Populations of Ultraluminous X-ray Sources in Galaxies: Origin and Evolution

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Abstract—A model of the population of ultraluminous X-ray sources (ULXs) in binary systems with black hole (BH) accretors is constructed by hybrid population synthesis and is compared with the model of the population of ULXs with magnetized neutron stars (NSs) that can be observed as pulsating ULXs (Kuranov et al. 2020). A model of the formation of BHs whereby their mass is determined by the mass of the CO core immediately before its collapse ($M_{\text{CO}}$) and “delayed” and “rapid” collapse models (Fryer et al. 2012) are considered. The possible transiency of ULXs due to accretion disk instability is taken into account. The parameters and evolution of ULXs in galaxies with a constant star formation rate (SFR) and in those with an old stellar population after an instantaneous star formation burst are computed. The maximum number of ULXs with BHs ($\sim 10$) is reached in galaxies with a stationary $\text{SFR} = 10 M_\odot \, \text{yr}^{-1}$ $\sim 1$ Gyr after the beginning of star formation. ULXs observed after the end of star formation are close binary systems in which BHs and/or NSs formed before the end of star formation, while long-lived donors with a mass $\sim M_\odot$ continue to overflow their Roche lobes after its end or have filled their Roche lobes even later. Several Gyr after the end of star formation the number of ULXs in galaxies with a mass $M_g = 10^{10} M_\odot$ is no more than 0.1, most of them are ULXs with NSs. Persistent sources with a Roche-lobe-overflowing optical star dominate in ULXs with NSs, irrespective of the adopted star formation model. The transient sources are an order of magnitude fewer. The ULXs accreting from the stellar wind of the optical component are an order of magnitude fewer than the sources with accretion via Roche lobe overflow.

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INTRODUCTION

Ultraluminous X-ray sources (ULXs) with a luminosity exceeding the Eddington one $L_{\text{Edd}}$ for compact objects, neutron stars (NSs) and black holes (BHs) of stellar masses, have been in the spotlight of astrophysical research for several decades. The interest in them stems from the necessity of understanding the so powerful electromagnetic radiation due to accretion, which, in particular, may point to unusually high masses (100–1000 $M_\odot$) of BHs in binary systems, the so-called “intermediate-mass BHs” (Colbert and Mushotsky 1999). Such BHs are interesting from the standpoint of the origin and evolution of supermassive BHs in galactic nuclei (for a discussion, see the reviews by Cherepashchuk (2016) and Volonteri et al. (2021)). ULXs are encountered in galaxies of all types (see, e.g., Bernadich et al. 2021) and their lists are continuously supplemented. The most complete catalog of those published by the time of writing this paper (Walton et al. 2021) contains 1843 ULX candidates in 951 galaxies.

Fabrika and Mescheryakov (2001) and King et al. (2001) independently suggested that the observed super-Eddington luminosities of ULXs result from the focusing of radiation by a supercritical accretion disk around a stellar-mass compact object. With the discovery of pulsed X-ray emission from ULXs (Bachetti et al. 2014), it was confirmed that not only BHs, but also magnetized NSs in close binary systems can be the accreting components of ULXs. The nature of ULXs is actively discussed (see, e.g., the reviews by Kaaret et al. (2017) and Fabrika et al. (2021)).

This paper is a continuation of the study by Kuranov et al. (2020, Paper I), in which the population of ULXs with magnetized neutron stars (NULXs) in a spiral galaxy like to the Milky Way...
Way was considered. In this paper we consider ULXs with accretors—stellar-mass BHs (BHULXs, $M_{\text{BH}} \lesssim 100 \ M_\odot$) and magnetized NSs in model galaxies with continuous and instantaneous star formation (SF). The former and the latter can serve as an approximation for spiral and elliptical galaxies, respectively. Thus, we investigated almost complete models of ULX populations (except for the still hypothetical sources with intermediate-mass BHs and ULXs in star clusters). In the context of this paper, we consider all high-luminosity X-ray sources with accreting NSs and call them NULXs, irrespective of whether they can be observed as pulsating ULXs.

By the time of core collapse, massive stars in close binary systems (CBSs) lose almost completely their hydrogen and helium envelopes (see, e.g., Tutukov et al. 1973; Laplace et al. 2021). A decrease in the mass of the collapsing core through neutrino losses leads to the loss of hydrostatic equilibrium by the stellar envelope and the ejection of part of its material; the energy source is hydrogen recombination (the Nadezhin–Lovegrove effect, Nadezhin 1980; Lovegrove and Woosley 2013). Taking this fact into account, we considered a model in which the gravitational mass of the forming BH is 90% of the baryonic mass of the presupernova CO core (hereafter model C). Taking into account the existing uncertainties regarding the stellar collapse mechanism, we also considered and compared the populations of ULXs in which the BH formation occurs via “delayed” (model D) and “rapid” (model R) collapse (Fryer et al. 2012). We also analyzed the influence of assumptions about the most important parameters of the evolution of CBSs with compact objects—the so-called “efficiency of common envelopes” and the magnitude of the natal kick, which accompanies the formation of compact objects. Below we describe the main assumptions and the method of computations and present and discuss their results, which are compared with the results of other authors. The Appendix gives the examples of typical evolutionary tracks for CBSs that pass through the ULX stage computed by the MESA evolutionary code (Paxton et al. 2011).

**THE METHOD OF COMPUTATIONS**

As in Paper I, we implemented a hybrid approach to population synthesis—a combination of a rapid simplified computation using analytical formulas before the Roche lobe overflow by the optical star with a companion, a compact object, with a subsequent detailed computation of the stage with mass transfer using a full evolutionary code. This approach allows us to investigate the pattern of mass transfer in CBSs much more accurately than does the population synthesis code and to determine the duration of the accretion stage and, consequently, to estimate more carefully the luminosity of the model sources, their number, and other characteristics. A similar hybrid method has already been used to simulate ULXs, (see, e.g., Shao and Li 2015; Shao et al. 2019) and the merger rate of binary BHs (Gallegos-Garcia et al. 2021). All our computations were performed for stars with metallicity $Z = 0.02$. The characteristics of the ULX population in a stellar system (galaxy) are determined by the star formation history, initial CBS parameters (such as, for example, the initial mass function of primary components), and evolutionary factors: the mass loss via the stellar wind, the pattern of mass transfer through which the progenitors of the accretors pass, the core collapse mechanism of their progenitors, and the magnitude and orientation of the natal kick that the compact object gets during its formation. The statistical distributions of CBSs in initial mass function of primary components, separations between the components, component mass ratios, and orbital eccentricities were taken into account. For BHs we considered the above-mentioned collapse mechanisms and various assumptions about the magnitude of the natal kick.

At the first stage of our computations we used a updated version of the BSE code (Hurley et al. 2002; see Paper I). The further stellar evolution was computed with the MESA code (Paxton et al. 2011, version 12778). To construct the ULX population model, the formation probability of individual systems computed with the population synthesis code was convolved with the star formation rate (SFR) and the duration of the mass transfer stage in individual systems found from our MESA computations.

The loss of angular momentum during the CBS evolution was described by the equation suggested by Soberman et al. (1997) that takes into account the mass transfer from the accretor to the accretor, the mass loss by the system from the donor vicinities (re-ejection), and the outflow of matter through the Lagrange point $L_2$. As in Paper I, it was assumed that $\gamma_{\text{mt}} \sim 0.1$, while the radius of the coplanar circumstellar disk is $\gamma_{\text{mt}} a$, where $\gamma_{\text{mt}} = \sqrt{3.0}$.

The mass loss rate by O–B stars was computed using the “Vink” option in the MESA code based on the algorithms suggested by Vink et al. (2000, 2001).
The mass loss by Wolf–Rayet stars was described by the formulas from Nugis and Lamers (2000).

To determine the masses of the compact remnants (NSs and BHs) in the cases of rapid and delayed collapse, we used the parametrization of the results of calculations by Fryer et al. (2012) suggested by Giacobbo and Mapelli (2018). The relations between the masses of BHs and the ZAMS masses of their progenitors are shown in Fig. 1. These relations are consistent with the conclusions of Smartt (2015) based on supernova observations that the bulk of the BH progenitors have masses greater than 18–20 $M_\odot$. The accuracy of the Giacobbo–Mapelli relations is sufficient for population synthesis, although it should be noted that some computations of the models of collapsing stars show that NSs can also have higher-mass progenitors (see, e.g., Ertl et al. 2020). The Giacobbo–Mapelli relations, in principle, make it possible to estimate the NS masses up to the maximum ones, but we assigned a mass of 1.4 $M_\odot$ to all NSs and limited the BH masses from below by 2.15 $M_\odot$ corresponding to the maximum estimated mass of the observed pulsars $M = 2.08 \pm 0.07$ $M_\odot$ (PSR J0740 + 6620, Fonseca et al. 2021).

