On the dynamical formation of accreting intermediate mass black holes

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ABSTRACT
We compute the probability that intermediate mass black holes (IMBHs) capture companions due to dynamical interactions and become accreting sources, and explore the possibility that the accreting IMBHs would appear as ultraluminous X-ray sources (ULXs). We focus on IMBHs originating from low-metallicity Population III stars. Two channels of IMBH formation are considered: from primordial halos in the framework of hierarchical clustering, and from non-mixed, zero-metallicity primeval gas in galactic discs. IMBHs can form binary systems due to tidal captures of single stars and exchange interactions with existing binary systems in galactic discs. We find that neither formation mechanism of the accreting IMBH binary is able to provide enough sources to explain the observed population of ULXs. Even at sub-ULX luminosity, the total number of accreting IMBHs with $L > 10^{36}$ erg s$^{-1}$ with dynamically captured companions is found to be < 0.01 per galaxy.

Key words: accretion, accretion discs - black hole physics, stars: formation - stars: evolution, galaxies: formation, X-rays: binaries

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1 INTRODUCTION

Intermediate mass black holes (IMBHs) are a class of objects with masses larger than standard stellar-mass black holes (BHs), but much smaller than the $\sim 10^6 - 10^9 M_\odot$ of super-massive black holes detected in the centers of galaxies, including our own Milky Way. The masses of stellar BHs are expected theoretically to span a range between roughly $\sim 5 - 50 M_\odot$ (Fryer & Kalogera 2001). These stellar-mass BHs are the end points of stellar evolution for sufficiently massive stars formed out of metal enriched gas. At zero metallicity, much more massive stars and black holes may be forming. Indeed it has been suggested that zero-metallicity stars can form with masses of $\sim 10^2 - 10^3 M_\odot$, and produce IMBHs directly as a result of stellar evolution (Heger et al. 2003). IMBHs can be remnants of zero-metallicity (Population III) massive stars of different origin. The first possibility is that IMBHs are produced by primordial Population III stars at early stages of galaxy formation and some could be left wandering in galactic halos, as suggested by numerical simulations (see Volonteri, Haardt & Madau 2003; Madau et al. 2004; Volonteri & Perna 2005 and references therein). Due to the so-called gravitational rocket mechanism (Madau et al. 2004; Madau & Quataert 2004; Merritt et al. 2004; Blanchet, Qusailah & Will 2005; Baker et al. 2006), IMBHs could receive kick velocities high enough to prevent their merging into the central galactic BH, but small enough not to leave the potential well of the Galaxy. Calculations by Volonteri & Perna (2005) indicate that the number of such “relic” IMBHs in the internal parts of a typical galactic halo can amount to a few dozens per galaxy. The second scenario is based on the recent suggestion by Jimenez & Haiman (2006) that about 10-30% of stars in galactic discs at $z \sim 3 - 4$ can be born from primordial gas due to inefficient mixing of the interstellar medium. If evolution of the most massive of these stars leads to the formation of IMBHs, they should be left inside the galactic disc and have the low velocity dispersion typical of galactic disc populations.

IMBHs can capture stellar companions due to dynamical interactions and appear as accreting sources (Madau & Rees 2001). For IMBHs formed in young, dense stellar clusters, these processes were considered by Blecha et al. (2006). These authors concluded that the dynamical formation of binaries with accreting IMBHs, observable as bright ultra-luminous X-ray sources (ULXs) in stellar clusters, is very inefficient. In this paper we further study this suggestion, focusing on the possible formation of ULXs in binary systems as a result of dynamical interactions of IMBHs with the galactic disc population.
ULXs are bright point-like objects observed in external galaxies. They are considered to form a separate class of objects apparently associated with young stellar populations. ULXs are characterized by high X-ray luminosity ($L_x \sim 10^{39} - 10^{42}$ erg s$^{-1}$) and often strong variability (Colbert & Mushotzky 1999). The observed number of ULXs is about 0.1 per galaxy for $L_x \gtrsim 2 \times 10^{39}$ erg s$^{-1}$ and 0.01 per galaxy for $L_x \gtrsim 10^{40}$ erg s$^{-1}$ (Colbert & Miller 2005).

