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The Role of Gravitational Radiation in the Evolution of Stars and Galaxies

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Abstract—The conditions for the formation of close binaries containing main-sequence stars, degenerate dwarfs of various types, neutron stars, and black holes of various masses are considered. The paper investigates the evolution of the closest binary systems under the influence of their gravitational-wave radiation. The conditions under which the binary components can merge on a time scale shorter than the Hubble time as a result of their emission of gravitational waves are estimated. A self-consistent scenario model is used to estimate the frequency of such events in the Galaxy, their observable manifestations, the nature of the merger products, and the role of these events in the evolution of stars and galaxies. The conditions for the formation and evolution of supermassive binary black holes during collisions and mergers of galaxies in their dense clusters are studied.

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1. INTRODUCTION

The existence of gravitational waves was predicted by the general theory of relativity [1]. The character of the dependence of their power on the masses of moving bodies directed searches for detectable sources of gravitational waves and manifestations of these waves in the Universe. It has long been understood that close binary systems containing the most compact astronomical objects, including degenerate dwarfs, neutron stars (NSs), and black holes (BHs) of various masses, are powerful sources of gravitational waves (GWs). The search for specific objects and phenomena that demonstrate the effect of GWs is complicated by the weakness of their observed manifestations. Indirect evidence of the presence of GWs and their defining influence on the evolution of cataclysmic close binaries was the observed distribution of the orbital periods of these stars [2]. Direct proof for the existence of GWs was the Nobel-Prize-winning detection of the decrease in the orbital period of a double radio pulsar [3]. A second Nobel Prize was awarded for the detection of mergers of the components of binary BHs and NSs in the LIGO experiment [4]. These successes have transformed studies of the role of GWs in the evolution of compact astrophysical objects into one of the most popular and productive areas of modern astrophysics.

Our understanding of the evolution of the main astronomical objects—stars, galaxies, and galaxy clusters—is now well developed [5–8]. The high initial multiplicity of stars and the dissipative nature of the orbital evolution of the closest multiple systems in the course of their nuclear evolution through the end of their evolution often leads to the formation of very close final binary systems with compact components: low-mass main-sequence (MS) stars, degenerate dwarfs, NSs, and BHs. It has long become clear that the radiation of GWs can significantly infuence the closest systems and explain the emergence of a number of interesting close binaries and phenomena associated with stars and galaxies. These include cataclysmic systems of various types, X-ray systems, single low-mass, nondegenerate helium stars, RCrB stars, Type I supernovae, gamma-ray bursts, and recently detected bursts of GWs. The nuclei of almost all galaxies harbor supermassive black holes (SMBHs). The high density of galaxy clusters and the high frequency of collisions and mergers of galaxies in clusters create the conditions for the formation of close binary SMBHs in galactic nuclei [9] and the disruption of the galaxies that are the merger products. This indicates the importance of a comprehensive analysis of the role of GWs in the evolution of astrophysical systems.

The final products of the nuclear evolution of stars—degenerate dwarfs, NSs, stellar-mass BHs, and SMBHs in the nuclei of galaxies—have no observed energy sources apart from their thermal energy. Their observed evolution is activated by accretion of the ambient gas, which, in the case of an SMBH with a suitable accretion intensity, generates

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the brightest sources of radiation in the Universe—quasars. In the presence of a close companion, the leading force of evolution in final binary systems becomes GWs, which facilitate the approach and eventual contact of the components [10–12]. The characteristic time for the coalescence of close binary components in years T can be estimated as [13]:

$$T = 10^8 (a/R_\odot)^4 \times M_\odot^3/(M_1 M_2 (M_1 + M_2)), \tag{1}$$

where a is the semi-major axis of the circular orbit and M_1 and M_2 are the masses of the components in solar units. Since the lifetimes of astronomical objects are limited to the Hubble time, we can estimate the sizes of binary systems with circular orbits for which GWs are evolutionarily significant:

$$a/R_\odot < 3(M_1/M_\odot)^{1/4} \times (M_2/M_\odot)^{1/4}((M_1 + M_2)/M_\odot)^{1/4}. \tag{2}$$

Let us estimate the intensity L of the GWs at the time of the merger of two BHs of the same mass as the ratio of the mass defect $\alpha \sim 0.1$ [4] and the time of their merging, assuming the major axis is comparable to the component radii:

$$L = \alpha c^5/G \sim 10^{25}\ L_\odot, \tag{3}$$

where c is the speed of light and G is the gravitational constant.

Interestingly, this intensity does not depend on the masses of the merging BHs, and its magnitude makes these systems "absolute" brightness standards at the time of their coalescence, "brighter" than the entire optical Universe within the horizon! The durations of the coalescences of the components of binary BHs with masses of 10–$10^{10}\ M_\odot$ are 0.001–10^6 s (see Fig. 1). It is also important that the duration of the merger of identical BHs is estimated to be about three times their orbital period at the time of the merger, regardless of their masses. This leads to a characteristic shape of the GW pulse at the time of a BH merger, which helps facilities such as LIGO identify coalescences of compact, sellar-mass relativistic objects.

Figure 1 presents the relationship between of the radii and masses of various objects in the world of stars and galaxies, and provides a visual aid for the analysis of the nature of "bright" sources of GWs and the role of GWs in the evolution of stars and galaxies. The main astrophysical objects are represented: planets P, main-sequence stars MS, degenerate dwarfs DD, neutron stars NS, black holes BH, binary stars BS, star clusters, galaxies, and clusters of galaxies. The straight lines indicate the dimensions of systems that collapse over the Hubble time when the density is equal to the mean density of the Universe, 10^{-29} g/cm^3 ($M \propto R^3$); the relation $M = 0.2R^2$ ($M \propto R^2$); the constraint on the sizes of close binary systems with identical components that merge during Hubble time, $\tau_{GWR} = T_H$; the upper limit for the zone of influence of GWs ($a \propto M^{3/4}$); and the radii of BHs ($M \propto R$).

The following relation warrants a special discussion:

$$M = 0.2R^2, \quad M/M_\odot = 10^3\ R_\odot (R/pc)^2. \tag{4}$$

Within a factor of two to three, this represents in Fig. 1 the observed masses and radii of clusters of galaxies, galaxies [14], and clusters of stars, and serves as an upper limit for the semi-major axes of binary stars [5]. This ratio was found for the molecular clouds of our Galaxy, which are the precursors of star clusters, by Larson [15]. It was then confirmed in an analysis of the parameters of star-formation zones in other galaxies [16], whose sizes are naturally close to the sizes of the original molecular clouds. This relation aso determines the relationship between the Keplerian velocities of stars V and the masses of the corresponding galaxies: $V \propto M^{1/4}$.

It is interesting that the continuation of all the lines indicated above to large scales leads to their intersection at a mass corresponding to the mass of the Universe within the horizon, $\sim 10^{22}\ M_\odot$. While the reason for the intersection of these lines due to to relativistic effects is obvious by virtue of their mutual conditionality, the reason for the line representing the dimensions of star clusters and galaxies ending up at this same intersection point remains unclear. The origin for the observed small dispersion of the relation $M \propto R^2$ could be either genetic or a product of the evolution of these objects. For example, collisions of galaxies can strip them of rarefied peripheral regions and reduce their size. With the observed radial distribution of their densities, this makes them denser. As will become clear below, dissipative mergers of galaxies in collisions can significantly increase their radii [21]. Low-surface-brightness galaxies have recently become known. Another obvious possible factor determining to the dispersion in the relation $M \propto R^2$ is the dispersion of the initial angular momenta of star clusters, galaxies, and galaxy clusters, which, for example, determines the appreciable dispersion of the distribution of semi-major axes of binary stars (see Fig. 1).