Note the increase in BH masses along the sequence of models D–R–C and the absence of BHs with masses below $\approx 4$ $M_\odot$ in model C. The natal kicks in model C are smaller than those in model D. These facts lead to differences in the number of ULXs and differences in the distributions of ULX populations in components masses and orbital periods. The “step” in the distribution of remnant masses in the case of rapid collapse is associated with the existence of a range of masses for stars that experience direct CO core collapse (Fryer et al. 2012).

As a rule, CBSs pass through common envelopes during the formation of ULXs. At the “fast” stage of our BSE computations before the formation of CBSs with BHs, we assumed that the common envelopes are formed as a result of the mass loss by the donors—red (super)giants with convective envelopes in the dynamic time scale; we used the criteria for the formation of common envelopes dependent on the component mass ratio and the relative donor core mass built into the BSE code. To treat the change in separation between the components, we adopted the $\alpha \lambda$ formalism of Webbink (1984) and de Kool (1990), which is based on a comparison of the orbital energy of the system and the binding energy of the donor’s envelope. We considered three values of the so-called “efficiency of common envelopes” $\alpha_{\mathrm{ce}} = 0.5$, 1, and 4. The parameter $\lambda$, which characterizes the
binding energy of the donor envelope, was taken from Loveridge et al. (2011). In a rough approximation, the separations between the components before the formation of a common envelope, $a_0$, and after its loss, $a_f$, are related as $a_f \propto \alpha_{cc} \lambda a_0$. If the CBS components merged in the common envelope, then the computations of the system evolution were terminated. Note that $\lambda$ is one of the most uncertain computation parameters (Ivanova et al. 2013, 2020). At the stage of accretion onto BHs, the formal criteria for the formation of common envelopes were not used. As was shown by McLeod et al. (2018) and studied in detail by Klencski et al. (2021a), the Roche lobe overflow by a red supergiant with a convective envelope onto the compact object companion, is followed by the stage of relatively stable mass loss, which passes into the stage of mass loss in the dynamic time scale. If the donor “confinement” in the Roche lobe became impossible during the MESA computations, which numerically manifested itself as a divergence of the code (see the lower right panel in Fig. 14 in the Appendix), then we assumed that the components merged. The period from the attainment of luminosity $10^{39} \text{erg s}^{-1}$ by the accretor to the merger of the components or the drop in luminosity below the specified limit, if the components did not merge, was taken as the lifetime of the system at the ULX stage.

Before the Roche lobe overflow by the primary (the initially more massive component, the BH progenitor), its evolution was deemed quasi-conservative. Only the loss of mass and angular momentum through the stellar wind was taken into account (at $T_{\text{eff}} \geq 10^{000} \text{K}$ according to Vink (2001) and at lower $T_{\text{eff}}$ according to de Jager et al. (1988)). The tidal interaction of the components was treated according to the algorithm adopted in BSE (see Hurley et al. 2002, Sect. 2.3).

It was assumed that BHs, like NSs, acquire an additional space velocity during their formation. The amplitude and distribution of the additional velocity during the BH formation are model parameters. At present, there is no consensus on this issue: for the arguments, see White and Van Paradis (1996) in favor of an insignificant velocity amplitude and the opposite point of view in the later paper by Atri et al. (2019). Two cases were considered: the kick whose amplitude is defined as $v_k = (1 - f_k) v$, where $v$ obeys the Maxwellian velocity distribution with dispersion $\sigma = 265 \text{ km s}^{-1}$ suggested for radio pulsars (Hobbs et al. 2005), while the parameter $f_k$ is determined by the fraction of the final stellar mass $M_{\text{fin}}$ infalling onto a neutron protostar with a mass $M_{\text{prot}}$ during the collapse: $f_b = M_{\text{fb}}/(M_{\text{fin}} - M_{\text{prot}})$; and the case of a Maxwellian velocity distribution with a mean velocity of $30 \text{ km s}^{-1}$ (see Fig. 1).

Omitting the well-known details, we will only note that in the context of ULXs it is important that the collapse mechanisms differ by the masses of the forming BHs. This fact and the magnitude of the natal kick accompanying the BH formation lead primarily to differences in the fraction of binary systems that remain bound during the first supernova explosion in the system and can potentially give rise to ULXs in the course of further evolution.

**Calculation of the X-ray Luminosity**

The X-ray luminosity $L_X$ in the case of accretion onto BHs and NSs is calculated based on the accretion rate of captured matter $\dot{M}_X$. If the optical component overflows its Roche lobe, then the accretion proceeds in the disk regime, $\dot{M}_X = \dot{M}_O$, where $\dot{M}_O$ is the mass loss rate by the optical star through the inner Lagrange point obtained from the MESA computations (see the examples in Fig. 14). If the optical star does not fill its Roche lobe and the mass loss occurs through the stellar wind, then the mass capture rate by the compact object is calculated using the Bondi–Hoyle–Littleton accretion formulas for a spherically symmetric wind. For example, for a circular orbit with a semimajor axis $a$, $\dot{M}_X = \frac{1}{4} \dot{M}_O \left( \frac{R_B}{a} \right)^2 \sqrt{1 + \left( \frac{v_x}{v_w} \right)^2}$, where $R_B = \frac{2GM_X}{v_w^2 + v_x^2}$ is the Bondi gravitational capture radius, $\dot{M}_X$ is the mass of the compact object, $v_w = v_p(M)(1 - R_O/a)^{1/2}$ is the stellar wind velocity at the orbit of the compact object, $v_x$ is the orbital velocity of the compact object, and $v_p = \sqrt{2GM_O/R_O}$ is the parabolic (escape) velocity on the photosphere of the optical star with mass $M_O$ and radius $R_O$. For elliptical orbits, the accretion rate from the wind depends on the orbital phase. In our computations we used the accretion rate averaged over the orbital period $P$, $\langle \dot{M}_X \rangle \approx \frac{1}{P} \int \dot{M}_X(t) dt = \frac{1}{P} \int \dot{M}_X(E)(dt/dE) dE$ ($E$ is the eccentric anomaly). For the adopted law of stellar wind variation with distance from the stellar photosphere and at $R_O/a \lesssim 0.3$, the averaged accretion rate increases weakly with eccentricity. Therefore, we neglect the dependence of the accretion rate averaged over the orbital period on orbital eccentricity. The average Bondi accretion rate from the stellar wind depends most strongly on the ratio $R_O/a$: $\langle \dot{M}_X \rangle \approx (1/64)\dot{M}_O \left( \frac{M_X}{M_O} \right)^2 \left( \frac{R_O}{a} \right)^2 \left( 1 - \frac{R_O}{a} \right)^2$.

We did not consider the possible gravitational focusing of the stellar wind, which can change the accretion efficiency, because it strongly depends on the assumed wind acceleration mechanism (El Mellah 2019).
We also neglected such effects as the wind Roche lobe overflow (Plavec et al. 1973) and the possible decrease in the parabolic (escape) velocity on the surface of the optical star due to the tidal effects (Hirai and Mandel 2021).

In the case of disk accretion, the X-ray luminosity is \( L_X = 0.1 M_X c^2 \) (where \( c \) is the speed of light). In the case of accretion onto magnetized NSs, we take into account the possibility of quasi-spherical accretion and a modification of “standard” Shakura–Sunyaev disks in the presence of a magnetic field (for more details, see Paper I). We took into account the possible cumulative instability of accretion disks. The disk stability criterion from Dubus et al. (1999) was used: a source is deemed a transient if the rate of mass inflow into the disk is less than some critical value, \( M_{\text{cr}} \), dependent on the masses of the components and the radius of the outer accretion disk edge. In quiescence, matter is accumulated in the disk. The accumulated disk mass is defined as \( M_{\text{disk}} = M_0(t) \Delta t \), where \( \Delta t = 30 \text{ yr} \) is the average time between outbursts chosen by us based on the calculations by Hameury and Lasota (2020) (see also Coriat et al. 2012). The accretion rate onto the compact object in the active state is assumed to be \( M_X = M_{\text{cr}} \). The duration of the outburst of a transient source (\( \Delta t_{\text{outb}} \)) is determined by the ejection of the entire accumulated disk mass: \( \Delta t_{\text{outb}} = M_{\text{disk}} / M_X \). At an accretion rate below a certain limit (0.001\( M_{\text{cr}} \)) the disks were assumed to be stable.