The nature of ULXs is unclear. Two competitive hypothesis (see Mushotzky 2004 for a recent review) suggest that either these sources are accreting binary systems with stellar-mass black holes and significant collimation of radiation (like SS433 in our Galaxy) seen along the jet axis (Fabrika & Mescheryakov 2001; King et al. 2001; Begelman, King & Pringle 2006), or they are manifestations of intermediate mass black holes with $M \sim 100 - 1000M_\odot$ (Colbert & Mushotzky 1999; Madau & Rees 2001). The first hypothesis is supported by observations of emission nebulae around some of these sources similar to that observed around SS433 (see Fabrika 2004 and references therein for more details), while the IMBH hypothesis is advocated by observations of $\sim 20$ s quasi-periodic X-ray oscillations in at least one source (Strohmayer & Mushotzky 2003). Observations of specific X-ray spectral features forming in the funnel of supercritical accretion disc seen along the jet may be crucial in distinguishing between these two possibilities (Fabrika 2004). For ULX sources which do not display a rapidly variable luminosity, another possible model is that of very young, fast rotating pulsars, whose X-ray luminosity is powered by their rotational energy (Perna & Stella 2004).

If accretion is the source of energy, the observed X-ray luminosity $> 10^{39}$ erg s$^{-1}$ suggests an accretion rate onto the compact star of $> 10^{-7}M_\odot$ yr$^{-1}$ (assuming 10% efficiency). Vonderer & Perna (2005) investigated the possibility that ULXs can be associated to wandering IMBHs which accrete material from the surrounding interstellar medium (see also Islam, Taylor & Silk 2004; Mii & Totani 2005; Mapelli, Ferrara & Rea 2006). These calculations showed that the typical accretion rate is too low to produce bright ULXs, unless the wandering IMBHs carry a substantial baryonic core with them (e.g. the stripped remnants of the original host galaxy of the wandering BH).

A different route which could provide a high accretion rate for IMBHs is mass transfer from a companion at an advanced evolutionary stage. There are two possibilities for an IMBH to capture a companion star: tidal interactions with single stars and exchange interactions with binary systems. Tidal interactions are efficient for sufficiently close fly-bys (at a distance
of the order of a few stellar radii), so the tidal capture rate is fairly small even for low velocity dispersion in the galactic disc; in addition, the tidal destruction of the entire captured star is very likely. The advantage of tidal captures is that sufficiently close binaries with IMBHs are formed and are likely to become bright X-ray sources.

In the case of exchange interactions, the characteristic cross-section is larger than for tidal captures – it scales in proportion to the binary semi-major axis. This increases the probability of interaction between an IMBH and the binary star. On the other hand, i) for large relative velocities between IMBHs and binaries, only a small fraction of sufficiently close systems (called “hard”, see below) can produce bound binaries after interaction, thus decreasing the effective cross-section; ii) after the exchange of the components, the binary’s semi-major axis increases thus decreasing the chances for the IMBH in such a binary to become a bright X-ray source.

In this paper we study both processes of formation and evolution of binaries with IMBHs in galactic discs using population synthesis calculations. High-velocity halo IMBHs will be considered, as well as low-velocity IMBHs formed in the galactic disc.

2 MODEL

Our model includes the following steps.

- We specify the population of IMBHs and its properties. For halo IMBHs we use the spatial distribution and velocities calculated by Volonteri & Perna (2005) as initial conditions, and keep pace with their trajectories in the galactic potential over $10^{10}$ yrs, selecting the crossings of the disc plane. For disc IMBHs, we follow the proposal by Jimenez & Haiman (2006) and consider their formation from massive stars as described below ($\S$2.2).
- We calculate the exchange interactions of IMBHs with different binary systems or tidal captures of single stars in the disc.
- Using a modified version of the SCENARIO MACHINE – the binary population synthesis code (Lipunov, Postnov & Prokhorov 1996a) – we calculate the subsequent evolution of captured systems.
- Summing up all probabilities for a given IMBH to appear as ULX in a binary formed during all disc crossings, and making appropriate normalizations, we calculate the expected number of ULXs in a typical spiral galaxy with assumed constant star formation.
2.1 IMBHs wandering in halos

The initial spatial and velocity distributions of IMBHs are taken from the numerical calculations by Volonteri & Perna (2005). Coordinates and velocities of these IMBHs have been taken from a stationary distribution corresponding to the present time (i.e. to the redshift $z = 0$). We have selected only those IMBHs which were found inside the region bounded by galactocentric distance $R < 15.4$ kpc in the galactic plane and height $|Z| < 3$ kpc over the galaxy plane. This choice reflects the model density profile adopted for the Galaxy stellar disc (exponential disc, with scale length 7.7 kpc and scale height 1.53 kpc). With this parameter choice, the stellar density at $|Z| > 3$ kpc becomes extremely small, so that the probability of capturing a companion is negligible. Our test demonstrated that IMBHs initially outside $|Z| < 3$ kpc contribute very little to the number of galactic plane crossings.

