravitational-wave binary systems with black holes (BH)

System	Type of components	Mass of components ($M_\odot$)	Initial stellar masses ($M_\odot$)
GW150914	BH+BH	36+29	100+80
GW151226	BH+BH	14.2+7.5	50+30
GW151012	BH+BH	23+13	75+50
GW170729	BH+BH	51+34	150+80

Massive X-ray binary systems containing a black hole (OB + BH)

System	Spectral class of components	Mass of components ($M_\odot$)	Orbital period/day
Cyg X-1	O9.7Iab+BH	19.16+14.81	5.60
LMC X-1	O(7-9)III+BH	30.6+10.3	3.91
M33 X-7	O(7-8)III+BH	70.0+15.6	3.45

"Classical" binary systems

System	Spectral class of components	Mass of components ($M_\odot$)	Orbital period/day
HD 193793	WC7+O4-5	27+60	2900
HDE 311884	WN6+O5V	51+60	6.24
WR 20a	WN6h+WN6a	83+82	3.69
HD 92740	WN7h+O9III-V	55+21	80.34
NGC 3603-A1	WN6a+WN6	116+89	3.77
Melnick 34 (LMC)	WN5h+WN5h	139+127	155.1
R136-38 (LMC)	O3V+O6V	56+30	3.39
UW CMa	O(7–8)If+O8f	43.5+32.5	4.39

merged in the early epochs of the Universe, when the metallicity of stellar matter was small (and hence the effect of stellar mass reduction due to stellar wind radiation was small), BHs originated from very massive stars. This circumstance additionally increases the probability of detecting GW bursts from a merger of the most massive stellar BHs.

For two massive BHs to merge under the effect of GW radiation in a time shorter than the age of the Universe, the distance between them should not exceed $\sim 50 R_\odot$ (Tutukov and Cherepashchuk, 2017). However, such a compact pair of BHs cannot be formed in the classical scenario of the evolution of single very massive close binaries of a solar chemical composition, because the initial stars with masses $\sim 100 M_\odot$ have very large radii ($R > 20 R_\odot$) and produce very strong stellar winds, which increase the separation of components. The large initial radii of the stars that are precursors of massive BHs imply that the initial separation of the components in the corresponding "classical" close binaries should be very large ($>50 R_\odot$). At the same time, due to radial loss of matter by stars in the form of stellar wind (the jeans mode of the mass loss), separation between the components increases in a secular fashion to significantly

exceed the critical value $50R_\odot$ over time. As a result, a pair of BHs with a large separation ($> 50R_\odot$) are formed in the process of the evolution of such a massive CBS, for which the BH merger time is larger than Hubble time ($1.4 \cdot 10^{10}$ years). GW radiation from the merging of such a wide pair of BHs cannot be observed.

Various possibilities for the formation of rather compact pairs of BHs were considered in Tutukov and Cherepashchuk (2017): the evolution of close binaries with a common envelope, the low metallicity of massive stars, such that the rate of mass loss in the form of stellar wind is insignificant, the evolution of close binaries in a dense molecular cloud, etc. Specific scenarios for the evolution of isolated massive close binary systems with the formation of compact pairs of BHs and the emergence of GW bursts were computed (Bogomazov et al., 2018; Belczynski et al., 2016; Bogomazov, 2014; Abubekerov et al., 2009). The stage of the GW binary system (observable merging BHs and merging NSs) is a very late stage in the evolution of massive CBS, later than the stage of X-ray binary systems (see Table 2).

Thus, the discovery of GW binary systems made it possible, across a very wide time interval, to trace the evolution of massive CBSs from two massive main sequence stars to two relativistic objects that subsequently merge under the effect of GW radiation. It is remarkable that virtually all stages of the evolution of massive CBSs over this very wide time interval can be satisfactorily described by theoretical models, and the results and predictions of their simulation can be confirmed by specific observational events.

4 Some new results obtained during last years in investigations of HECBS

In a recent review (Tutukov and Cherepashchuk, 2020) the achievements of observations and theory for CBS as well as tasks for further research in this important field of astrophysics were summarized. Let us point out some of them, related to HECBS.

4.1 Discovery of radio-pulsing white dwarf binary stars

Systems have been discovered recently wherein the white dwarf magnetic field is 10^8–10^9 G, and a white dwarf, upon mass exchange, has spin up to a very short rotation period of 30–118 s. As a result of this process there is currently no accretion onto the white dwarf (the AR Sco and AE Aquarii systems, see Marsh et al., 2016; Ikhsanov, 1998; Ikhsanov and Beskrovnaya, 2012; Beskrovnaya and Ikhsanov, 2015; Potter and Buckley, 2018). The white dwarf is observed in these systems in the ejecting-pulsar regime.