The detection probability of a transient source in its active state is determined by the ratio of the time the source stays in the outburst \( \Delta t_{\text{outb}} \) and the duration of the entire cycle: \( p_{\text{outb}} = \Delta t_{\text{outb}} / (\Delta t_{\text{outb}} + \Delta t) \). We assumed that the transience pattern of disk accretion is the same for BHs and NSs and is possible for the disks forming via the Roche lobe overflow and through the capture of matter from the stellar wind. Under supercritical disk accretion onto BHs, \( \dot{M}_X > \dot{M}_{\text{Edd}}(M_X) \), the beaming of X-ray radiation from the inner parts of the disk is taken into account. In this case, the luminosity of spherically symmetric radiation derived from the observed X-ray flux and the distance to the source is \( L_X = \frac{1 + \ln \dot{m}_0}{b} \dot{m}_0 L_{\text{Edd}}(M_X) \), where the beaming factor \( b = \max(10^{-3}, 73/\dot{m}_0^2) \), \( \dot{m}_0 = \dot{M}_X/\dot{M}_{\text{Edd}} \) (King 2009). When modeling the population of such sources, we took into account the fact that the detection probability of a system with a BH at the supercritical accretion stage is inversely proportional to the beaming factor \( b \). An example of the evolutionary track computed by the MESA code with the phase of a transient ULX at the stage of Roche lobe overflow by the optical component in case B of mass loss (after the main sequence) is shown in Fig. 15 in the Appendix.

In the case of disk accretion onto a NS with a magnetic field, the relation between the magnetospheric radius and the spherization radius, at which the local energy release exceeds the Eddington limit and an outflow of matter begins, becomes important (for more details, see Paper I and references therein as well as Grebenev 2017). Under supercritical accretion onto magnetized NSs, the beaming is determined by the geometrically thick edge of the supercritical disk at the magnetospheric boundary, \( H/R \sim 1 \), so that \( b \sim 1/2 \) (see Paper I, the theoretical calculations in Mushtukov et al. (2021), and the estimate of the beaming factor \( b \sim 0.25 \) from the observations of NGC 300 ULX-1 harboring a NS (Binder et al. 2018)).

**RESULTS OF OUR COMPUTATIONS**

Table 1 provides a list of the ULX formation models considered and their parameters and, as an example, the calculated number of ULXs for a model galaxy with a constant star formation rate, 1 \( M_\odot \text{ yr}^{-1} \), over 10 Gyr. For comparison, the number of NULXs calculated in Paper I by assuming a log-normal distribution of the NS surface magnetic field with a typical strength \( \log B = 12.5 \text{ G} \) is given in the table. Since in our model all NSs are formed with the same mass of 1.4 \( M_\odot \) and get the same natal kicks with \( \sigma(v_k) = 265 \text{ km s}^{-1} \), the cells in the table for NSs corresponding to \( \sigma(v_k) = 30 \text{ km s}^{-1} \) were left blank. However, such NULXs are taken into account when calculating the total number of sources in the models.

Let us consider in more detail the change in the distributions of parameters (component masses and orbital periods) for CBSs in which ULXs with BHs are formed at various evolutionary stages.

As the main versions of our computations, we consider the models of complete stellar core collapse (C in the table) and delayed collapse (D) with \( \alpha_{\text{ce}} = 1 \) and a Maxwellian distribution of natal kicks with \( \sigma(v_k) = 265 \text{ km s}^{-1} \) taking into account the scale factor \( f_b \) determined by the fraction of presupernova matter infalling onto the proton-neutron star (models C265-1 and D265-1).

Figures 2 and 3 show the successive change in the parameters of CBSs—the progenitors of systems in which the BH companion overflows its Roche lobe in the course of evolution and reaches the ULX stage after an instantaneous star formation burst in the models C265-1 and D265-1, respectively. We selected the systems based on our BSE computations. Their further evolution is computed using the MESA code to estimate the possible lifetime as a ULX (X-ray
Table 1. The number of ULXs with different accretors and types of mass transfer between the components at 10 Gyr after the beginning of star formation in a model galaxy with a constant star formation rate, $1 \, M_\odot \, \text{yr}^{-1}$, for various compact-object formation models, the distribution of their natal kicks, and the common-envelope efficiency parameter $\alpha_{\text{ce}}$. The accretion occurs via mass transfer through the vicinities of $L_1$ in the BH_RLOF and NS_RLOF systems and via the stellar wind in the BH_wind and NS_wind systems. The number of persistent sources is given in parenthesis.

| Model   | Compact object formation mechanism | $\sigma(v_k)$ (km s$^{-1}$) | $\alpha_{\text{ce}}$ | N ULXs | N BH_RLOF | N BH_wind | N NS_RLOF | N NS_wind |
|---------|----------------------------------|-----------------------------|----------------------|--------|------------|------------|------------|------------|
| C265-05 | CO                               | 265 0.5                     | 0.88                 | 0.40   | 0.03       | 0.44       | 0.007      | (2 x 10$^{-4}$) |
|         |                                  |                             | (0.76)               | (0.32) | (<10$^{-3}$) | (0.44)     |            |            |
| C265-1  |                                  | 265 1.0                     | 1.49                 | 0.36   | 0.62       | 0.51       | 0.008      | (2.4 x 10$^{-4}$) |
|         |                                  |                             | (0.76)               | (0.25) | (0.005)    | (0.50)     |            |            |
| C265-4  |                                  | 265 4.0                     | 3.38                 | 0.02   | 0.10       | 3.15       | 0.101      |            |
|         |                                  |                             | (3.31)               | (0.02) | (0.063)    | (3.14)     |            |            |
| C30-05  |                                  | 30 0.5                      | 1.58                 | 1.08   | 0.05       |            |            |            |
|         |                                  |                             | (1.22)               | (0.78) | (0.004)    |            |            |            |
| C30-1   |                                  | 30 1.0                      | 1.84                 | 0.72   | 0.61       |            |            |            |
|         |                                  |                             | (0.96)               | (0.44) | (0.017)    |            |            |            |
| C30-4   |                                  | 30 4.0                      | 3.51                 | 0.04   | 0.22       |            |            |            |
|         |                                  |                             | (3.43)               | (0.03) | (0.172)    |            |            |            |
| D265-05 | Delayed                          | 265 0.5                     | 0.75                 | 0.11   | 0.19       | 0.44       | 0.007      | (2 x 10$^{-4}$) |
|         |                                  |                             | (0.54)               | (0.10) | (0.001)    | (0.44)     |            |            |
| D265-1  |                                  | 265 1.0                     | 0.78                 | 0.07   | 0.20       | 0.51       | 0.008      | (2.4 x 10$^{-4}$) |
|         |                                  |                             | (0.56)               | (0.05) | (0.001)    | (0.50)     |            |            |
| D265-4  |                                  | 265 4.0                     | 3.41                 | 0.04   | 0.11       | 3.15       | 0.101      |            |
|         |                                  |                             | (3.27)               | (0.04) | (0.004)    | (3.14)     |            |            |
| D30-05  |                                  | 30 0.5                      | 0.89                 | 0.15   | 0.29       |            |            |            |
|         |                                  |                             | (0.54)               | (0.10) | (0.00)     |            |            |            |
| D30-1   |                                  | 30 1.0                      | 0.88                 | 0.07   | 0.29       |            |            |            |
|         |                                  |                             | (0.54)               | (0.03) | (0.005)    |            |            |            |
| D30-4   |                                  | 30 4.0                      | 3.49                 | 0.04   | 0.20       |            |            |            |
|         |                                  |                             | (3.29)               | (0.02) | (0.042)    |            |            |            |
| R265-1  | Rapid                           | 265 1.0                     | 0.81                 | 0.07   | 0.23       | 0.51       | 0.008      | (2.4 x 10$^{-4}$) |
|         |                                  |                             | (0.57)               | (0.05) | (0.008)    | (0.50)     |            |            |
| R30-1   |                                  | 30 1.0                      | 0.63                 | 0.03   | 0.09       |            |            |            |
|         |                                  |                             | (0.53)               | (0.02) | (0.003)    |            |            |            |
Fig. 2. Evolution of close binary stars that gives rise to systems with BHs and Roche-lobe-overflowing optical components. The figure corresponds to the model C265-1 with $\alpha_{ce} = 1$ and a Maxwellian distribution of natal kicks with $\sigma = 265$ km s$^{-1}$. The figure shows the relations between the masses of the components and orbital periods on the zero-age main sequence (ZAMS), by the beginning of the first mass transfer in the system (RLOF1i) and at its end (RLOF1f), before the formation of the compact object (before collapse) and after its formation (after collapse). The color scale marks the evolutionary stages of the components in accordance with the BSE notation: 1—the ZAMS, 2—the Hertzsprung gap, 3—the core He-burning stage, 4—the first red giant branch, 5—the early asymptotic giant branch (AGB) stage, 6—the late AGB stage, 7—the helium remnant of the star after the envelope loss, 8—the He stars in the Hertzsprung gap. The black dots mark the compact object. At the Roche lobe overflow (RLOF) stage the CBS components with stable mass loss and the ones encountering the common envelope are indicated by the circles and stars, respectively. The symbols in the figure do not have any absolute values associated with the birthrate of CBSs with the corresponding parameters, but indicate the “motion” of the computational grid points and their evolutionary status. The lower right panel shows the relations between the parameters of the stars in a CBS at the time of RLOF by the BH companion; the color scale corresponds to the number of systems per galaxy mass $M_G = 10^{10} M_\odot$. 