The number of IMBHs within this spatial boundaries in a Milky Way sized galaxy strongly depends on the assumed density peak cut during hierarchical clustering. If IMBH formation happens only in rare $3.5 \sigma$ density peaks, the average number of wandering IMBHs with $R < 15.4$ kpc and $|Z| < 3$ kpc is $1.3$ (Volonteri & Perna 2005). We also made a run for IMBHs originated from more common $3\sigma$ peaks. In that case there are on average 126 IMBHs per galaxy.

After the initial velocity and position of an IMBH are selected, we let the IMBH orbit to evolve in the galactic potential. The motion of each IMBH is traced for $10^{10}$ yrs with a time step of $10^4$ yrs. The large integration time is chosen to increase the number of galactic disc crossings, as we have only several dozens IMBHs from direct numerical simulations; with the typical IMBH orbital period of several $10^6$ yrs, we expect up to several thousand crossings in our calculations. This artificial increase in the number of trials helps to obtain statistically significant results when calculating dynamical interactions with stars. The final results are normalized appropriately.

Trajectories of IMBHs are calculated in a way similar to that used in calculations of the spatial evolution of isolated neutron stars in our Galaxy (see, for example, Popov et al. 2005 and references therein). We made use of the axisymmetric galactic potential initially proposed by Miyamoto & Nagai (1975). The potential includes three parts: disc, spheroid and halo, which are described in detail in Blaes & Madau (1992). IMBHs mostly cross the galactic plane at small ($< 0.5$ kpc) galactocentric radii (see Fig. 1). Spatial velocities of IMBHs at each galactic plane crossing are collected and used for the calculation of exchange
interactions with binaries and tidal captures of stars. Typical orbital periods of these IMBHs are about $10^7$ years, while their velocities at the galactic plane crossings are $\sim 300-400$ km s$^{-1}$.

2.2 IMBHs from low-metallicity gas

According to Jimenez & Haiman (2006), a fraction of about 10-30% of gas in galaxies can preserve primordial (low-metallicity) composition at $z \sim 3 - 4$. The most massive stars formed from such a pristine gas can produce IMBHs at the end of evolution. Adopting a galactic star formation rate of $1 \, M_\odot$ per year for $10^8$ yrs (as in Jimenez & Haiman 2006), and using 0.1 for the fraction of primordial gas content, we obtain that $10^7 \, M_\odot$ of gas in the galaxy is transformed into zero-metallicity stars at $z = 3 - 4$.

To estimate the number of IMBHs formed in this way, we need to specify the initial mass function, the mass interval(s) in which BHs are formed, and the BH masses. The initial mass function is taken in a power-law form:

$$f(M) \propto M^{-\alpha}. \quad (1)$$

Two values of the index $\alpha$ were considered: 2.35 (the classical Salpeter value) and $\alpha = 1.35$. The second choice is motivated by the possibility of a significant flattening of the initial mass function for very massive stars which can lead to the increase of the number of ULXs in simulations. For example, the extreme variant $\alpha = 0$ (flat initial mass function) was discussed, for example, by Contini, Davoust & Considere (1995). The mass range of zero-metallicity stars which evolve into black holes was chosen to consist of two intervals: from 30 to 140 $M_\odot$ and from 260 to 1000 $M_\odot$ (Woosley, Heger & Weaver 2002). Inside the first mass interval, we assumed $M_{\text{BH}} = 0.5 M_{\text{star}}$, while inside the second interval $M_{\text{BH}} = 0.75 M_{\text{star}}$. 

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This specific choice, however, does not affect our results significantly. Neither does the choice of the upper mass limit (for example, 500 $M_\odot$ as in Omukai & Palla 2003) because the stellar initial mass function rapidly decreases towards higher values.

The velocity distribution of disc IMBHs was assumed to be Maxwellian with a characteristic velocity dispersion of 10 km s$^{-1}$, which is typical for young massive stars in the Galactic disc. We assume that the velocity dispersion remains constant with time and do not trace the individual motion of such IMBHs. This means that we neglect the possible dynamical heating of the IMBH population; any increase of the velocity dispersion, however, would reduce the efficiency of the dynamical interactions of IMBHs with stars.