What can explain the "stability" of the relation $M \propto R^2$ over the wide range of masses for star clusters, galaxies, and clusters of galaxies (see Fig. 1)? It is possible that this reflects the expected initial correlation between the angular momenta J of the gas precursors of galaxies and molecular clouds and their masses, which can easily be derived: $J \propto M^{7/4}$.

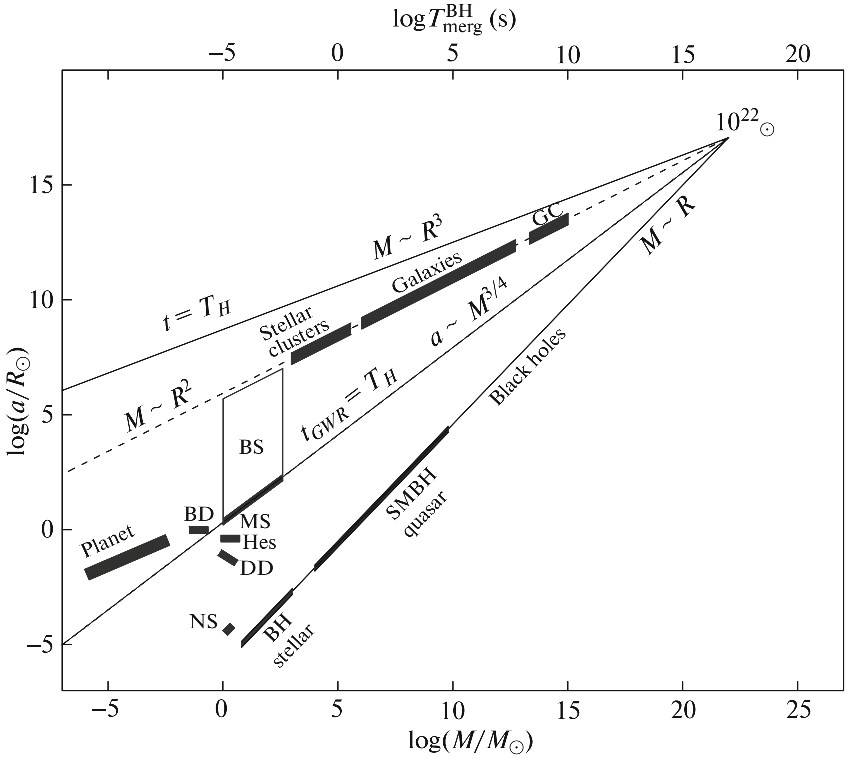

Fig. 1. Astronomical objects in a plot of their radii (or semi-major axes) versus their masses. The upper scale shows estimates of the coalescence times and the orbital periods of two identical BHs with the masses indicated on the lower scale. The lines indicate the sizes of systems with the average density of the University, $\sim 10^{-29}$ g/cm^3, collapsing over the Hubble time ($T = T_H$); the observed correlation between the sizes of star clusters, galaxies, and clusters of galaxies and their masses ($M \propto R^2$); the maximum semi-major axes of systems of two equal-mass objects merging over Hubble time T_H ($a \propto M^{3/4}$); and the radii of BHs ($M \propto R$). The positions of planets, brown dwarfs (BD), main sequence stars (MS), degenerate dwarfs (DD), binary stars (BS), low-mass helium stars (Hes), neutron stars (NS), stellar-mass black holes (BH), and supermassive black holes (SMBH) are indicted.

However, the complete absence of such a correlation for the stellar-mass gas clouds that produce binary stars with masses of 0.1 $M_{\odot}$–100 $M_{\odot}$ then remains unclear. These are equally distributed over the logarithm of their semi-major axes (see Fig. 1) [5], and therefore overthe logarithm of the angular momentum, within broad limits of the latter: $\delta \log J \sim 2.5$. Of course, it may be that the relation $M \propto R^2$ simply reflects the obvious observational selection effect due to the surface brightnesses of star clusters and galaxies with a relatively small observed dispersion for the mass–luminosity relation for galaxies. However, it now seems possible that the relation $M \propto R^2$ may reflect the hierarchy of the tidal influence of the original turbularized gas medium during its evolution from larger to smaller scales. The radius r of the zone of influence of a gravitating body with a mass m is given by $r = R(m/M)^{1/2}$, where M is the mass of a nearby gravitating object and R is the distance between them. For cosmological reasons, clusters of galaxies with masses of $\sim 10^{15}$ $M_{\odot}$ and sizes of about a megaparsec [17] are the first to emerge during the expansion of the Universe [17] (see Fig. 1). During the collapse and the accompanying gravitational fragmentation of these clusters, galaxies appear, whose sizes are limited from above by the indicated tidal influences. Continued growth in the density of galaxies leads to the appearance of molecular clouds, clusters of stars, and multiple stars, whose radii are also determined by tides due to higher-order systems. This sequence ends with multiple stars, whose maximum dimensions are limited by the tidal influence of their host galaxies and star clusters [5]; the sizes of stars and planets are determined by other processes. As a result, this scenario could explain the observed connection between the masses and sizes of clusters of stars and galaxies, as well as the Universe ($M \propto R^2$, see Fig. 1). This probably explains the reason for the line $M \propto R^2$ in Fig. 1 passing through the "point" corresponding to the size and mass of the Universe within $z < 1$.

Note that the gas clouds that are the progenitors of stars, star clusters, galaxies, and galaxy clusters all have the same mass spectrum [18]:

$$dN/dM \propto M^{-2}. \tag{5}$$

Deviations of the "observed" initial functions of stars and galaxies from this reference relation can be explained by the influence of the stellar winds of massive stars with the solar chemical composition, the absorption of low-mass galaxies by massive galaxies in clusters [18], and the possible destruction of gas-rich low-mass galaxies during bursts of star formation.

The reason for the appearance of a stable initial mass spectrum for the gaseous precursors of astronomical objects, $dN/dM \propto M^{-2}$, over a very wide range of masses ($M_\odot$–10^{15} $M_\odot$) remains unclear. It is likely that this distribution reflects the mass spectrum of the original gas precursors of stars, galaxies and clusters of galaxies. In many ways, the "topography" of Fig. 1 is determined by the relations (4) and (5). Equation (5) in the integral form $N \sim M_U/M$ can be used to estimate the number of different objects and the frequency of events in the Universe within $z < 1$. Here, $M_U \sim 10^{22}$ $M_\odot$ is the mass of the Universe for a mean density of $\sim 10^{-29}$ g/cm^3. As always, refining the "topography" of Fig. 1 requires determining the role of the inevitable observational selection effects.

An analysis of the distribution of astronomical objects and systems of objects in Fig. 1 can be used to establish the main directions for searches for systems whose evolution is most likely to be determined mainly by GWs. Obviously, the members of the binary systems that are the most promising active generators of GWs, produced by the evolution of close binary systems, include long-lived low-mass main-sequence stars (MS), non-degenerate helium stars (Hes), helium, carbon–oxygen, and oxygen–neon degenerate dwarfs (DD), neutron stars (NS), and black holes (BH). The combination of these seven types of objects gives rise to twenty-eight classes of close systems. Our current study is dedicated to the formation and evolution of some of these under the influence of GWs. The formation of fairly close systems of binary SMBHs requires analysis of galaxy mergers, and represents a separate area of study.