$P_{\text{orb}} (d)$

$M_2$

$M_1$

$N_{\text{PreBH + RLOF, BSE}}$

$10^1$ $10^2$ $10^3$ $10^4$
luminosity $L_X > 10^{39}$ erg s$^{-1}$) and the number of ULXs in the population with a specified star formation model (as an example, see Eq. (11) for the Milky Way in Paper I). It is assumed that by the time the BH companion overflows its Roche lobe, the orbit had time to be circularized (in accordance with the formalization of this process in BSE). The dots in the left column of panels and on the upper two right panels correspond to the points of the grid of the initial parameters that traverse the entire evolutionary path from ZAMS to the formation of BH (not normalized). The bulk of the BH progenitors fill their Roche lobes on the main sequence and in the Hertzsprung gap. As a result of the Roche lobe overflow, the components of a significant fraction of CBSs merge; the survived systems become closer if they have passed through

Fig. 3. Same as Fig. 2 for the model D265-1.
the common envelope in which the masses of the accretors barely change; in systems with mass transfer the separation between the components grows, the masses of the accretors increase; the primary components reach the stage of giants or, having lost the envelope, become helium stars (see the RLOF1f panels). In the course of evolution, the giants, which, as a rule, are massive, also lose the remnants of the helium envelopes via the stellar wind (see the “before collapse” panel). Note the wide range of masses of the companions of future BHs—from \( \sim 1 \) to \( \sim 100 \, M_\odot \), and the long orbital periods of a number of systems. Because of these facts, first, the optical components of ULXs can be red giants, as confirmed by observations (see, e.g., López et al. 2020), and, second, the formation of ULXs is possible after the end of star formation, providing the existence of ULXs in elliptical galaxies.

A comparison of Figs. 2 and 3 shows, in accordance with Fig. 1, that, in view of the adopted parametrization of the BH formation, the BHs in model C are relatively more massive than those in model D. In model C there are no BHs with masses less than \( 3 \, M_\odot \) as defined by the masses of the CO cores of their progenitors, whereas in model D the BH masses can extend to the maximum NS masses. Because of the larger natal kicks in model D, there are fewer low-mass donors and the maximum ULX periods are also shorter. We do not consider model R in detail, because in this model the BH masses and natal kicks are close to their values in model D (Fig. 1) and, as a result, it leads to a ULX population similar to that in model D (see Table 1).

Table 1 gives the total number of ULXs in our models. As mentioned above, some of the sources can be transient ones due to the accumulation instability of accretion disks, whose formation is characteristic of low accretion rates. According to our computations, in the models C265-1 and D265-1 approximately 70% of all sources with BHs in which the donor overflows its Roche lobe are persistent sources. The number of sources with a wind is a pop factor of 2–3 greater than the number of sources with Roche lobe overflow due to the continuous reproduction of systems with massive donors with a powerful wind. However, for the same reason, almost all of the sources with wind-accreting BHs are transient ones. Persistent sources absolutely dominate among the objects with NSs with Roche-lobe-overflowing donors, while transients dominate among the objects with a wind. The fraction of persistent sources, as a rule, grows with \( \alpha_{ce} \), because an increase in the component separation corresponds to an increase in \( \alpha_{ce} \) and the captured wind does not generate a luminosity higher than \( 10^{39} \, \text{erg} \, \text{s}^{-1} \). A decrease in \( \alpha_{ce} \) also leads to an increase in the fraction of persistent sources with Roche lobe overflow; the number of persistent sources with a wind decreases, because fewer systems reach the evolutionary stages with a sufficiently strong wind.

Figure 4 illustrates the evolution of the relationship between persistent and transient sources in the cases of an instantaneous star formation burst and star formation with a constant rate over 1 Gyr. In the first case, among the systems in which the donor overflow its Roche lobe, persistent sources dominate over \( \sim 3 \) Gyr, i.e., as long as the donors are stars with masses slightly larger than \( M_\odot \). For lower-mass donors the rate of mass loss (accretion onto the BH) is too low for the existence of stable disks. In the case of systems with donors that do not overflow their Roche lobes, persistent sources exist only for the first \( \sim 30 \, \text{Myr} \) as long as there are donors with masses exceeding about \( 7 \, M_\odot \) with a sufficiently strong wind at the stage of giants. For all of the remaining evolution time, except for the first several tens of Myr, transient sources in systems with a wind are the dominant population.

In the model D265-1 the situation is qualitatively the same with some differences attributable to the difference of the BH and donor masses. In the case of star formation over 1 Gyr, transient sources prevail over persistent ones over the star formation time and approximately the same time after its end due to the reproduction of systems with massive donors. Then, the numbers of persistent and transient sources become equal. The existence of ULXs after the end of star formation is possible due to the presence of binary systems with donors of low and moderate masses (\( \lesssim 2 \, M_\odot \)) overflowing their Roche lobes much later than the end of star formation.

In the case of NULXs, systems with Roche-lobe-overflowing donors always dominate. In these systems the donor wind is, as a rule, not strong enough to provide a luminosity exceeding the \( 10^{39} \, \text{erg} \, \text{s}^{-1} \) threshold.

**Dependence of ULX Characteristics on Population Age**

As mentioned in the Introduction, ULXs are observed in both early and late galaxies. At the same time, they differ in characteristics (Walton et al. 2021; Bernadich et al. 2021). Therefore, it is interesting to find out how the ratio of NULXs and BHULXs changes for different BH formation models and types of mass transfer (Roche lobe overflow or wind accretion), depending on the star formation parameters and population age. The question of which sources can prevail in galaxies of different ages, BHULXs or NULXs, is related to the same problem. As above, we consider in detail the BH formation models C and D.
Fig. 4. Evolution of the number of ULXs with persistent (solid lines) and transient (dashed lines) disk accretion for an instantaneous star formation burst (left panels) and constant star formation over 1 Gyr with SFR = 10 $M_\odot$ yr$^{-1}$ (right panels) for the models C265-1 and D265-1 (upper, middle, and lower rows, respectively).
We considered three models for the formation of populations in galaxies with a mass of $10^{10} M_\odot$: instantaneous star formation, star formation with a constant SFR = $10 M_\odot$ yr$^{-1}$ over 1 Gyr, and star formation with a constant SFR = $1 M_\odot$ yr$^{-1}$ over 10 Gyr. In the latter case, we took the estimate for the formation time of the Galactic thin disk from Miglio et al. (2021).

Figure 5 presents the results of our computations of the change in the number of ULXs with BH and NS with time for the three star formation histories considered and different BH formation mechanisms. For comparison, we chose the population models in which the common envelope parameter $\alpha_{ce} = 1$ was used in the computations of evolution leading to ULXs.

All of the models with different star formation have a common feature—rapid formation of ULXs and a rapid decrease of their number with the termination of star formation. For the model C265-1 with star formation over 10 Gyr (in the right column in Fig. 5,
Fig. 6. Distributions of ULXs with a BH and a Roche-lobe-overflowing donor in component masses (upper panels), orbital periods (lower left panel), and X-ray luminosity (lower right panel) as a function of time after the star formation burst. The upper and lower plot show the models C265-1 and D265-1, respectively. The distributions are normalized to the galaxy mass $M_G = 10^{10} M_\odot$. 

$M_{BH}$ variations from 2 to 17, $\log P_{orb}(d)$ from $-0.3$ to 3.9, and $\log L_x$ from 39 to 41.75 are shown.
this is illustrated by demonstrating a decrease in the number of ULXs up to a population age of 14 Gyr. In the model with an instantaneous star formation burst, the first BHULXs begin to form several million years after the outburst, with the collapse of the most massive stars and the attainment of the stage of giants by their companions. As a rule, the ULX stage is short (≤10⁷ yr, see the examples in the Appendix). Therefore, the number of BHULXs in all models decreases continuously. The number of BHULXs formed with small kicks decreases slightly more slowly than the number of sources in which the BHs acquired large kicks, but the difference is unimportant—two orders of magnitude in both cases. By 10 Gyr, the initial number of sources decreases by 4–5 orders of magnitude. Thus, if we take instantaneous star formation and the same mass for all model galaxies, then at t = 10 Gyr there should be one ULX with BH for several tens of galaxies.