### 2.3 Formation of binaries due to exchange interactions

The probability of a dynamical interaction $p$ between an IMBH and a (binary) star in a time interval $\Delta t$ is:

$$p = 1 - \exp\left\{ -\frac{\Delta t}{\tau} \right\},$$

(2)

where $\tau = (n\langle V \rangle \sigma)^{-1}$ is the characteristic time of interaction, $n$ is the local stellar density, $\sigma$ is the cross section of the interaction, and $V$ is the relative velocity of IMBHs and the (binary) star at infinity.

We have used two fitting formulas for the exchange cross section: one proposed by Hills (1992) and one by Hut, Heggie & McMillan (1996). Hills (1992) simulated encounters between “hard” binaries with equal mass binary components ($M_0$) and intruders with extreme masses relative to the masses of the components. In the limiting case of large IMBH mass ($M_{IMBH} \gg M_0$), the mean time ($\tau$) of the exchange interaction can be estimated as

$$\tau = 1.9 \times 10^{14} \text{yr} \left( \frac{1/pc^3}{n} \right) \left( \frac{\langle V^2 \rangle^{1/2}}{10 \text{ km/s}} \right) \times$$

(3)

$$\left( \frac{\text{A.U.}}{a_0} \right) \left( \frac{0.5M_\odot}{M_0} \right) \left( \frac{M_0}{M_{IMBH}} \right)^{5/6},$$

where $a_0$ is the semimajor axis of the binary.

Hut, Heggie & McMillan (1996) calculated the exchange cross section in the limit of very low-speed intruders only. These authors, however, expanded their calculations for a wide range of mass ratios. The equation obtained by Hut, Heggie & McMillan (1996) for the exchange cross section has a complicated dependence on the masses of all interacting systems. Let $x = m_1/M_{12}$, $y = m_3/M_{123}$ and $M_{ij} = m_i + m_j$, where $m_1$ is the ejected component, $m_3$ is IMBH. Then
\[ \sigma \simeq \frac{G M_{123} a}{V^2} \frac{m_{23}^{7/2} M_{23}^{1/6}}{M_{12}^{1/3} M_{13}^{5/2} M_{123}^{5/6}} \exp(3.70 + 7.49x - 1.89y - 15.49x^2 - 2.93xy - 2.92y^2 + 3.07x^3 + 13.15xy - 5.23xy^2 + 3.12y^3). \] (4)

This formula fits 75% of the numerical calculations to better than 20%; larger discrepancies are restricted to mass ratios where the cross sections are probably too small to be of importance in applications. Hut et al. have also compared their formula with results obtained by other authors, and found that the agreement is generally satisfactory. The results of our calculations presented below also do not depend significantly on the details in the formula for the exchange cross section, i.e., we obtain similar numbers of ULXs using Eq. (3) and Eq. (4).

2.4 Tidal capture

IMBHs should tidally interact with single stars, too. A detailed description of the dissipation in the tidal capture process can be found in Fabian et al. (1975). The tidal capture cross section can be computed from the requirement that the deposition of kinetic energy during the encounter, \( \Delta E_T \), is larger than the relative energy of the pair at infinity: \( E = \mu v_{\infty}^2/2 \). Here \( \mu = M_1 M_2/(M_1 + M_2) \) is the reduced mass of the pair of stars with masses \( M_1 \) and \( M_2 \).

It is interesting to compare the tidal cross section to the exchange interaction one. As the gravitational focusing dominates in both cases, the cross section ratio is given by the formula (Hills 1992):

\[ \frac{\sigma_{\text{tidal}}}{\sigma_{\text{exch}}} \simeq 2.5 \frac{R_s}{a_0}, \] (5)

where \( R_s \) and \( a_0 \) are, respectively, the radius of the star and the semimajor axis of the pre-encounter binary. In our calculations, however, we use a more precise formula for the tidal capture cross section from Kim & Lee (1999), rather than the simple scaling given above. These authors present a convenient fitting formula for the cross section of tidal capture for two stars with a large mass ratio as a function of their relative velocity at infinity.