4.2 Discovery of luminous red novae

A new class of cataclysmic binary systems has been discovered recently: luminous red novae (LRN) associated with low mass late close binary systems (Kashi, 2018; Kurtenkov et al., 2015; Williams et al., 2015; Lipunov et al., 2017). The difference between red novae and ordinary ones is that their spectra do not contain lines of elements which accompany thermonuclear processes on the white dwarf surface; they

also differ by the mass of dumped envelopes. It is assumed that the dump of the common envelope due to the transfer of the orbital angular momentum of stars to the envelope manifests itself as a flash of a peculiar nova, a luminous red nova.

The absolute stellar magnitude of a red nova at the maximum brightness is rather high: $M \leq -10^m$. The total explosion energy is large: $\sim 10^{48}$ erg. Examples of red novae are V838 Mon, V1309 Mon, V31LRN2015.

4.3 Discovery of very high mass CBS

Investigations of massive CBS are important for understanding the formation of binary BH and NS, the merging of which leads to GW radiation. Very massive WR+OB binary systems have been discovered. It was established that most massive stars belong not to stars of spectral class O, but to WR stars of WN5-7h or WN5-7ha types. These WR stars are WN stars and have the evidences of hydrogen lines in their spectra and relatively high radii compared to "classical" WR stars. Frequently such massive WN stars are observed among WR+OB binary systems (Cherepashchuk, 2013). Examples of such very massive WR+OB binaries are the following.

System WR20a (WN6a/O3f + WN6a/O3f, $p = 3^d.686$), masses of its components $83M_\odot$ and $82M_\odot$ (Bonanos et al., 2004); System NGC3603-A1 (WNa + WN6, $p = 3^d.7724$), masses are $(116 \pm 31)M_\odot$ and $(89 \pm 16)M_\odot$ (Schnurr et al., 2008).

For short-period massive close binaries with a high speed of axial rotation of the components, M-evolution scenario can be realized (de Mink et al., 2009), when a meridional circulation of matter occurs in the body of the star due to its fast axial rotation. As a result the envelope of the more massive star is enriched in helium, and the star starts to exhibit WR-star features even before it fills its Roche lobe. Such a star, which has an almost homogenous chemical composition enriched in helium, unlike regular chemically inhomogeneous stars, does not increase its radius in the process of nuclear evolution, but rather decreases it. Therefore, such a homogenous star never fills its Roche lobe in the process of evolution. The tidal synchronization time is known to be very strongly dependent on the star radius R (as $(R/a)^{-6}$, where a is the radius of the relative orbit) (Zahn, 1977).

Due to the relatively low rotational speed of the less massive star with relatively small radius the meridional circulation of matter in its body may be inefficient, and the star can develop a significant inhomogeneity of its chemical composition as hydrogen burns out in its core. Because the enrichment of helium in the star's envelope is in this case insignificant, the less massive star expands; it may be the first to fill up its Roche lobe and to start losing mass through the inner Lagrange point. Such an M-scenario for close binary evolution radically differs from the classical one, according to which the more massive system star is the first to fill up its Roche lobe. The M-scenario can be used to naturally explain the formation of massive ($M > 10M_\odot$) BH in very tight X-ray binary systems such as M33X-7 ($P_{orb} = 3.45$ days) and IC10X-1 ($P_{orb} = 1.43$ days). The case of M-evolution may also be of importance for "classical" close binaries, such as the WR20A system, which consists of two very massive WR stars (83 and $82M_\odot$) with a surface excess of helium and burning of hydrogen in the center, as well as for very close binary WR+O systems, such as CQ Cep, CX Cep, and the very massive WR+O system HD311884 (van der Hucht, 2001).

The M-evolution of close binary systems is of particular interest as an explanation

of massive ($M > 10M_{\odot}$) BHs in X-ray binary systems. The idea of matter mixing in the interiors of massive stars was used by Tutukov and Cherepashchuk (1985, 1993, 1997) to explain massive BHs in X-ray binary systems.

4.4 Ultra luminous X-ray sources (ULX) as HECBS

Observational data have been obtained recently which indicate that at least some compact ULX sources are either X-ray pulsars or BHs with stellar mass which are in a highly supercritical accretion mode in massive X-ray binary systems at special evolution stages. It was shown in Fabrika et al. (2015) that most ULXs in other galaxies, whose luminosity is in the X-ray range up to $\sim 10^{42}$ erg/c, are supercritical accretion disks in binary systems with BH, similar to supercritical microquasar accretor SS433 in our Galaxy (Cherepashchuk, 1981).

To date, several X-ray pulsars in binary systems that exhibit the ULX phenomenon have been discovered by NuSTAR orbital X-ray observatory (see a review of Kaaret et al., 2017, which contains all necessary references).

For example, M82-X-2, a ULX source in M82 galaxy, whose maximum X-ray luminosity exceeds 10^{40} erg/s, turned out to be an X-ray pulsar with a period of 1.37 s orbiting a donor star with an orbital period of $\sim$2.5 days. The period of axial rotation of X-ray pulsar decreases at a rate of $dP_{puls}/dt = -2 \cdot 10^{-10}$ s s^{-1} (Bachetti et al., 2014). The occurrence of coherent X-ray pulsations definitely indicates the presence of a neutron star whose observed luminosity greatly exceeds the Eddington limit. It is possible that an accretion to magnetic poles of a neutron star with a strong magnetic field, which significantly differs from the spherical one, is observed in this case (Basko and Sunyaev, 1975).