As Fig. 4 shows, the “long-lived” sources with BHs are transient ones. The difference in the BH formation mechanisms leads to a difference in the number of BHULXs that at each instant of time does not exceed a factor of 2–3. Note the almost complete coincidence of the behaviors of models C and D.

In the more realistic cases of star formation over 1 and 10 Gyr, the number of BHULXs at the star formation stage slightly increases: the sources that have completed the ULX stage are replaced by newly formed sources with similar characteristics and, in addition, sources with lower-mass donors whose formation time is longer are added. After the end of the star formation stage, the number of ULXs remains almost constant for some time due to the existence of semidetached objects in which the BH companions are low-mass (∼1 M⊙) stars at the stage of mass transfer in case B (at the shell hydrogen burning phase). Then, the number of ULXs drops (see Figs. 7–12).

As an illustration, Fig. 6 shows the evolution of the BH masses M_BH, the donor masses M_2, the orbital periods P_orb, and the X-ray luminosity L_X in the models C265-1 and D265-1 after an instantaneous star formation burst. The models with longer star formation may be considered as a sum of such bursts, but on a smaller scale.

In the model C265-1 there are no BHs with masses greater than ∼9 M⊙ and BHs with M_BH ≈ (3–5) M⊙ dominate (see Fig. 1). In the model D265-1 BHs with masses ∼3 M⊙ dominate. BHs
with higher masses (up to $\approx 14 \, M_\odot$, Fig. 1) are also formed, but the lifetime of systems with high BH masses is short. In the model C265-1 BHULXs with $M_2 < 1.5 \, M_\odot$, which, as a rule, must be persistent, dominate after $t \approx 100$ Myr (Fig. 4). BHULXs with orbital periods $\lesssim 300$ days prevail over the entire evolution time. The same must be observed in the model with continuous star formation. The BHULX luminosities lie mostly within the range $10^{39} - 2 \times 10^{39}$ erg s$^{-1}$.

In the model D265-1 the BH masses are slightly lower than those in C265-1. The model D265-1 is virtually indistinguishable from C265-1 in donor mass—donors with masses $M_2 < 1.5 \, M_\odot$ also dominate, but the typical orbital periods in this model are $\lesssim 100$ days. The X-ray luminosities are slightly lower than those in the model C265-1; they exceed only slightly $10^{39}$ erg s$^{-1}$, because the accretion rates are lower in closer binary systems.

In Figs. 7–12 the models C265-1 and D265-1 are compared for the case of star formation with a constant SFR = 1 $M_\odot$ yr$^{-1}$ over 10 Gyr. For each model we compare the distributions of parameters for systems with Roche lobe overflow (BH_RLOF) and wind accretion (BH_wind). Basically, these are the characteristics of the population of ULXs with BHs in a spiral galaxy. For comparison, Fig. 13 shows the relations between the distributions in the same parameters for NULXs obtained in Paper I for the model with the standard characteristic magnetic field $\log B = 12.65$.

The characteristic features of the models are as follows. A concentration of the BH and donor masses to the minimum values and low values of the orbital periods, whose combination provides mass transfer stability, is typical for the model C265-1 for BH_RLOF. The most massive BHs allowed by model C (up to $\approx 11 \, M_\odot$) are absent among the “observed” BH_RLOF systems due to their short lifetime.

A smaller spread of BH masses with a lower concentration near the minimum values is typical for ULXs with wind accretion. In this case, the orbital periods are predominantly from $\approx 10$ to $\approx 50$ days, but can reach values exceeding 100 days. The donor masses can reach $\approx 70 \, M_\odot$. The latter implies the possibility of the existence of donors (super)giants, consistent with observations (for a detailed discussion, see the review by Fabrika et al. (2021)). Note the existence of donors with masses 1–2 $M_\odot$ and high
X-ray luminosities that are reached during outbursts. Most of the sources must be transient ones, consistent with the conclusions based on Fig. 4.

The luminosities of most BH_RLOF sources lie in the range \((1 - 3) \times 10^{39}\) erg s\(^{-1}\), i.e., at the threshold boundary of luminosities at which the objects are classified as ULXs. The bulk of the BH\_wind sources reach a luminosity of \(10^{40}\) erg s\(^{-1}\), but it should be kept in mind that this is the luminosity of the discharging accumulated disks.

A more uniform distribution of parameters is typical for the models D265-1 with Roche lobe overflow and wind accretion, because the spread of BH masses and natal kicks is larger than that in model C. Although in models D ULXs can have lower BH masses than those in models C, the upper limit on their masses is also close to 8 \(M_\odot\). Among the donors of the BH\_RLOF models there is no pronounced concentration to masses \(\lesssim 3 \, M_\odot\); just as in models C, there are donors with masses up to 100 \(M_\odot\), i.e., ULXs with supergiant components must be present in the population. In this “family” a significant fraction of sources have comparable masses, providing mass transfer stability. There are donors with masses \(\lesssim 25 \, M_\odot\); the corresponding sources must be transient. Just as among the models C265-1 BH\_RLOF, the overwhelming fraction of ULXs have luminosities no greater than \(~3 \times 10^{39}\) erg s\(^{-1}\), but there is a “tail” extending to \(3 \times 10^{41}\) erg s\(^{-1}\).

Basically, the models D265-1 BH\_wind differ from the models C265-1 BH\_wind, as do the models D265-1 BH\_RLOF, by a more uniform distribution of parameters. The BH masses do not have such a pronounced concentration to \((4 - 7) \, M_\odot\), but are uniformly distributed in the range \((3 - 8) \, M_\odot\). The fraction of systems with \(M_d \lesssim 25 \, M_\odot\) is insignificant; there are virtually no donors with masses below 20 \(M_\odot\). The range of orbital periods for D265-1 BH\_wind is the same as that for C265-1 BH\_wind, but with a lower concentration to relatively short periods. As a result, D265-1 BH\_wind systems are less concentrated in the luminosity range \(10^{39} - 10^{40}\) erg s\(^{-1}\). The limiting luminosity is the same: \((3 - 4) \times 10^{41}\) erg s\(^{-1}\).

ULXs with NSs (Fig. 13) differ from ULXs with BHs (C265-1 BH\_RLOF), except for the uniquely determined accretor mass, by a narrower range of donor masses (there are virtually no donors that are...
much less massive than 10 $M_\odot$) and a slightly larger range of orbital period that does not rule out supergiant donors in accordance with observations (see, e.g., Israel et al. 2017). Because of the destruction of the NS accretion disks when interacting with the NS magnetospheres (Paper I), the sources can have super-Eddington luminosities that almost reach $10^{41}$ erg s$^{-1}$, but the bulk of them must have $L_X \approx 10^{39} - 10^{40}$ erg s$^{-1}$.

**DISCUSSION OF RESULTS**

The presented results depend on the model assumptions that are commonly used in population synthesis computations.

- Compact object formation parameters.

  As noted above, the formation of ULXs with BHs is determined by the BH formation during stellar core collapse (the BH mass, a possible natal kick) and the accretion rate onto the compact object. The masses of the forming BHs in all of the models considered do not exceed 15 $M_\odot$. In our computations we used standard assumptions about the evolution of stars with solar chemical composition. In alternative scenarios (for example, chemically homogeneous evolution of massive stars in close binary systems; Marchant et al. 2017), in low-metallicity stars the BH masses can reach 60 $M_\odot$. In this case, the number of bright ULXs with $L_X > 4 \times 10^{39}$ erg s$^{-1}$ in galaxies with stationary star formation with SFR = 1 $M_\odot$ yr$^{-1}$ can be $\sim 0.13$. This is comparable to our computational result for solar chemical composition (see the lower left panel in Fig. 7).

- Stellar evolution parameters before the compact-object formation.

  One of the most significant uncertainties in describing the evolution of massive stars is associated with the mass loss through the stellar wind. As Figs. 2 and 3 show, by the time the BH progenitors overflow their Roche lobes, a significant fraction of them are giants and supergiants. There are observational and theoretical arguments that $\dot{M}_{\text{wind}}$ determined from observations and calculated theoretically, which are commonly used in the population synthesis and evolutionary codes, are overestimated (see, e.g., Beasor et al. 2021; Fink 2021). This also applies to the BSE and MESA codes. In that case, the separation between the components after the end of mass loss through the point $L_1$ must be larger than the adopted one, while for the common envelopes the reverse is true. In both cases, this can lead to a decrease in the total number of BHULXs. The number of wind-accreting sources, which are predominantly transient ones, can also increase.
As was noted by Kippenhahn and Weigert (1967) in their pioneering work on the evolution of close binaries, the CO cores of the helium remnants of stars after the mass loss during Roche lobe overflow are less massive than those of single stars with the same initial mass. The reason is that in single stars the masses of the helium cores increase as a result of shell hydrogen burning, while in the remnants of the components of binary systems the convective cores are reduced as a result of the wind mass loss. The difference in the core masses can lead to a difference in the values of the mass delimiting the NS and BH progenitors in single stars and binary components. It should be noted that, as a rule, the $M_{\text{in}} - M_{\text{fin}}$ relations for single stars are used in population synthesis codes.