It is clear from Fig. 1 that initial binary systems of any kind separated by distances comparable to the sizes of galaxies are too wide for GWs to play an appreciable role in their evolution. The formation of sufficiently close systems containing the products of the evolution of their components requires very efficient mechanisms for the loss of orbital angular momentum and the approach of the components in the course of the system's evolution. In the case of stellar binary systems, angular-momentum loss realized via their common envelopes, if the donor star loses gas faster than the accretor is able to accrete it, while remaining within its Roche lobe [19, 20]. The tidal deceleration of binary SMBHs in the nuclei of merging galaxies represents essentially the same mechanism [9]. The assumption of the dissipative deceleration of a binary system with component masses M_1 and M_2 in a common envelope with mass M and radius R makes it possible to write an estimate for the final semi-major axis of the system a_f, based on the condition for the initial energy of a binary system to go into disrupting the common envelope of a stellar system or the merger of two galaxies [5]:

$$a_f = a_0 M_r M_2 / {M_1}^2, \tag{6}$$

where a_0 is the initial semi-major axis of the binary system, with $M_1 > M_2$. This is equal to the size of the donor in the case of common envelopes of binary stars, and the radius of the more massive galaxy in the case of a galaxy merger. M_r is the mass of the compact donor in a close stellar binary or the SMBH mass in the case of a galaxy merger. Despite all the remaining uncertainty of this approach, it remains a reliable and popular way of estimating the results of the evolution of gravitating close-binary systems [5–7], and was adopted in our current study.

The disruption of common envelopes is not without observable manifestations. The observed distribution of the orbital semi-major axes of binary stars indicates that up to half of all planetary nebulae are produced by the decay of common envelopes of close binary stars [5]. A distinctive feature of planetary nebulae formed in this way could be a high rate of expansion of their envelopes, reaching several hundred km/s. Observational selection effects complicate the detection of the binary hot cores in planetary nebulae, but a large number of these are now known. The disruption of a common envelope can be divided into two phases. In the first, the accretor is immersed in the common envelope, and slows down in this envelope on the thermal time scale of the donor envelope at the moment it forms the common envelope. Immersed in the dense layers of the donor, the accretor moves toward a rapid stage of approach of the compact components and disruption of the common envelope on its dynamical time scale, which can reach a few weeks or months for the closest systems. During this time, the system ejects a shell with a characteristic mass of the order of a solar mass and radiates an energy of the order of the thermal energy of the common envelope. This rapid ejection is manifest a so-called "red nova"—an explosion with energy intermediate between those of bright novae and weak supernovae. Such rare, but bright, novae have long been known. The theoretical estimate of their frequency in the Galaxy—once every few years—makes them very rare against the background of the frequency of ordinary novae, $\sim$30 yr^{-1}. However, they are an integral element in the evolution of close binary stars. Some fairly wide binary stars may be manifest as bright infrared sourcs in the phase of the disruption of the common envelope, due to the formation of a large amount of dust in their giant, dense outflowing envelopes. This question is worthy of detailed study.

To understand the conditions for the formation of binary stars and their evolution, it is important to know the initial distributions of the main parameters of binary stars: the masses of the primary components M_1, the initial component-mass ratio $q = M_2/M_1$, and the orbital semi-major axes a. Analysis of the observed parameters of MS binary stars taking into account observational selection effects enables derivation of the desired formation function of binary stars in the Galaxy [5]:

$$d^3\nu = 0.2 d\log(a/R_\odot) \times (M_\odot/M_1)^{2.5} d(M_1/M_\odot) f(q) dq, \tag{7}$$

where $f(q) = 1$ for $1 < a < 3000\ R_\odot$ and $f(q) \propto q^{-2}$ for $3000 < a/R_\odot < 10^6$.

With all the remaining uncertainties accompanying this search, this function remains a reliable basis for assessing the frequencies of various types of events associated with binary stars in our Galaxy and scenario modeling of an ensemble of Galactic binary stars. The position of binary stars is marked in the Figure. Binary stars with initial semi-major axes below 3000 $R_\odot$ are called close because their components with masses above $\sim$0.8 $M_\odot$ fill their Roche lobes during their evolution, and can generate the closest binary systems, requird for their components to merge over the Hubble time due to the radiation of GWs. The upper limit for the sizes of binary stars is determined by the tidal influence of the Galaxy, and therefore coincides with (4).

2. STELLAR SOURCES OF GW RADIATION

Analysis of the Figure shows that the closest binary systems with the most compact components (MS stars, non-degenerate helium stars, degenerate dwarfs, NSs, and stellar BHs) are the most promising for the stellar generation of intense GWs. In this section, we consider the role of GWs in the evolution of such stellar systems.

Let us consider the role of GWs in the evolution of close binaries containing MS and non-degenerate helium stars. The radii of brown dwarfs with masses of 0.01 $M_\odot$–0.1 $M_\odot$ are close to 0.1 $R_\odot$, and the radii of MS stars with masses of 0.1 $M_\odot$–1.5 $M_\odot$ can be represented by the expression $R/R_\odot = M/M_\odot$. Using (2), we find that the components of contact systems with equal masses in the range 0.04 $M_\odot$–$M_\odot$ should merge on a time scale shorter than the Hubble time due to GW radiation. The determining factor in the evolution of binary components with masses greater than 0.8 $M_\odot$ is their nuclear evolution, which masks the influence of GW radiation due to its high rate. However, there are also significant issues for systems whose components have lower masses. It has long been known that, due to the limitation on the size of their accreting components of $\sim$3 $R_\odot$, young close binary stars with MS components have orbital semi-major axes exceeding $\sim 6(M/M_\odot)^{1/3}$ [5], which makes them “inaccessible” to GW radiation. That is, to bring these systems into the region of parameters in which GW radiation plays an important role, they must get rid of excess angular momentum.

Three scenarios for the approach of binary components are possible. The first is the rare decay of an unstable, very close multiple system. MS components with masses in the range 0.3 $M_\odot$–1.5 $M_\odot$ have intense magnetic stellar winds, which bring them into contact with each other through spin-orbit interactions, with the formation of W UMa-type stars and cataclysmic systems. However, the action of the magnetic stellar wind also masks the effect of GW radiation. The more likely third option is the evolution of the primary component with the formation of a common envelope, whose disruption brings about the formation of a semi-detached cataclysmic close-binary system. The observed distribution of mass-transfer rates for cataclysmic systems has established that all systems of this kind with orbital periods of less than two hours evolve under the influence of GW radiation [5]. The evolution of cataclysmic variables with orbital periods of more than two hours is governed by the magnetic stellar wind or the nuclear evolution of the donor [5, 7]. By analogy, we conclude that the driving forces of evolution are the same for low-mass X-ray binaries with accreting NSs or stellar-mass BHs.

The degenerate accretors of cataclysmic systems are divided into carbon–oxygen and oxygen–neon, as demonstrated by a chemical analysis of their envelopes. The abundance of neon in oxygen–neon novae is a factor of 100 greater than solar value, which suggests a significant role for mixing of the matter accreted between flares with the material of the degenerate dwarf itself and the erosion of this latter material during nova explosions [22]. The erosion of the accretor in cataclysmic close binaries during nova outbursts probably rules out the possibility that their degenerate components exploded as Type Ia supernovae. Once again, analysis of the evolution of close binaries proves to be a reliable tool for studying the structure and evolution of stars. The relative observed frequency of oxygen–neon novae is only a factor of two lower than the total frequency of novae [23], most of which are the products of explosions of carbon–oxygen dwarfs. The actual relative frequency of the appearance of oxygen–neon dwarfs in cataclysmic systems is much lower, since the frequency of outbursts increases rapidly with the mass of a degenerate dwarf [24]. The theoretical estimate of the total frequency of the formation of cataclysmic systems in the Galaxy is $\sim$0.01 yr^{-1}, close to the observed frequency [5].