Madau & Rees (2001) estimated the tidal capture rate of massive IMBHs (Population III remnants) at the Galactic center. They noted that, although the capture rate in dense stellar regions is high enough, because of the high velocity dispersion the close encounters leading to the tidal disruption of the main-sequence star will be very common, leading to a consistent decrease in the estimate of surviving binary systems which can appear as ULXs.
2.5 Binary population synthesis

We used the population synthesis method to take into account different types of binaries interacting with IMBHs. Specifically, the modified version of the SCENARIO MACHINE code by Lipunov, Postnov & Prokhorov (1996a) was adopted.

i) Halo IMBHs. In this case, for each IMBH and for each galactic plane crossing, we randomly selected $N$ binary systems whose evolution is calculated according to standard initial distributions (see below). Since each IMBH crosses the galactic plane $N_{\text{cross}} \sim 10^4$ times during $10^{10}$ yrs, the total number of potential encounters with binaries is $N_s = N \times N_{\text{cross}}$. Statistically significant results are obtained for $N_s \sim 10^5$, so in our calculations we selected several tens of binaries per each IMBH. A few thousand bright X-ray sources typically appeared in a population synthesis run consisting of $10^5$ binaries with IMBHs.

ii) Zero-metallicity stars. Similarly, to obtain statistically significant results, for each IMBH originated from zero-metallicity stars in the disc we modeled $N \sim 10^5$ binary systems.

2.5.1 Initial binary distributions

Initial distributions of binary parameters are taken according to standard premises widely used in the population synthesis calculations (Popova et al. 1982).

a) Orbital separation $a$.

We use equprobable distribution in the logarithmic scale.

$$dN/d(\log a) = \text{const,} \quad \max\left\{\frac{20R_\odot}{R_L(M_1)}\right\} < a < 10^4R_\odot,$$

where $R_L(M_1)$ is the radius of the Roche lobe of the primary component. The lower limit is determined by the condition of coalescence of the components at the main sequence. The choice of the upper limit is dictated by the following considerations. First, wide binaries (with semimajor axes up to $10^7R_\odot$) are soft and will be disrupted by dynamical interactions with an IMBH, so it is not necessary to compute their evolution in detail. Hence we used the upper limit $10^4R_\odot$ for initial binary semi-major axis. This value is also close to the boundary beyond which binaries will be destroyed by dynamical interactions in stellar systems with velocity dispersion of around 100 km/s, which is typical for central regions of galaxies. The account in the statistics for wide binaries with $10^4 < a/R_\odot < 10^7$, which can be present in galactic disks, is easily made as we use flat probability distribution in the logarithmic scale.

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1 See the on-line material at http://xray.sai.msu.ru/~mystery/articles/review/
For correction we just need to divide the calculated rates by a numerical coefficient of the order of two as we took binaries from one half (from $\sim \log a = 1$ up to $\log a = 4$) of the full range (from $\log a = 1$ up to $\log a = 7$).

b) Masses of the components. We use the Salpeter mass function for the mass of the primary (i.e. more massive) star:

$$\frac{dN}{dM_1} \propto M_1^{-2.35}, \quad 0.1M_\odot < M_1 < 120M_\odot.$$  \hspace{1cm} (7)

c) Mass ratio of the binary components $q = M_2/M_1 \leq 1$.

$$\frac{dN}{dq} \propto q^{\alpha_q}.$$  \hspace{1cm} (8)

We present results for $\alpha_q = 1$, i.e. components with equal masses are more probable. This value is favored by some population synthesis analysis (e.g. Lipunov, Postnov & Prokhorov 1996a). Calculations were also made for $\alpha_q = 0$ (flat mass ratio distribution). For this value we obtain a smaller number of bright X-rays sources with IMBHs, but the difference is less than a factor of two.

d) Initial orbital eccentricities are assumed to be zero. This simplification is justified by the fact that, for the close binaries of interest, tidal circularization occurs on time scales much shorter than other characteristic evolutionary times. The number density of stars in the galactic disc is assumed to be one per cubic parsec. This value is an order of magnitude higher than that in the solar vicinity, but it should be typical for central regions of galaxies, in which we are interested (Marochnik & Suchkov 1996). Our results on the bright source statistics can, however, be easily generalized to other values of the stellar density since they scale linearly with it.

The disc (for the case of wandering IMBHs) is modeled as a flat structure with semithickness of 300 pc. Since most crossings happen at small galactocentric radius, such a thick disc is a reasonable approximation. We assume that all stars belong to binaries. As the fraction of massive stars in binary systems is not less than 50%, this appears to be a safe assumption.

2.5.2 Formation of binaries with IMBH

The evolution of a binary system is considered as a sequence of stages, and the duration of each one is defined by the shortest evolutionary timescale of one of the binary components. The states of stars and binary parameters at the beginning of a stage uniquely determine the fate of the binary up to the end of the stage.