The Number of ULXs

Figure 5 shows that by $t = 10$ Gyr in a galaxy with a constant SFR = $1 \ M_\odot \ yr^{-1}$ over 10 Gyr the total number of ULXs must exceed the number of ULXs in a galaxy of the same mass with instantaneous star formation approximately by a factor of 300. For a galaxy with a star formation burst lasting 1 Gyr the ratio is close to 15. However, these ratios may turn out to be not quite correct, given that the metallicity in old galaxies, as a rule, is significantly lower than the solar one. Unfortunately, the evolution of CBSs with $Z \ll Z_\odot$ has not been systematically studied. Only for the evolution of CBSs with donor masses up to $\approx 53 \ M_\odot$, $Z_{\text{Fe}}/Z_{\text{Fe,\odot}} \gtrsim 0.2$, and a fixed initial donor-to-compact object mass ratio of 0.6 did Klencki et al. (2020, 2021b) find that the mass transfer beginning at the core He-burning stage could occur both on a long nuclear time scale ($\approx 10^5 \ yr$) and a fast thermal time scale ($<10^5 \ yr$). The probability of the existence of semidetached ULXs with massive giant donors increases with increasing duration of the mass loss phase. In both cases, the hydrogen envelope is not lost completely. It is important that the “new” modes of mass loss do not raise significantly the BH progenitor mass threshold (up to $\approx 25 \ M_\odot$) and, as a result, the total number of BHULXs must change only slightly.

Since one of the main goals of our study was to consider the influence of parameters of the evolutionary scenario on the relative number of BHULXs and NULXs, in Table 2 we give the ratios of the numbers...
As Table 2 shows, at $\alpha_{ce} = 0.5$ and 1 the ratio of the numbers of BHULXs and NULXs is $\approx (0.5-2.5)$. The models with $\alpha_{ce} = 4$, for which the ratio is a few hundredths, drop out of the general trend. However, such a value of $\alpha_{ce}$ requires that an energy much greater than the orbital energy of the binary system be expended on dispersing the common envelope. Possible additional energy sources (for example, the release of recombination energy) and other processes accompanying the formation and ejection of common envelopes are actively studied, but they do not yet allow definite conclusions to be drawn and numerical simulations of this process to be performed (see Ivanova et al. (2020) and references therein). Therefore, given all the uncertainties and simplifications of the population synthesis, it can be argued that the numbers of ULXs with BH and NS accretors in the galaxies with a constant star formation rate are comparable. The same can also be stated for the models D265-1 and R265-1 (Fig. 5).

In the case of a population with instantaneous star formation at 10 Gyr after the star formation burst in the models C265-1, the numbers of BHULXs and NULXs must also be comparable (Fig. 5). In the model D265-1 by $t = 10$ Gyr the number of NULXs is higher than that of BHULXs approximately by a factor of 5. Remarkably, in the model R265-1 only NULXs remain by this time. The reason is that the most numerous BH progenitors with masses 20–35 $M_\odot$ (based on the initial mass function) give an excess of relatively massive BHs for a small kick and a small Blaauw effect (Fig. 1). Therefore, such systems remain close and they have greater chances to merge in the common envelopes at the second mass transfer stage. In addition, the closer the binary system, the smaller the chance that it will be transient.

Regarding the transient sources, it should be kept in mind that the duty cycle is primarily a function of the system’s orbital period and accretion rate and can differ by a factor of 2–3 from 30 years adopted by us toward both lower and higher values. Therefore, the number of transient sources is fairly uncertain. As noted by Hameury and Lasota (2020), for long duty cycles, which, according to their calculations, reach $\approx 60$ years, some of the sources that are observed as persistent ones may actually be transients in quiescence.

Note also that the membership in the NULX class is determined based either on observations of coherent X-ray pulsations (Bachetti et al. 2014) or on...
the presence of the cyclotron line scattering feature in the X-ray spectrum (Walton et al. 2018). Both signatures are sufficient, but not necessary, because the magnetic fields of accreting NSs can lie within a wide range, from $\sim 10^8$ to $\sim 10^{14}$ G. The pulsations of an accreting magnetized NS can be suppressed in the propeller mode (Tsygankov et al. 2016) or be washed away during the interaction of radiation with matter at the stage of supercritical accretion onto the NS magnetosphere (S.A. Grebenev, in preparation). The cyclotron feature in the X-ray spectrum of ULXs can be observed at a certain NS magnetic field, and its origin in radiation-dominated accretion columns requires additional studies. These selection effects can reduce the observed ratio of NULXs and BHULXs, leaving the most reliable criterion of a high compact-object mass as a signature of BHULXs in non-pulsating sources.

A significant uncertainty factor for the ratio of the numbers of NULXs and BHULXs is the rate of NS formation as a result of electron captures in stellar cores (Poelarends et al. 2017 and references therein). This phenomenon must be accompanied by small natal kicks (Dessart et al. 2006), reducing significantly the binary breakup frequency compared to the NS formation accompanied by a “standard” natal kick with $\sigma(v_k) = 265$ km s$^{-1}$.

**Comparison with Other Studies**

The theoretical studies of the ULX populations are few in number. Let compare our results with the studies of other authors using population synthesis. It was found in the computations with the Star-Track code by Wiktorowicz et al. (2017, 2019) that the number of NULXs for solar chemical composition exceeds the number of BHULXs 100 Myr after the end of a star formation burst. These authors did not use the hybrid method to compute the rate of mass transfer when the optical component overflows its Roche lobe, but they simulated populations of stars with various chemical compositions. Furthermore, it was assumed in these papers that the beaming factor is the same for supercritical accretion onto BHs and NSs, which is not the case for magnetized NSs (see our Paper I and the analysis by Mushtukov et al. (2021)). To within the adopted normalizations, the total number of ULXs in our computations (see Fig. 5), on the whole, is consistent with these results (see Fig. 2 in Wiktorowicz et al. (2017) and Fig. 1 in Wiktorowicz et al. (2019)).
In their recent paper Wiktorowicz et al. (2021) separately investigated the role of stellar wind accretion. However, their treatment of the Bondi–Hoyle–Littleton accretion for elliptical orbits differs significantly from that adopted by us. The accreted mass, when averaged over the orbital period, is virtually independent of the orbital eccentricity, while the approximate formula (2) in Wiktorowicz et al. (2021) depends on \( e \) as \( \sim 1/\sqrt{1-e^2} \). In several models considered by Wiktorowicz et al. (2021) the number of ULXs for wind accretion exceeds the number of ULXs for accretion after the optical star overflows its Roche lobe, which was not found in any of our models (see Fig. 5, the upper row). This is apparently related to a different treatment of the stellar wind accretion rate in the work of the Polish group.

After the discovery of the first pulsating source M82 X-2 (Bachetti et al. 2014), Shao and Li (2015) considered a model of ULXs with NS accretors, but, in contrast to our Paper I, they ignored the peculiar effects due to the interaction of NS magnetospheres with accretion disks. They assumed a constant beaming factor \( b = 0.1 \) for all accreting NSs. Model systems with \( L_x > 10^{39} \text{ erg s}^{-1} \) were selected. Thus, by adopting a specific population formation history, the model by Shao and Li (2015) may be considered as a model of the complete sample of NSs in the population reaching a high luminosity due to a fixed geometrical factor. Taking the star formation rate for the Galaxy to be \( 3 \, M_\odot \, \text{yr}^{-1} \) over 13 Gyr, Shao and Li estimated that in the Galaxy there must currently exist about 30 ULXs with NSs (with donor masses greater than \( 2 \, M_\odot \)), which slightly exceeds our estimate of \( \sim 1 \) system per \( 1 \, M_\odot \), even if we take into account the fact that, according to Paper I, we took the beaming factor to be \( \approx 0.3 \).

The same authors (Shao and Li 2020) found that \( \sim 10 \) ULXs with BHs could exist in the Galaxy (with the star formation history described above). They used the model by Raithel et al. (2018), in which the helium core of a presupernova collapsed (given the Nadezhin–Lovegrove effect), while the natal kicks were modeled by the distribution from Hobbs et al. (2005) with a scale factor \( 3 \, M_\odot/M_\text{BH} \). Given the differences in the assumptions about star formation, presupernova masses and natal kicks, this model is roughly consistent with our model C265-1 for BHULXs.