The nuclei of virtually all galaxies harbor SMBHs with masses of $10^5\ M_{\odot}$–$10^{10}\ M_{\odot}$ [25]. Their interaction with the surrounding stars in the galactic nucleus deserves a special consideration. Stars of different classes in the immediate vicinity of these BHs can form close pairs with them. GW radiation brings the components in such binaries closer with time, but not always before they come into contact with their Roche lobe. SMBHs have such low densities that they can first fill their Roche lobes in this approach process. As a result, their compact companions can be "absorbed" by the SMBH before they can fill their Roche lobes. Such events in galactic nuclei probably occur without visible manifestations, apart from the expected pulse of GW radiation. This picture of the absorption of stars in binaries with SMBHs and its possible observable manifestations require special investigation. The condition for such an absorption can be found using (2), assuming that the donor has filled its Roche lobe:

$$M_{\rm BH}/M > (c/v_{\rm ff})^3, \tag{8}$$

where $M_{\rm BH}$ is the mass of the SMBH, M the mass of the donor, c the speed of light, and $v_{\rm ff}$ the escape velocity at the donor surface. It follows from this condition that NSs will be absorbed when in binaries with BHs with masses above $\sim$50 $M_{\odot}$, degenerate dwarfs in binaries with $M_{\rm BH} > 10^6\ M_{\odot}$, and long-lived, solar-mass MS stars in binaries with $M_{\rm BH} > 10^8\ M_{\odot}$. In the case of lower masses for SMBHs in binaries with stars, stars filling their Roche lobes in hyperbolic orbits can be disrupted by tidal forces on their dynamical time scale. Several dozen such events on the scale of supernova explosions were registered in optical and ultraviolet, corresponding to the disruption of MS stars with masses from one to forty solar masses [69]. The frequency of such explosions is determined by the diffusion rate of the stellar component of galactic nuclei in the vicinity of the central SMBHs.

Potential donors that are able to fill their Roche lobes that move in circular orbits around low-mass SMBHs are of no less interest. This applies, in particular, to MS stars in close binaries with SMBHs in galactic nuclei. If we assume for MS stars with masses less than $\sim$1.5 $M_{\odot}$ the relationship $R_{\rm MS}/R_{\odot} = M_{\rm MS}/M_{\odot}$, it can be found using (2) that the ratio of the maximum semi-major axis occuring in the case of evolution governed by GW radiation within the Hubble time to the minimum BH mass is close to $(M_{\rm MS}/M_{\odot})^{-5/12}(M_{\rm BH}/M_{\odot})^{1/6}$. For example, for $M_{\rm MS} \sim M_{\odot}$ and $M_{\rm BH} \sim 10^9\ M_{\odot}$, this ratio reaches about 30. That is, low-mass stars that have fallen from the periphery of the galactic nucleus into the region within $\sim$10^{16} cm of the galactic enter due to mutual collisions will evolve under the influence of GW radiation into a semi-detached binary with the central SMBH [26]. The lifetime and characteristic rates of mass transfer can be estimated using (1). The ratio of the mass-transfer rate to the rate corresponding to the Eddington luminosity is given by $\sim 0.03(M/M_{\odot})^{2/3}(M_{\odot}/M_{\rm BH})^{1/3}$. That is, as a rule, the "accretion" of individual stars by a SMBH due to GW radiation will be undetectable against the background of a bright quasar. However, such acts of the accretion of individual stars can be manifest as flares of radiation. Analysis of the light curves of active galactic nuclei can be an effective tool for analyzing their sources of power.

It is interesting that the magnetic stellar wind, which drives the evolution of cataclysmic systems with orbital periods above three hours, gives way to GW radiation when the accretor is a SMBH, since the ratio of the characteristic times for the donor magnetic wind and GW radiation is $\sim 10(M/M_{\odot})^{7/3}(M_{\odot}/M_{\rm BH})^{4/3}$. That is, when $M_{\rm BH}/M_{\odot} > 6(M/M_{\odot})^{7/3}$, GW radiation becomes the leading evolutionary factor for semi-detached systems with low-mass MS donors. However, we must also take into account that such stars with masses less than $\sim$1.5 $M_{\odot}$ have deep convective envelopes, which means that they expand rapidly when they come into contact with their Roche lobe in response to the rapid loss of matter from their envelopes; this means that they can be completely disrupted on a time comparable to the dynamical time scale, forming a massive gas disk (envelope) near the SMBH. Similarly, tides can also disrupt Roche-lobe-filling degenerate dwarfs around SMBHs with masses below $\sim$10^6 $M_{\odot}$. Accretion of the disk gas resulting from the disruption of the star at the Eddington rate for the SMBH will lead to a hard radiation flare lasting $\sim 10^8(M/M_{\rm BH})$ years. It is interesting that similar flares with energies $\sim$10^{52} erg have been observed [27]. However, it is now clear that these flares may also be due to inhomogeneity of the disk material accreted by the SMBH. Reliable identification of acts of tidal disruption of stars in the vicinities of SMBHs and the accretion of their matter by quasars requires detailed analyses of the observed properties and light curves of quasars. Such analyses are also needed for studies of the structure and physics of the gas accretion disks of quasars.

The masses of nondegenerate helium stars lie in the range 0.5 $M_\odot$–100 $M_\odot$ [5, 7], their radii are $R_{\rm He}/R_\odot = 0.2(M/M_\odot)$, and their luminosities are $L_{\rm He}/L_\odot = 250(M_{\rm He}/M_\odot)^4$ [28]. Most of these stars are products of the evolution of close binary stars. As a result of the approach of the binary components in the common-envelope stage, a helium star may fill its Roche lobe under the influence of GW radiation in the stage of helium burning in its core, with its companion being a degenerate dwarf, NS, or stellar-mass BH. The frequency of the occurrence of such systems in the galaxy is about 0.001 $\rm yr^{-1}$ [29]. The above helium-star radii can be used to estimate the rate of mass transfer under the influence of GW radiation in semi-detached systems with a helium star filling its Roche lobe: $10^{-7}(M/M_{\rm He})^{2/3}\ M_\odot\ \rm yr^{-1}$ [30], where M is the mass of the accretor. With solar mass components, this rate is close to those demonstrated by cataclysmic systems. The short lifetime of such systems and the low frequency of their occurrence makes them rare: $\sim 10^4$ [30] in the Galaxy. Therefore, reliable examples of such systems with nondegenerate helium donors are not yet known. Stars such as AM CVn may be produced by the evolution of such systems, as well as the evolution of close binaries with evolved, low-mass MS stars [29]. The increase in the mass-transfer rate with increasing SMBH mass implies the rapid disruptionnof the helium star, and leads to a flare of radiation whose duration depends on the viscosity of the gas and the mass of the BH.

Let us consider the coalescence of the components of close binary degenerate dwarfs, which can produce Type Ia supernovae, R CrB stars, novae, NSs, and helium stars. The evolution of such systems has attracted much attention in recent years, for obvious reasons. The evolution of the components of close binaries with masses of $M_\odot$–10 $M_\odot$ in the common-envelope stage leads to the formation of close systems of degenerate dwarfs. Three classes of degenerate dwarfs are known: helium (Hed) 0.1 $M_\odot$–0.55 $M_\odot$, carbon–oxygen (COd) 0.55 $M_\odot$–1.2 $M_\odot$ and oxygen–neon (ONed) 1.2 $M_\odot$–1.4 $M_\odot$, [2]. The six resulting possibilities for mergers of degenerate dwarfs under the influence of GW radiation provide opportunities for describing a number of different types of stellar objects and phenomena.

The currently most popular "duet" is binary degenerate CO dwarfs, whose coalescence is probably the origin of Type Ia supernova explosions [2], with energies $\sim 10^{51}$ erg [33]. The estimated frequency of occurrence of such events in our Galaxy is $\sim$0.003/year [30, 32]. The role of Type Ia supernovae is fundamental in a number of areas of modern astrophysics. Considered the current brightness "standard", they are the basis of the modern scales for time and distance in modern astrophysics and cosmology. Analysis of the evolution of the apparent brightness of Type Ia supernovae with time has led to the conclusion that the expansion of the Universe may be accelerating with time. However, note that a detailed recent study of the observational properties of these explosions has revealed an almost 40% difference in the masses of nickel produced in the absence of any observed difference in their light curves [47]. At the same time, a study of the chemistry of stars of different ages has shown that Type Ia supernovae are the main suppliers of iron in the Universe. In addition, as simple estimates show, these supernovae are the main generators of the galactic winds of elliptical galaxies and the winds of the bulges of disk galaxies. That is, it is mainly Type Ia supernovae that lead to the low gas contents of elliptical galaxies. All this underscores the need for a thorough analysis of scenarios for their formation and the mechanism for their explosions.