At each evolutionary stage $i$ of the binary $j$ ($j = 1..N, N \sim 10$ for halo IMBHs and
For IMBHs originated from low-metallicity stars), we calculate the probability of the exchange interaction \( p_{\text{capt}}^{ij} \) with an IMBH during the BH galactic plane crossing time \( t_{\text{cross}} \) for the case of wandering IMBHs:

\[
p_{\text{capt}}^{ij} = \frac{t_{\text{cross}}}{\tau_{ij}},
\]

\( (9) \)

For IMBHs inside the disc originated from zero-metallicity stars this probability reads:

\[
p_{\text{capt}}^{ij} = \frac{t_{\text{Gal}}}{\tau_{ij}}.
\]

\( (10) \)

Here \( t_{\text{Gal}} = 10^{10} \) yrs is the galactic age.

### 2.5.3 Evolution of binaries with IMBH

After an IMBH acquires a companion, we calculate the new semimajor axis \( a_f \) of the newborn binary system. For exchange interactions, \( a_f \) is calculated according to Hills (1992).

For \( M_{\text{IMBH}} \gg M_0 \) the harmonic mean semimajor axis of the post-encounter binary for all exchange collisions in the limit of hard binaries is:

\[
a_f = 12 a_0 (M_{\text{IMBH}}/100M_\odot)^{2/3},
\]

\( (11) \)

where \( a_0 \) is the semimajor axis of the binary system before the exchange interaction. As it was shown in Hills (1992), the distribution of \( a_f \) has the following property. For \( M_{\text{IMBH}}/M_0 = 1000 \) (for which \( a_f/a_0 = 56 \)), there are almost no binaries in the semimajor axis range \( a_f \sim (1-20)a_0 \). The number of binaries rises rapidly for semimajor axis \( a_f > 50a_0 \). That is why the use of Eq. (11) does not underestimate significantly the number of accreting systems formed due to exchange interactions.

For binaries formed through tidal captures we assume that all captured stars survive in a circular orbit around the IMBH at \( r = 2r_t \), where \( r_t = (M_{\text{BH}}/m)^{1/3}R \) is the tidal-breakup radius.

After the binary parameters are determined, we calculate the evolutionary track of the system using the population synthesis code. Calculations continue up to the age \( t = 10^{10} \) yrs.

The statistics of accreting binary sources is collected for all halo IMBHs and disc IMBHs.

### 2.6 Bright sources statistics

Since we calculate the probability to capture a companion from a given (randomly selected) binary system, it is necessary to take into account two effects. The first regards the duration, \( t_{\text{stage}}^{ij} \), of the stage \( i \) at which the system \( j \) was taken. The second is due to the fact that
the ULX stage \((t_{ij}^{\text{ULX}})\) is just a short episode in the life of the formed system. We assume that an accretion rate \(\dot{M}\) yields a bolometric luminosity \(L_{\text{bol}} = \eta \dot{M} c^2\), where \(\eta \sim 0.1\) is a typical value of the accretion efficiency (Frank, King & Raine 1992). In Figs. 2-3 and 5-6 we have marked the value \(\dot{M} \sim 10^{-6} M_\odot \, \text{yr}^{-1}\), which corresponds to a bolometric luminosity of \(L_{\text{bol}} \sim 10^{40} \, \text{erg} \, \text{s}^{-1}\). This is the value we will be referring to when computing the statistics of ULXs. Since the processes we study here yield very small probabilities for the observation of bright sources, we limit our results to the bolometric luminosities, keeping in mind that these in turn provide an upper limit to the X-ray luminosities.

Given our definition of ULX, for each crossing \(k\) of the galactic plane by an IMBH, we obtain the probability that it can shine as a ULX:

\[
p_k = \frac{1}{N} \sum_{j=1}^{N} \sum_{i} p_{ij}^{\text{catt}} \frac{t_{ij}^{\text{stage}}}{t_{\text{Gal}}} \frac{t_{ij}^{\text{ULX}}}{t_{\text{Gal}}}.
\]  

(12)

Here \(t_{\text{Gal}}\) is the galactic age, and \(t_{ij}^{\text{stage}}\) is the duration of the stage at which the donor was captured.

The probabilities \(p_k\) given above refer to each IMBH used in our calculations. We sum these probabilities in each galactic plane crossing by all IMBHs, and then divide the result by the number of merging trees from which these IMBHs were selected. The final statistics of the number of observable bright X-ray sources can be obtained as follows:

\[
N_{\text{systems}} = \frac{1}{N_{\text{gal}}} \sum_{1}^{N_{\text{BH}}} \sum_{k}^{k_{\text{max}}} p_k.
\]  

(13)

Here \(N_{\text{gal}}\) is the number of galaxies (merging trees). For 3.5\(\sigma\) halos \(N_{\text{gal}} = 30\), for 3\(\sigma\) halos \(N_{\text{gal}} = 1\). The number of IMBHs, \(N_{\text{BH}}\), is equal to 40 in the case of 3.5\(\sigma\) halos, and 126 for 3\(\sigma\) halos. The total number of galactic plane crossings for each IMBH, \(k_{\text{max}}\), is calculated explicitly and is of order of \(10^3\).