In contrast to the papers by Wiktorowicz et al., Shao and Li used, like us, the hybrid population synthesis method and the rate of accretion onto the compact object from the stellar wind averaged over the orbital period for elliptical orbits, but did not consider the formation of transient ULXs via accretion from unstable disks around compact objects.

Thus, the main differences between our computations and the above studies are that we took into account the possibility of transient accretion onto the compact object, which gives rise to ULX both when the optical star overflows its Roche lobe and for accretion from the stellar wind in semidetached systems and the treatment of accretion onto magnetized NSs (for more details, see Paper I). The results of independent computations of the ULX population by various groups with similar assumptions about the compact-object formation and CBS evolution parameters are generally consistent. Therefore, it is extremely important to measure the parameters of ULXs in various galaxies to construct their observed distributions to clarify the ways of ULX formation.

### CONCLUSIONS

At present, supercritical accretion onto compact objects (neutron stars and black holes), which was first considered by Shakura and Sunyaev (1973), is observed as the phenomenon of ultraluminous X-ray sources. In Paper I we analyzed in detail the evolution of ULXs with magnetized NSs at the stage of supercritical accretion using the hybrid population synthesis method and showed that they reproduce the range of parameters for pulsating sources (PULXs). In the
hybrid method the stages with accretion onto compact stars are computed by taking into account the evolution of a Roche-lobe-overflowing optical component using the MESA evolutionary code. In this paper we continued Paper I by studying the formation of ULXs with BHs in massive binary systems in galaxies with different star formation histories (proxies for early-type galaxies with ongoing star formation and old elliptical galaxies).

We considered several BH formation models during the core collapse of massive stars: model C, in which the BH mass is determined by the stellar CO-core mass before the collapse, and models D and R, i.e., delayed and rapid BH formation in the case of collapse with fallback onto the proto-NS (Fryer et al. 2012), which are commonly used in the literature. We assumed that the BH gets a natal kick with a Maxwellian distribution and a characteristic velocity of 265 km s\(^{-1}\) scaled to the fraction of matter infalling onto the proto-NS from the collapsing core (models C, D, R265) and with a fixed characteristic velocity of 30 km s\(^{-1}\) (without any scaling to the fraction of infalling matter) (models C, D, R30). In our computations of the orbital evolution of binaries the efficiency of the common envelope emerging during intense mass transfer between the components was varied: \(\alpha_{ce} = 0.5, 1, 4\). When computing the X-ray luminosity during the accretion of matter onto the compact object, we took into account the possible transient pattern of disk accretion due to the thermal instability of accretion disks (Dubus et al. 1999). The observed X-ray luminosity \(L_X\) from supercritical accretion disks around BHs was scaled to the beaming factor as prescribed by King (2009).

The results of our calculations of the number of ULXs in a model galaxy with a constant \(1 \, M_\odot\) yr\(^{-1}\) at 10 Gyr are summarized in Table 1. The number of persistent (non-transient) sources is given in parentheses. Table 2 gives the ratio of the numbers of BHULXs and NULXs in a galaxy with stationary star formation for various compact object formation models. The number of ULXs with BHs is comparable to or prevails over the number of ULXs with NSs in model C (except for the common envelope parameter \(\alpha_{ce} = 4\)) and, conversely, it is smaller than the number of NULXs in models D and R.

Two models, C265-1 and D265-1, with \(\alpha_{ce} = 1\) (model R differs only slightly from D) were studied in more detail:

- Figures 2 and 3 illustrate the evolution of close binaries leading to the formation of systems with BHs and Roche-lobe overflowing optical components. Our computations were performed by a modified BSE population synthesis code (Hurley et al. 2002).

- Figure 4 shows the evolution of the number of persistent and transient ULXs with BHs and, for comparison, ULXs with NSs in systems with Roche lobe overflow (RLOF) and accretion from the stellar wind of the optical component after an instantaneous star formation burst (left) and in a model galaxy with a stationary SFR=\(10 M_\odot\) yr\(^{-1}\) over 1 Gyr (right). In the models C265-1 with BH accretors transient sources completely dominate by the time \(t = 10\) Gyr. This applies both to the models with RLOF and to the models with wind accretion. Remarkably, the number of objects observed by \(t = 10\) Gyr depends weakly on the star formation model.

In the models D-261 transient sources with RLOF also dominate by the same time after the beginning of star formation, with their numbers being comparable in both models, just as for the compact object formation model C265-1. In both cases, this is explained by the fact that these transient sources are CBSs in which BHs formed by a donor with a mass \(~ M_\odot\) overflows its Roche lobe in case B of mass transfer (after leaving the main sequence, see Fig. 15). For stars with \(M \sim M_\odot\) the dependence of the main-sequence lifetime on mass has an exponent close to 3–4 and the 1-Gyr difference in star formation time plays no role.

In the models with NSs, irrespective of the adopted star formation, persistent sources with RLOF dominate. The transient sources are fewer by an order of magnitude. The sources with wind accretion are fewer than those with RLOF by several orders of magnitude.

- Figure 5 compares the evolution of the number of ULXs for various BH formation models (C, D, R) and star formation histories with the subdivision of sources with BHs and NSs accreting via RLOF and from the stellar wind of the optical component. The maximum number of ULXs in galaxies (~10) is reached in models C. The number of ULXs with NSs can be comparable to (and, after the end of star formation, exceed) the number of ULXs with BHs. Note that the sources observed after the end of star formation are CBSs in which BHs were formed before the end of star formation, while long-lived donors with a mass \(~ M_\odot\) filled their Roche lobes after the end of star formation (see Fig. 15).
Fig. 14. Examples of the computations of the mass transfer and accretion rates after the RLOF by the optical component in a CBS with $M_{BH} = 2.75 \ M_{\odot}$, $M_d = 1.8 \ M_{\odot}$, $P_{\text{RLOF}} = 7.9 \text{ days}$ (upper panel), $M_{BH} = 2.25 \ M_{\odot}$, $M_d = 2.8 \ M_{\odot}$, $P_{\text{RLOF}} = 3.1 \text{ days}$ (lower left panel), and $M_{BH} = 7.5 \ M_{\odot}$, $M_d = 89 \ M_{\odot}$, $P_{\text{RLOF}} = 1300 \text{ days}$ (lower right panel). The black, red, and blue lines correspond to $M_{L1}$, the rate of disk accretion onto the BH $M_{BH}$, and the rate of mass loss from the system taken to be $0.1 M_{L1}$, respectively. The systems are ULXs if $M_d > M_{\text{Edd}}$. In the first case, the donor overflows its Roche lobe at the shell hydrogen burning stage on the red giant branch. The mass loss is interrupted for a short time when the radius of the donor surface becomes less than the radius of maximum penetration of the surface convection zone during the preceding evolution (Kippenhahn et al. 1967). In the second case, RLOF also occurs at the donor shell hydrogen burning stage, but at an earlier phase than in the first case, and the ULX stage lasts longer due to the lower initial donor mass. In the case of a massive supergiant donor in a wide system (lower right panel), the ULX stage precedes the formation of a common envelope.

- Figures 6–12 show the distributions of ULXs with BHs in BH mass $M_{BH}$, optical component mass $M_d$, orbital period $P_{\text{orb}}$, and observed X-ray luminosity $L_X$ in a model galaxy with a constant SFR $= 1 \ M_{\odot} \text{ yr}^{-1}$ at 10 Gyr after the beginning of star formation. The differential and cumulative X-ray luminosity and component mass distributions were constructed. The systems accreting via RLOF and from the stellar wind are shown separately. For comparison, Fig. 13 shows analogous distributions for ULXs with NSs accreting via RLOF.

Examples of our computations of the rate of mass transfer through the inner Lagrange point by the MESA code and the resulting accretion rates onto BHs are given in the Appendix.

Our calculations of the number of ULXs with BHs in galaxies with various star formation histories can be used to clarify the formation channels of ULXs, which are a subject of debate in modern literature. The question about the masses of the putative BHs in specific ULXs also remains open. In the BH formation models considered by us the BH masses do not exceed $15 \ M_{\odot}$ (Fig. 1), which does not contradict the $M_{BH}$ measurements by Motch et al. (2014). Some
models of ULXs also admit BH masses of 30–50 $M_\odot$ (Ambrosia et al. 2021), although so far there are no reliable dynamical determinations of the BH masses in ULXs. Our work was aimed at a detailed study of the contribution of various possible ULX progenitors to their total number and was restricted to the evolution of stars with solar chemical composition. A consideration of the evolution of stars with subsolar chemical composition, which can lead to the formation of a higher-mass BH, is the subject of a separate study that we plan to carry out in the future.

**APPENDIX**

**Examples of Evolutionary Tracks**

Figure 14 shows examples of our MESA computations of the mass loss rates by the donors in CBSs with BHs in which the evolution leads to the formation of ULXs.