Despite the apparent simplicity and reliability of the scenario of merging degenerate CO components of binary systems as the mechanism for Type Ia supernovae, many fundamental questions remain, including the role of the total mass of the CO dwarfs in determining the explosion energy, the role of tidal processes and the accretion stream in heating the accreting dwarf, the place where carbon begins to burn, and the formation of a detonation front in the explosion. Studies of the role of the total mass of the dwarfs and the completeness of the burning of the available nuclear fuel in determining the explosion energy can help clarify our understanding, not only of the physics of the explosion itself, but also of the possible acceleration of the Universe, which appears to weaken their brightness with distance [31]. According to scenario modeling of the evolution of the population of binary stars, the total mass of the CO dwarfs merging over the Hubble time has decreased by $\sim$30% over time [30], for the moment, leaving the conclusion that the Universe's expansion is accelerating in place. We note, however, that our understanding of the completeness of the burning of nuclear fuel in CO dwarfs, which determines the brightness of their explosions as Type Ia supernovae, remains incomplete.

Let us briefly consider the possible fate of other compact components that coalesce in close binary stars under the influence of GW radiation. The coalescence of oxygen–neon dwarfs, whose total mass is obviously greater than the Chandrasekhar limit, leads to the explosive combustion of oxygen and neon. However, the energy provided by this fuel is lower than that of carbon–oxygen dwarfs, and their radii are smaller. Their smaller radii increases the depth of the potential well for the products of their explosions. As a result, the nuclear energy of these dwarfs may not be enough for their complete destruction. Therefore, a rapidly rotating NS—millisecond radio pulsar—can be formed after the explosion, accompanied by a partial loss of matter. The frequency of such explosions in the Galaxy is 4×10^{-4} yr^{-1}[34]. The optical manifestations of such an explosion are unclear. Numerical studies of the physics of this type of explosion are necessary in order to find the place of the products among anomalous supernovae or novae.

The merging of CO and ONe dwarfs, with a frequency of $\sim 6 \times 10^{-4}$ yr^{-1} [34], probably leads to a Type 1a supernova; again, identifying the specific character and observational manifestations requires numerical simulations. The coalescence of helium degenerate dwarfs leads to the onset of helium burning. A supernova-scale explosion in this case seems unlikely, since the onset of helium burning in the core of a red giant with a mass comparable to the solar mass preserves the star, transferring it to a horizontal branch. The end product of the evolution of merging helium dwarfs will be a carbon–oxygen dwarf. The merging of helium dwarfs with carbon–oxygen or oxygen–neon dwarfs, with a frequency of ~ 0.04 yr^{-1} [34], may lead to Type 1a supernova-scale explosion when the nuclear fuel is detonated, but the conditions for this detonation and its possible manifestations have not yet been studied. In the absence of detonation, the coalescence product could become an R CrB star—a helium giant, whose evolution quickly ends with the loss of its helium envelope due to the intense stellar wind inherent to these stars [5]. The role of GWs in the evolution of semidetached cataclysmic binary stars with orbital periods shorter than two hours and donor masses smaller than $\sim 0.3\ M_\odot$ [5] deserves special mention. GW radiation reduces the orbital period of these systems to one hour, with the possible subsequent destruction of the donor on its dynamical time scale, with the formation of a gaseous disk near the accretor [5]. For donor masses $0.3\ M_\odot$–$1.5\ M_\odot$, a leading factor in the evolution of such systems is the magnetic stellar wind, while the main evolution factor is the nuclear evolution of the donor when $M > M_\odot$.

Let us now discuss the coalescence of the components of close binaries containing NSs and stellar BHs. The evolution of close-binary components with masses $10\ M_\odot$–$30\ M_\odot$ ends with the formation of NSs; the influence of the common envelope that arises during the evolution of such systems leads to the formation of a close binary containing two NSs [5, 7, 35]. The evolution of the closest of such systems under the influence of GW radiation brings their components into contact. Model estimation of the frequency of such events in the Galaxy is $\sim 3 \times 10^{-4}$ yr^{-1} [30]. Disruption that arises during contact between the components in the deep gravitational potential is usually identified with gamma-ray bursts, whose energy of 10^{48}–10^{52} erg corresponds to the binding energy of a NS. The time evolution of the frequency of gamma-ray bursts traces the history of star formation in the Universe, with a maximum at $z \sim 2$, corresponding to an age of 2×10^9 yr [36, 37].

The observed gamma-bursts are a very heterogeneous family, and can be divided into four groups according to the duration of the outbursts: ultrashort ~ 0.2 s, short ~ 1.5 s, average ~ 30 s, and long $\sim 10^4$ s [38, 39]. If the duration of the outbursts is of the order of the Keplerian time for orbits that are close to the accreting object, then ultrashort flares could be associated with the merger of two NSs, as was the case for GW 170817, and short bursts with mergers of NSs and stellar BHs in close binary systems. The theoretical ratio of the frequencies of these events based on scenario modeling is about three [30], which coincides with observational estimates [40]. It is interesting that short and ultrashort gamma-ray bursts also have different gamma-ray energies [41]. One possible mechanism for short gamma-ray bursts is mergers of ONe degenerate dwarfs in our own Galaxy, with a frequency of $\sim 3 \times 10^{-5}$ yr^{-1}. After the nuclear fuel rapidly burns out in the merger product, the collapse of the resulting rapidly rotating star can lead to the formation of an extremely close binary NS, with the subsequent coalescence of its components due to GW radiation leading to a GW flare such as was observed by LIGO for GW 170817, and with this GW burst coincident in on the celestial sphere and in time with a short gamma-ray burst. This suggests that we can attribute some of gamma-ray bursts to mergers NSs and BHs. A similar scenario could also be realized in the collapse of a Type 1b,c supernova in an extremely close binary system [42]. In this case, the rapidly rotating core can form an extremely close binary NS during its collapse, with the rapid merging of the NS components due to GW radiation producing a short gamma-ray burst.

Note that, despite the obvious agreement of modern concepts on the nature of gamma-ray bursts and bursts of GW radiation, estimates of the observed frequency of LIGO events [4] remain appreciably lower than model estimates for the frequency of coalescences of NSs and BHs [30]. We can offer two possible ways to reduce the theoretical estimates. One is the possibility that the forming NSs and BHs acquire speeds of several hundred km/s during the collapse and the decay of the binaries, for example, due to an asymmetric neutrino discharge. Another possibility may be associated with the chemistry of the precursors of the LIGO events [67]. The most massive stars that are the progenitors of stellar BHs have very powerful stellar winds, which prevent their expansion after the MS stage, and consequently hinder the formation of a common envelope [5]. However, a common envelope is absolutely necessary for bringing the evolved components into the large orbital semi-major axes that are necessary for the efficient action of GW radiation. One obvious way to save the hydrogen-rich envelope of the star, ensuring its expansion and the formation of a common envelope, is to appeal to rare primordial stars with low metal abundances and weak winds. That is, it is possible that massive LIGO systems are rare products of evolution, namely, the earliest binary systems with small metal abundances. It is clear that further work is needed to clarify all these estimates based on both theoretical models and LIGO observations.