### 3 RESULTS FOR EXCHANGE INTERACTIONS

In this section we present the results of our calculation for exchange interactions.

#### 3.1 Halo IMBHs

In Fig. 2 we show the number of accreting binaries with IMBHs per galaxy for 3.5\(\sigma\) halos (dotted and dashed lines), and in Fig. 3 for 3\(\sigma\) halos. It can be seen that the probability
to form an ULX through exchange interaction of a halo IMBH with binaries in the galactic
disc is extremely small.

In particular, for the cross section from Hut, Heggie & McMillan (1996), which is more re-
alistic in our case, we obtain that the probability to observe a source with $\dot{M} > 10^{-6} M_\odot \text{yr}^{-1}$
is only $\sim 3 \times 10^{-14}$ per per galaxy. For the Hills’ cross section the result is even smaller:
$\sim 1.8 \times 10^{-14}$.

Relaxing the threshold on the accretion rate for an ULX increases the number of sources, but insignificantly: e.g. for an accretion rate of only $10^{-10} M_\odot \text{yr}^{-1}$, we get $N_{\text{ULX}} \simeq 10^{-9}$ per galaxy. Therefore, the number of accreting X-ray sources of any luminosity due to “primor-
dial” IMBHs capturing companions via exchange interactions with binaries in the galactic
disc is negligible.

In our calculations we found two main types of donors feeding IMBHs. Most frequently
the companions are red giants. In this case the accretion rate is $> 10^{-6} M_\odot \text{yr}^{-1}$. The
duration of this stage should be rather small: $\sim 10^4 \text{yrs}$, as this time is determined by
the thermal time of the convective envelope. Since the mass ratio in the IMBH binaries is
very high, we also performed calculations under the assumption that the duration of the
accretion stage is determined by the helium burning time in the stellar core, which is 0.1
of the hydrogen burning time. Again, the results are not significantly changed. Both results
are shown in the Fig. 2 for the case of $3.5\sigma$ halos, and in Fig. 3 for $3\sigma$ halos.

In some instances we found accreting white dwarfs as companions. In this case the
accretion rate is smaller ($\dot{M} < 10^{-8} M_\odot \text{yr}^{-1}$), but the duration of the stage can be much
longer. Such systems are formed if the semimajor axis of the binary before the interaction
with an IMBH is small.

In Figure 4 we show the distribution of sources with $\dot{M} > 10^{-6} M_\odot \text{yr}^{-1}$ versus the
time of the on-set of the ULX stage. For most systems this time is larger than the orbital
periods of the IMBHs, which are about $10^7 \text{yrs}$, since we chose for our calculations only
those IMBHs that spend most of their life close to the galactic plane. Because of that, most
accreting systems follow the IMBH spatial distribution. Still, as the fraction of systems
in which accretion starts on timescale shorter than the orbital period is non-zero, a slight
concentration (on the level of few per cents) towards the galactic plane (and center) appears.
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Figure 2. Integral distribution of the accretion rate for BHs wandering in a galactic halo. IMBHs born in $3.5\sigma$ halos are taken into account. Solid line: systems formed via tidal captures. Dotted line: systems formed via exchange interaction (using Hut, Heggie & McMillan 1996 fitting formula for the cross section). Dashed line: systems formed via exchange interaction (Hills 1991 fitting formula). The vertical dotted line shows the accretion rate, corresponding to the luminosity $L_{bol} = 10^{40}$ erg s$^{-1}$, where $L_{bol} = 0.1 M c^2$. Upper panel: the duration of accretion is equal to the thermal time ($\sim 10^4$ yrs) of the red giant’s envelope. Bottom panel: the duration of accretion is equal to the He-burning time in the stellar core.