Figure 15 shows an example of the changes in the parameters of a binary system with initial masses of the BH $M_{\text{BH}} = 3.8 \, M_\odot$ and the optical donor star $M_d = 1.1 \, M_\odot$ and an initial orbital period $P_{\text{orb}} =$
2.7 days in which a transient ULX is formed at stage B of mass transfer (after the main sequence).

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REFERENCES

1. M. A. Abramowicz, B. Czerny, J.-P. Lasota, et al., Astrophys. J. 332, 646 (1988).
2. E. Ambrosi, L. Zampieri, F. Pintore, and A. Wolter, arXiv: 2111.02879 (2021).
3. P. Atri, J. C. A. Miller-Jones, A. Bahramian, et al., Mon. Not. R. Astron. Soc. 489, 3116 (2019).
4. M. Bachetti et al., Nature (London, U.K.) 514, 202 (2014).
5. S. Banerjee, K. Belczynski, C.-L. Fryer, et al., Astron. Astrophys. 639, A41 (2020).
6. E. R. Beasor, B. Davies, and N. Smith, arXiv: 2109.03339 (2021).
7. M. C. Bernadich, A. D. Schwope, K. Kovlakas, et al., arXiv: 2110.14562 (2021).
8. B. Binder, E. M. Levesque, and T. Dorn-Wallenstein, Astrophys. J. 863, 41 (2018).
9. T. A. Callister, W. M. Farr, and M. Renzo, Astrophys. J. 920, 157 (2021).
10. A. M. Cherepashchuk, B. Czerny, J.-P. Lasota, et al., Astrophys. J. 519, 89 (1999).
11. M. Coriat, R. P. Fender, and G. Dubus, Mon. Not. R. Astron. Soc. 424, 1991 (2012).
12. L. Dessart, A. Burrows, C.-D. Ott, et al., Astrophys. J. 644, 1063 (2006).
13. G. Dubus, J.-P. Lasota, J.-M. Hameury, et al., Mon. Not. R. Astron. Soc. 303, 139 (1999).
14. I. El Mellah, J.-O. Sundqvist, and R. Keppens, Astron. Astrophys. 622, L3 (2019).
15. T. Erli, S. E. Woosley, T. Sukhbold, et al., Astrophys. J. 890, 51 (2020).
16. S. N. Fabrika and A. V. Mescheryakov, in Proceedings of the IAU Symposium No. 205, Ed. by R. T. Schilizzi (2001), p. 268.
17. S. N. Fabrika, K. E. Atapin, A. S. Vinokurov, et al., Astrophys. Bull. 76, 6 (2021).
18. E. Fonseca, H. T. Cromartie, T. T. Pennucci, et al., Astrophys. J. Lett. 915, L12 (2021).
19. C. L. Fryer, K. Belczynski, G. Wiktorowicz, et al., Astrophys. J. 749, 91 (2012).
20. M. Gallegos-Garcia, C. P. L. Berry, P. Marchant, et al., arXiv: 2107.05702 (2021).
21. N. Giacobbo and M. Mapelli, Mon. Not. R. Astron. Soc. 480, 2011 (2018).
22. S. A. Grebenev, Astron. Lett. 43, 464 (2017).
23. J.-M. Hameury and J.-P. Lasota, Astron. Astrophys. 643, A171 (2020).
24. R. Hirai and I. Mandel, arXiv: 2108.03774 (2021).
25. G. Hobbs et al., Mon. Not. R. Astron. Soc. 360, 974 (2005).
26. J. Hurley et al., Mon. Not. R. Astron. Soc. 329, 897 (2002).
27. G. L. Israel et al., Mon. Not. R. Astron. Soc. 466, L48 (2017).
28. N. Ivanova, S. Justham, X. Chen, et al., Astron. Astrophys. Rev. 21, 59 (2013).
29. N. Ivanova, S. Justham, and P. Ricker, Common Envelope Evolution, AAS–IOP Astron. Book Ser. (IOP, Boston, 2020).
30. C. de Jager, H. Nieuwenhuijzen, and K. A. van der Hucht, Astron. Astrophys. Suppl. Ser. 72, 259 (1988).
31. P. Kaaret, H. Feng, T. Roberts, et al., Ann. Rev. Astron. Astrophys. 55, 303 (2017).
32. A. King et al., Astrophys. J. Lett. 552, L109 (2001).
33. A. R. King, Mon. Not. R. Astron. Soc. 393, L41 (2009).
34. R. Kippenhahn and A. Weigert, Zeitschr. Astrophys. 65, 251 (1967).
35. R. Kippenhahn, K. Kohl, and A. Weigert, Zeitschr. Astrophys. 66, 58 (1967).
36. J. Klenczki, G. Nelemans, A. G. Istrate, et al., Astron. Astrophys. 638, A55 (2020).
37. J. Klenczki, G. Nelemans, A. G. Istrate, et al., Astron. Astrophys. 645, A54 (2021a).
38. J. Klenczki, A. G. Istrate, G. Nelemans, et al., arXiv: 2111.10271 (2021b).
39. M. de Kool, Astrophys. J. 358, 189 (1990).
40. A. G. Kuranov, K. A. Postnov, and L. R. Yungel’son, Astron. Lett. 46, 658 (2020).
41. E. Laplace, S. Justham, M. Renzo, et al., arXiv: 2102.05036 (2021).
42. K. M. López, M. Heida, P. G. Jonker, et al., Mon. Not. R. Astron. Soc. 497, 917 (2020).
43. E. Lovegrove and S. E. Woosley, Astrophys. J. 769, 109 (2013).
44. A.-J. Loveridge et al., Astrophys. J. 743, 49 (2011).
45. M. MacLeod, E. C. Ostriker, and R. Stone, Astrophys. J. 863, 5 (2018).
46. P. Marchant et al., Astron. Astrophys. 604, A55 (2017).
47. A. Miglio, C. Chiappini, J. T. Mackereth, et al., Astron. Astrophys. 643, A85 (2021).
48. S. Molch et al., Nature (London, U.K.) 514, 198 (2014).
49. A. A. Mushtukov et al., Mon. Not. R. Astron. Soc. 501, 2424 (2021).
50. D. K. Nadezhin, Astroph. Space Sci. 69, 115 (1980).
51. T. Nugis and H. J. G. L. M. Lamers, Astron. Astrophys. 360, 227 (2000).
52. B. Paxton et al., Astrophys. J. Suppl. Ser. 192, 3 (2011).
53. M. Plavec, R. K. Ulrich, and R. S. Polidan, Publ. Astron. Soc. Pacif. 85, 769 (1973).
54. J. T. Poelarends, S. Wurtz, J. Tarka, et al., Astrophys. J. 850, 197 (2017).
56. C. A. Raithel, T. Sukhbold, and F. Özel, Astrophys. J. 856, 35 (2018).
57. N. I. Shakura and R. A. Sunyaev, Astron. Astrophys. 24, 337 (1973).
58. Y. Shao and X.-D. Li, Astrophys. J. 802, 131 (2015).
59. Y. Shao et al., Astrophys. J. 886, 118 (2019).
60. S. J. Smartt, Publ. Astron. Soc. Austral. 32, 016 (2015).
61. G. E. Soberman et al., Astron. Astrophys. 327, 620 (1997).
62. S. S. Tsygankov, A. A. Mushtukov, V. F. Suleimanov, et al., Mon. Not. R. Astron. Soc. 457, 1101 (2016).
63. A. V. Tutukov, L. R. Yungel’son, and A. Klyaiman, Nauch. Inform. 27, 3 (1973).
64. J. S. Vink, arXiv: 2109.08164 (2021).
65. J. S. Vink, A. de Koter, and H. J. G. L. M. Lamers, Astron. Astrophys. 362, 295 (2000).
66. J. Vink et al., Astron. Astrophys. 369, 574 (2001).
67. M. Volonteri, M. Habouzit, and M. Colpi, Nat. Rev. Phys. 3, 732 (2021).
68. D. J. Walton et al., Astrophys. J. Lett. 857, L3 (2018).
69. D. J. Walton, A. D. A. Mackenzie, H. Gully, et al., Mon. Not. R. Astron. Soc. (2021); arXiv: 2110.07625.
70. R. F. Webbink, Astrophys. J. 277, 355 (1984).
71. N. E. White and J. van Paradijs, Astrophys. J. Lett. 473, L25 (1996).
72. G. Wiktorowicz et al., Astrophys. J. 846, 17 (2017).
73. G. Wiktorowicz et al., Astrophys. J. 875, 53 (2019).
74. G. Wiktorowicz, J.-P. Lasota, K. Belczynski, et al., Astrophys. J. 918, 60 (2021).
75. F. Yuan and R. Narayan, Annual Rev. Astron. Astrophys. 52, 529 (2014).

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