Scenario analyses and scenario models demonstrate the possibility of mergers between NSs or stellar BHs and degenerate dwarfs of various types in close binary systems under the influence of GW radiation. The total frequency of such events in the Galaxy is $\sim 10^{-3}$ yr^{-1} [30]. The observational manifestations of such events have not yet been studied. Based on general principles, it seems reasonable to assume that the dwarf with its dynamical time scale will be disrupted in a few seconds. The result will be the formation of a long-lived X-ray source with an actively evaporating accretion–reduction disk near a compact object, or of an (infra)red Thorne–Zytkow-type object with an intense stellar wind. There may be examples of objects of the first kind among known X-ray sources, and objects of the second kind among the brightest infrared stars. The lifetimes of both types of relativistic objects with massive disks and massive extended envelopes are determined entirely by the intensity of their winds, and can be relatively short; their number in the Galaxy is small. The depletion of the matter of their compact disks due to their high initial angular momentum can be accompanied by the formation of large decretion disks near such NSs and BHs, with the possible subsequent formation of planets in these disks [43]. The role of the decretion part of the disk is underestimated due to its low activity, but most are products of its evolution [5]. An accreting compact object surrounded by a gas disk is a traditional model for X-ray sources [5–7]. The disk can be either a relict, as in the scenario presented above, or be continuously fed by an external source, such as an interstellar medium, a stellar wind from a nearby companion, or a companion itsef with a mass below 0.3 $M_\odot$ that fills its Roche lobe [2]. As in the case of cataclysmic binaries, only in the latter case will the driving force of evolution of such a system be GW radiation.

The evolution of stars with masses higher than $\sim 30\ M_\odot$ ends with the formation of stellar-mass BHs with masses higher than $\sim 6\ M_\odot$ [7, 42, 44]. The theoretical relationship between the mass of the progenitor MS star $M_{\rm MS}$ and the mass of the BH [5] is $M_{\rm BH}/M_\odot = 0.05(M_{\rm MS}/M_\odot)^{1.4}$. This assumes that the BH's mass is equal to the mass of the low-energy carbon combustion products in the core of the massive star. The component masses for the six binary BH mergers detected by LIGO were 7 $M_\odot$–36 $M_\odot$ [4, 44, 45], which, according to the relation above, corresponds to initial masses for their progenitors 33 $M_\odot$–110 $M_\odot$. The initial mass function (5) of stars assumes the concentration of the BH mass distribution at low masss, but the known mass distribution of LIGO BHs shows the opposite trend, namely, a concentration around the highest masses [45]. This is likely a consequence of the increase in the "working" interval of orbital semi-major axes for binary BHs merging under the action of GW radiation with the BH mass (2), and the usual observational selection effect of the increase in the volume of space monitored by LIGO with increasing mass, and therefore the radiated energy of the merging BHs. We must recall here that, although the absolute "brightness" of a source of GWs (3) does not depend on the mass of the merging BHs, the total energy radiated during the merging is proportional to their mass. An empirical estimate of the merger frequency for stellar BHs in our Galaxy remains uncertain [4, 46]: 10^{-6}–10^{-5} yr^{-1}. Theoretical scenario estimates [30, 34] give 10^{-4}–10^{-5} yr^{-1}, as was noted above. This does not necessary contradict the empirical estimate, due to a number of remaining uncertainties in the scenario program, but, obviously, both these estiates require clarification.

Summing up the role of GW radiation in the evolution of stars, the formation of compact binary systems made up of the remnants of the nuclear evolution of their components leads to GW radiation becoming the main factor in the subsequent evolution of these systems. The approach of the components leads to filling of their Roche lobes, mass transfer, and, in many cases, the complete destruction of the components.

These processes are marked by the appearance of bright sources of stationary and transient X-rays and gamma-rays, as well as bursts of GW radiation. Thus, the presence of the GW radiation provides real opportunities to study the evolution of the components of close binary systems and such systems themselves before the complete exhaustion of the driving forces of their evolution. Modeling of these processes and studies of the physics of phenomena associated with GW radiation, such as Type 1a supernovae, gamma-ray bursts of various types, and the coalescence of the compact products of the evolution of various types of stars are now subject to detailed and comprehensive study. We note the need for multifaceted observational information about the properties of the most compact stars and systems comprised of such objects in the later stages of their evolution.

3. THE ROLE OF RADIATION OF GW RADIATION IN THE EVOLUTION OF GALAXIES

Let us now consider the conditions for the formation and evolution of SMBHs in the nuclei of galaxies. Galaxies are giant clusters of stars and gas with masses of $10^7\ M_\odot$–$10^{13}\ M_\odot$ [8]. The mass–radius relation for galaxies is represented by Eq. (4) and the Figure. A galaxy can be described as a sum of two main components: spheroidal and disk. Elliptical galaxies are represented by only a spheroidal component, and disk spiral galaxies have both a spheroidal bulge and a disk. The spheroidal component is a cluster of old stars with masses of less than a solar mass. Galaxies with masses higher than $\sim 10^{10}\ M_\odot$ also have a dark gravitating component of unknown nature [48]. The winds of elliptical galaxies and the bulges of spiral galaxies are supported by Type Ia supernovae, or, ultimately, by GWs, which facilitate the merging of degenerate dwarfs. Galactic winds prevent the accumulation of gas lost by old stars in elliptical galaxies and the bulges of spiral galaxies. The spheroidal component of a galaxy is probably the sum of the products of the original collapse of the proto-galaxy and the products of the coalescence of the galaxy with nearby satellites and neighbors during their evolution in the parent cluster. The disk component of a galaxy is a product of the dissipative evolution of the gas component of the galaxy over the Hubble time [49]. Galaxies contain about half the stars in a galaxy cluster, with the remaining stars belonging to the stellar background, emphasizing the role of collisions and the decay of some of the galaxies of the cluster in the course of their evolution.

The discovery of SMBHs with masses of $10^6\ M_\odot$–$10^{10}\ M_\odot$ in the nuclei of most galaxies is one of the most significant achievements of 20th century astronomy. Their intensive accretion of gas—up to $\sim 100\ M_\odot$ per year—makes SMBH quasars the brightest sources of stationary radiation in the Universe. The large energies of accreting SMBHs make them active factors in the evolution of galaxies. The SMBH masses are 10^{-5}–10^{-2} of the masses of their galaxies, with the characteristic value of this fraction being ~ 0.001 [50]. Due to the usual observational selection effects, this fraction has the meaning of an upper limit. The highest fractions probably correspond to partially disrupted products of galaxy mergers [51]. The paths for SMBH formation in very young galaxies with ages of less than a billion years are not yet completely clear.

Several scenarios for the emergence of SMBHs in the nuclei of galaxies have been proposed, based on general considerations. SMBHs in galactic nuclei may be relicts of the early stages of the evolution of our Universe, and in this case they may prove to be centers of formation of galaxies, rather than products of their evolution. Their progenitors could also be supermassive stars of corresponding masses with low metal abundances in the dense nuclei of galaxies. In addition, the coalescence of galaxies and their central SMBHs may play a certain role in the growth of SMBH masses [51]. However the most likely scenario is currently believed to be the rapid increase in the SMBH mass due to the super-Eddington accretion of gas and stars. The characteristic time scale for doubling of the mass accreting at the Eddington limit of a SMBH is $\sim 10^8$ yr. Tripling of the accretion rate over one billion years would enable an increase in the mass of the SMBH by a factor of a billion, and thus completely solve the problem of the rapid growth of SMBH masses in early stages of the evolution of galaxies. There are several possible ways to circumvent the Eddington limit on the accretion rate in this case. First, a three to fivefold excess of the Eddington accretion rates of SMBHs in galactic nuclei at $z > 2$ is probably already observed [52]. Second, a thin, hot disk near a SMBH can be cooled efficiently by neutrinos [53, 54], and effectively lose its energy in the polar directions in the form of ordinary radiation and wind from an accretion disk. In addition, as was found above, a fairly massive SMBH can absorb degenerate dwarfs and MS stars whole, avoiding the gas phase and thus bypassing the Eddington limit. These arguments probably resolve the problem of the observed “too rapid” mass growth of SMBHs in the nuclei of distant and young galaxies.