Studies (Lui et al., 2015; Kosec et al., 2018) discovered relativistic baryon collimated outflows (jets) from ULX sources M81ULS-1 and NGC300 ULX-1 with outflow velocities exceeding (0.17–0.24)c. For more information on ULX sources see a review (Kaaret et al., 2017).

4.5 Gamma-ray bursts and kilonova GW170817

The short gamma-ray bursts accompanying the gravitational-wave burst GW170817, which is due to the merger of two neutron stars (see Catalog: Abbott et al., 2019), made it possible to study the physics of nucleosynthesis in the merger of two neutron stars in detail and to test the model of the formation of short gamma-ray bursts and relativistic jets. The arrival times of electromagnetic and GW bursts were used to show that the propagation velocity of GWs in space coincides with high accuracy with the speed of light.

Significant success has been achieved in the optical identification of long cosmic gamma-ray bursts, including linear polarization of intrinsic optical radiation that accompanies the gamma-ray burst (Troja et al., 2017). A wealth of data has been accumulated in recent years that favors the model of long gamma-ray bursts as a phenomenon accompanying the collapse of the rapidly rotating core of a very massive star and the formation of an extremely fast-rotating Kerr BH with relativistic jets. The fast rotation of the massive star core may be maintained in this model by the

orbital motion of a nearby satellite in a short-period late close binary system (Tutukov and Cherepashchuk, 2003, 2004).

4.6 Pulsars in binary systems

The masses of about 80 pulsars – neutron stars in binary systems – have been determined (see review in Cherepashchuk, 2013 and references therein). The masses of X-ray pulsars and radiopulsars as well as the masses of type-I X-ray bursters and masses of neutron stars on GW binary system GW170817 do not exceed $3M_\odot$, the upper limit of the neutron star mass predicted by General Relativity.

The number of massive (M_p is about $2M_\odot$ or greater) neutron stars that have been discovered is now five: J0348+0432 ($M_\mathrm{p} \cong (2.01 \pm 0.04)M_\odot$, $P_{spin} = 39.123$ ms); J614–2230 ($M_\mathrm{p} = (1.97 \pm 0.04)M_\odot$, $P_{spin} = 7.95$ ms); B1516+02B ($M_\mathrm{p} = (2.08 \pm 0.19)M_\odot$, $P_{spin} = 3.15$ ms); J1748–20217 ($M_\mathrm{p} = 1.88^{+0.02}_{-0.08}M_\odot$, $P_{spin} = 80.34$ ms); J1748–24461 ($M_\mathrm{p} = 1.91^{+0.02}_{-0.01}M_\odot$, $P_{spin} = 9.57$ ms). Owing to this important result the soft equation of state of neutron matter can be rejected.

The masses of millisecond pulsars are on average $\sim 0.13M_\odot$ greater than those of ordinary pulsars, whose periods are of the order of seconds. This result is consistent with the conclusion of the theory of recycled pulsars regarding mass exchange in CBS.

The discovery of two radio pulsars in the J0737-3039AB binary system (Burgay et al., 2003), which confirmed the prediction of recycled pulsars (Bisnovatyi-Kogan and Komberg, 1974), enables various tests of General Relativity.

An analysis of the secular reduction in the orbital periods of radiopulsars in the PSR1913+16, J0737–3039AB, PSR1534+12 and PSR J0348+0432 binary systems provided indirect evidences of the existence of gravitational waves, encouraging researchers to create laser gravitational wave antennas (Herzenstein and Pustovoit, 1962; Braginsky, 1965). In 2015, the LIGO observatory was the first to detect GW signals from merging BH in a binary system, which confirmed the validity of GR and brought the study of BH to a qualitatively new level.

This discovery was awarded with the Nobel Prize in 2017.

5 Conclusion

We described two "golden" eras in investigations of highly evolved close binary systems: X-ray astronomy era and gravitational wave one. Big observational and theoretical progress in the investigations of HECBS allowed us to obtain many fundamental results concerning the physics and evolution of stars and relativistic astrophysics. We hope that new and extremely interesting results will be obtained in this field of astrophysics owing to the successful operation of "Spectr-Roentgen-Gamma" space X-ray observatory as well as due to the commissioning of optical giant ground-based Extremely Large Telescope, as well as TMT and LSST telescopes.

The forthcoming launch of the James Webb Space Telescope will bring many new results in investigations of HECBS. Combining with the enhancement of next-generation gravitational-wave antennas, these advancements will provide unique opportunities for investigations of HECBS in the framework of multi-messenger astronomy (see e.g. Cherepashchuk, 2019).

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