Analysis of the conditions for growth of the SMBH masses raises the question of the reasons for the observed limitation of the growth of SMBH masses in galactic nuclei to a characteristic value of $\sim 10^{-3}$ of the mass of an elliptical galaxy or a bulge of a disk galaxy [50], while the gas supply reaches ten percent of the galaxy mass, even in massive disk galaxies. One possible reason could be the Eddington limit on the accretion of cold dusty gas. Increasing the mass of the SMBH lowers the temperature of the disk radiation as $T(\mathrm{K}) \sim 10^7 (M_\odot/M_{\mathrm{BH}})^{1/4}$. When the relative mass of the SMBH is higher than 0.001, this radiation effectively inhibits the accretion of cold dusty gas, excluding the stationary accretion of gas by the galactic nucleus and the growth of the SMBH mass. It is important to remember that the opacity of dusty gas is almost a factor of 1000 greater than the opacity of hot, ionized gas. The flare accumulative accretion activity of quasars remains, but it is not effective in increasing the mass of the SMBH. Elliptical galaxies probably do not contain any cool interstellar gas. Simple energy estimates for heating and cooling of gas in elliptical galaxies show that galaxies with masses less than $\sim 10^{12}\ M_\odot$ remain free of gas, due to the galactic winds, which are supported by Type Ia supernovae. Analytical estimates show at the same time that the accretion of the winds of elliptical galaxies by the SMBHs in their nuclei does not lead to a significant increase in the masses of these SMBHs, due to the high velocity of these winds. That is, the SMBHs in the nuclei of elliptical galaxies should basically have formed before the associated disk galaxy was transformed into an elliptical galaxy, probably via collisions.

Another likely reason for the observed "limitation" of the relative mass of a SMBH to $\sim 10^{-3}$ of the mass of the spheroidal component may be the active participation of galaxies in the collisional evolution of galaxies in dense clusters. Let us consider the condition for a merger of galaxies and the SMBHs in their nuclei. As in the case of the coalescence of stars in a common envelope (6), a merger occurring during a collision of galaxies with velocities comparable to the escape velocities at their edges can be divided into two stages [51]. In the first, the nucleus of the galaxy and its SMBH are decelerated by the tidal influence of the stellar medium. The characteristic time scale for this deceleration based on a simple estimate for a homogeneous model is $\tau_{fr} \sim T_{\rm K}(M/m)$, where $T_{\rm K}$ is the Keplerian time, M the mass of the more massive galaxy, and m the mass of the less massive galaxy. Since The characteristic Keplerian times of galaxies are $\sim 10^8$ yr, galaxies with masses greater than 0.01 of the mass of the more massive galaxy with which it collides can be absorbed by the latter galaxy over a time shorter than the Hubble time. Lower-mass galaxies and, in particular, globular clusters can "coexist" at times exceeding the Hubble time. The nuclei of merging galaxies with SMBHs approach each other in accordance with (5) up to some distance, limited by the condition for total disruption of the parental galaxy. For some SMBHs to merge due to the action of GW radiation in the second stage, this distance must be less than (2), $\sim 3(M_{\rm BH}/M_\odot)^{3/4}$. As a result, based on (4), we find the limit on the mass of a SMBH in this scenario, based on the condition of preserving the product of the galaxy merger at the "common envelope" phase for the binary SMBH:

$$M_{\rm BH}/M < 0.002(M/10^{10} M_\odot)^{1/5}, \qquad (9)$$

where M is the mass of two merging identical galaxies. Fulfillment of this condition ensures the preservation of the stellar component of the galaxy merger product and the coalescence of their SMBHs over a time shorter than the Hubble time. Violation of this condition will lead to the complete scattering of the stars of the merging galaxies and preservation of the binary SMBH in a wide orbit, excluding the coalescence of its components. The dependence of the above fraction on the mass of the merging galaxies is weak. It is clear that observational selection effects distinguish galaxies with the most massive SMBHs that have survived such mergers, which probably selects for the observed mass ratio of the SMBHs and their galaxies. The disruption of a large portion of the colliding galaxies replenishes the stellar component of the cluster's galaxies, including a significant fraction of all the stars in galaxy clusters. A search for isolated, possibly starless, binary SMBHs in the gaseous medium of the intergalactic gas—the remnants of possible destructive collisions of galaxies whose merging times exceed the Hubble time—is of interest.

Thus, mergers of galaxies during their collisional evolution probably rule out the preservation of galaxies with relative SMBH masses greater than the limit (9), which contributes significantly to the observed correlation $M_{\rm BH} \sim 0.001M$ [50]. Thus, GWs can probably contribute to the preservation of galaxies when they merge. As can be easily demonstrated using (4), in the absence of GW radiation, most mergers would result when $M_{\rm BH}/M > 10^{-5}(M/(10^{10}\ M_\odot))^{1/2}$ to the complete destruction of galaxies by their merging SMBHs. Despite their rarity, galaxies with binary SMBHs in their nuclei are known [53, 56, 57]. A close pair of SMBHs was found in the quasar PG 1302-102, with an orbital period of about five years. The orbital period of the double core of the galaxy PSO J334.2028+01.4075 with a mass of $\sim 10^{10}\ M_\odot$ is only 542 days. The time of the merger of this binary SMBH due to GW radiation assuming their masses are $\sim 10^8\ M_\odot$ is only 250 yr. All of this underlines the high frequency of galaxy collisions and mergers of SMBHs during the evolution of galaxies in their clusters. The appearance of galaxies with active nuclei not coincident with the centers of mass of their galaxies [58] could serve as additional indirect evidence of mergers of galaxies and their nuclei. This deviation can reach one kiloparsec, and exceeds 100 parsecs for ten percent of galaxies. Finally, the very existence of correlation between the SMBH mass and the mass of the bulge of disk galaxies or the total mass of elliptical galaxies provides an additional argument in favor of the collisional nature of the mass increase of both components.

Note that most collisions of galaxies in clusters occur at speeds that are markedly higher than the escape velocities at the edges of the colliding galaxies; as a rule, the sizes and masses of the colliding galaxies also differ appreciably. Elliptical galaxies probably do not experience substantial perturbations, while disk galaxies may lose some of their gaseous disk. It is important that the surface density of the gas increases with decreasing mass for disk galaxies. As a result, a large disk galaxy may lose part of its gaseous disk. The time for diffusive filling of the gas-free area of the disk is $\tau \sim T_\mathrm{K}(r/H)^2$, where T_K is the Keplerian time of the disk, r the size of the gas-free zone, and H the thickness of the gaseous disk, which determines the turbulent velocity of the gas [49]. This time can be quite large and the main factor in "filling" the traces of such collisions will probably be the differential rotation of the galactic disk. That is, part of the disk of a spiral galaxy for some time becomes a gas-free elliptical galaxy. The search for such hybrid, symbiotic galaxies bearing traces of past collisions is an interesting new observational challenge. It is interesting that the accelerated diffusion of gas from disk galaxies toward their centers during bursts of star formation caused by collisions can be a product of an increase in the flaring of their gaseous disks, which, according to this last relation, reduces the diffusion time of the gas to the Keplerian time. This is observed in galaxies with bursts of star formation, whose star-formation rates are almost a factor of 100 higher than is usual for galaxies of their masses [68].

Let us consider the collisional evolution of galaxies in their clusters. Observations indicate that most galaxies are members of clusters with sizes of 0.5–3 megaparsec and masses of $10^{13}\ M_\odot$–$10^{15}\ M_\odot$ [55]. They are well described by Eq. (4) and the correlation $M \propto R^2$ (see Fig. 1), underscoring the previously noted possible leading role of clusters of galaxies in the formation of this correlation. The characteristic velocities of galaxies in clusters are $\sim$1000 km/s. Estimates based on Eq. (4) show that clusters collide with each other several times over the Hubble time, leading to a number of interesting phenomena. As is shown by numerical simulations, gravitational tidal drag leads to the approach of the most massive galaxies toward the cluster core and their coalescence into a supermassive cD galaxy with a mass of $\sim 10^{13}\ M_\odot$ [59]. The escape velocity at the edge of these galaxies approaches the characteristic velocities of the most massive galaxies in the cluster, leading to the high efficiency of their capture of neighboring galaxies. The cD cores of galaxies are the most likely places for SMBH mergers, and therefore the most effective generators of low-frequency bursts of GWs, marking the times of these megers.

Most collisions of disk galaxies occur at speeds exceeding the escape speeds at their edges. In the presence of comparable gas masses, this leads to the elimination of a gaseous component from the collision products and their transformation into elliptical galaxies with a small fraction of gas in the colliding galaxies [60]. We should note here that elliptical galaxies are already present in the dense nuclei of even young galaxy clusters at $z = 2$ [61]. It is possible that an initial burst of star formation in a sufficiently spherically symmetric galaxy can also clear it of gas through the action of massive supernovae [62]. A collision or close passage of two disk galaxies can lead to a powerful starburst. Such a burst of star formation can also remove the gas component of the galaxies. Indeed, it has long been noted that the proportion of elliptical galaxies in clusters increases by an appreciable factor over time. The fraction of elliptical galaxies in clusters reaches half of the total number of galaxies, while this fraction is about five percent in the field [63]. It is possible that the low proportion of elliptical galaxies in the field indicates the fraction of elliptical galaxies that are products of an original burst of star formation, and the high proportion of elliptical galaxies of clusters indicates the large role of collisions in their formation. Studies of the radial color gradients and metallicities of elliptical galaxies demonstrate that they do indeed grow with time due to the absorption of low-mass satellites [66]. Note that collisions of low-mass, gas-rich galaxies that deprive them of their gas also disrupt them, thus replenishing the population of the stellar medium in clusters of galaxies.

Collisions of gas-rich galaxies lead to bursts of star formation, and increased turbulent activity and gas viscosity in the galactic disk. This contributes to the accumulation of gas in the central regions of the galaxy. This is probably the nature of bursts of star formation in galaxies in which the time scale for star formation changes from the Hubble to the Keplerian time, or almost a factor of 100, according to estimates derived from observations. At the same time, the accumulation of gas in the galactic nucleus leads to the activation of star formation and the acceleration of gas accretion onto the SMBH. It follows that quasars can be activated not only by the disruption of an unstable accretion disk, similar to a dwarf nova, but also by collisions, and probably even fairly close passes of neighboring galaxies. Traces of past mergers and bursts of star formation can be revealed by analyses of the chemical and kinematic structure of the stars in the nucleus of our Galaxy [70].

Keeping elliptical galaxies free of gas is a problem that is resolved by the action of Type 1a supernovae.

They not only compensate for the radiative losses of hot gas, but also for masses of galaxies smaller than $\sim 10^{12}\ M_\odot$ that are capable of removing gas lost by old stars in galaxies [59]. In more massive cD galaxies, the action of Type Ia supernovae is insufficient to remove all gas from the deep potential wells in their central regions, and this gas is involved in supporting star formation in the nuclei of these galaxies. The characteristic star-formation rate in central galaxies of clusters is almost a factor of 100 higher than the rate of accretion of gas onto the central SMBHs [65]. Some of the gas of a cD galaxy can be obtained from the dense gaseous component of the nucleus of the parent cluster. The contribution of the motion of stars to gas heating in elliptical galaxies is estimated to be less than the contribution of supernovae. Simple estimates show that the hot wind of clusters of galaxies are heated mainly by the motion of the galaxies of a given cluster in its intergalactic gas.

The presence of SMBHs in the nuclei of galaxies leads to a number of additional effects in addition to the usual accretion of gas and the activation of quasars. Merging binary SMBHs are weak accretors due to the fast movement of the merging BHs. However, they can be powerful accelerators of stars of various types that "collide" with them. For example, single SMBHs in galactic nuclei accelerate the components of binary stars in the galactic nucleus [64]. The condition of energy conservation can be used to estimate the speed of the runaway star V, assuming that its companion that is captured by the SMBH is close to filling its Roche lobe: $V \sim v(M/m)^{1/3}$, where M is the SMBH mass, m is the mass of each of the components of the original binary star, and v is the escape velocity at the surface of the binary components. Assuming that the masses of the accelerated stars are $\sim M_\odot$, we find that SMBHs with masses greater than $\sim 10^5\ M_\odot$ can accelerate MS stars, degenerate dwarfs, NSs, and stellar BHs to relativistic speeds. Estimating the number of such superfast stars requires analysis of the efficiency of the diffusion feeding of a SMBH with binary stars from the host-galaxy disk and collisions of galaxies. Close binary SMBHs in galactic nuclei can also accelerate stars in their vicinity. However, since the semi-major axes of such systems are limited by GW radiation (2), the speeds of the stars that are lost in this process are limited to $\sim 400(M_{\rm BH}/M_\odot)^{1/8}$, regardless of their nature. Both both the observational discovery of superhigh-velocity stars and of observable manifestations of the ultrafast planetary nebulae created by them, with kinetic energies of the order of the energy of supernovae, are currently of great interest.

4. CONCLUSION

We have analyzed the most powerful effective stellar and galactic sources of gravitational waves, based on modern ideas about the evolution of multiple stars and galaxies. The most powerful sources of GWs are binary BHs with masses $5\ M_\odot - 10^{10}\ M_\odot$ (see Fig. 1). The characteristic coalescence times and orbital periods of merging BHs are $\sim 10^{-4} M_{\rm BH}/M_\odot$ s. The intensity of the GWs at the time of their coalescence does not depend on the masses of the merging BHs, and is equal to $\sim 10^{25}\ L_\odot$, which exceeds the luminosity of the entire Universe within $z = 1$: $\sim 10^{22}\ L_\odot$. The bursts of GWs [4] registered by LIGO have confired much of our modern understanding of the evolution of massive close binary stars [5, 7], suggesting that merging degenerate dwarfs remain the most promising model for Type 1a supernovae [2]. Figure 1 clearly demonstrates that the formation of binary systems that are sufficiently close for the activation of powerful GWs requires a significant reduction of their semi-major axes in the course of their evolution. This is effectively carried out via the common envelopes of stellar binaries and, during mergers, first of all, of massive galaxies (6). GW radiation is an active factor in the evolution of close binary stars with compact components, such as cataclysmic binaries and X-ray binaries with low-mass donors.

The merging of galaxies during their collisional evolution in dense cores of clusters is important for the activation of galactic sources of GWs—close SMBHs. Collisions can lead to the formation of both elliptical galaxies and fairly close SMBH systems, whose evolution can lead to the merging of the components and such systems. The observed correlation between the sizes of galaxies or clusters of galaxies and their masses (see Fig. 1 and Eq. (4)), which also limits the size of Galactic binary stars from above, is also interesting. The hypothesis that this correlation has a tidal nature requires additional verification and justification. The arguments presented above make it possible to keep elliptical galaxies free of gas and star formation due to Type 1a supernovae, which, in turn, are the products of GW radiation by close binary degenerate dwarfs.

Our analysis of the role of GWs in the evolution of binary stars and galaxies presented here enables the formulatioin of a number of topical problems, whose solutions will contribute to the expansion of our understanding of their evolution.

(1) Theoretical and observational aspects of the physics of common envelopes.

(2) The process of the coalescence of compact stars of various types and identification of ways to search for observable manifestations of this proces.

(3) The process of merging of galaxies with SMBH in their nuclei.

(4) The interaction of different types of stars with SMBHs in the nuclei of galaxies.

(5) Observational searches for and comprehensive studies of close systems of compact objects, which are promising from the point of view of the radiation of gravitational waves.

(6) Searches for super-high-velocity stars accelerated by SMBHs in galactic nuclei.

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