3.2 Disc IMBHs

In the case of IMBHs originated in the galactic disc from zero-metallicity massive stars we obtain a somewhat higher number of ULXs $\sim 10^{-8}$ per galaxy (see Fig 5). A more effective formation of accreting binaries in this case results from the smaller velocity dispersion of the
Figure 3. Integral distribution of the accretion rate for IMBHs wandering in the galactic halo. IMBHs from 3σ halos are used. Lines and panels as in Figure 2.

disc IMBHs as compared to the halo ones. Still, this is not enough to explain observations. The results of calculations are presented in Fig. 5 for the Salpeter initial mass function of zero-metallicity stars ($\alpha = 2.35$). In the case of $\alpha = 1.35$ results are generally similar. The number of sources is several times higher, but still not enough to explain the observed population of ULXs. Taking even flatter initial mass function we can increase this number further more, but still not enough.
Figure 4. Total number of accreting IMBHs (i.e. independent of their luminosity) vs. time of the on-set of accretion (time is counted since the moment of formation of the binary system). Calculations are performed for IMBHs from $3.5\sigma$ halos and assuming that the time scale for accretion is set by the thermal time of the convective envelope. Time is in Myrs. Results are presented for two variants of the cross-section according to Hills (1991) and Hut et al. (1991). For each variant the sum in all bins is normalized to unity.

4 RESULTS FOR TIDAL CAPTURE

4.1 Halo IMBHs

The tidal capture of halo IMBHs is a significantly more effective mechanism of formation of bright accreting binaries. Still, the number of ULXs formed by means of this channel is found to be very small, $\sim 10^{-7}$ per galaxy. Accounting for low-luminosity sources increases the number of accreting IMBHs (but not ULXs) to $\lesssim 0.01$ per galaxy (see Figs. 2, 3).

As in the case of exchange interactions, we also performed calculations where, instead of the very short Kelvin-Helmholtz timescale of the red giant envelope, we took the He-burning time in the stellar core. Results are not changed significantly.

For some ranges of $\dot{M}$, in our calculations we found only a few accreting systems. As we present here integral distributions, this results in the appearance of “plateaus”. This is clearly seen in the figures: the lines for tidal capture often demonstrate a “step-like" shape.

For tidal captures, we find three main types of accreting components to IMBHs. Two of them are the same as in the case of exchange interactions (red giants and white dwarfs). For low accretion rates $\dot{M} < 3 \times 10^{-9} M_\odot$ yr$^{-1}$, companions are mainly white dwarfs. For high accretion rates $\dot{M} > 10^{-6} M_\odot$ yr$^{-1}$, most companions are red giants. For the intermediate range $3 \times 10^{-9} < \dot{M} < 3 \times 10^{-8} M_\odot$ yr$^{-1}$ the accreting components can be dwarf main sequence stars. In these systems accretion occurs because of orbital decay due to gravitational wave emission. This mechanism of binary orbital angular momentum removal is
Figure 5. Integral distribution of the accretion rate for IMBHs formed in the Galactic disc from primordial metal-free gas \((\alpha = 2.35)\). Lines and panels as in Figure 4.

effective for very close binaries which can be formed after tidal captures. The mass accretion rate in this case is determined by the orbital decay timescale.

4.2 Disc IMBHs

IMBHs formed in the disc have much lower velocity dispersion \((\sim 10 \text{ km s}^{-1})\) than halo IMBHs, so binaries formed in the galaxy plane due to tidal captures by them will have
larger semimajor axes than those formed from captures by high-velocity halo IMBHs. This
results in less effective ULX formation, see Figs. \ref{fig:ULX}

5 DISCUSSION AND CONCLUSIONS

In this paper we have demonstrated that the probability to form an ULX by IMBHs wander-
ing in the galactic halo through capturing of a stellar companion is very low. There are
three reasons for that (see Eq. \ref{eq:prob}). First, the very probability of capturing a stellar companion by
IMBHs in the galactic disc is extremely small. For halo IMBHs it is mainly due to their high
velocities during the galactic disc crossings. Captures are more probable in the central re-
gions of galaxies with higher stellar density, but still their numbers are insufficient to explain
the observed ULX statistics in galaxies. Another reason is that the bright accretion stage is
usually very short (see also \cite{Blecha et al. 2006}). The third reason is that to form an ULX,
it is usually necessary to capture a component at a particular stage of its evolution, when
the orbital separation is small, such as, for example, a very close binary with a white dwarf,
or a system just before coalescence. For disc IMBHs evolved from zero-metallicity stars the
same three arguments are valid.

Taken together, the three processes listed above, (1) capturing of any component, (2)
short duration of the ULX stage, and (3) small probability to find a star which is going to
be captured on a specific evolutionary stage, reduce the number of observable ULXs by \sim 9
orders of magnitude.

We have quantified the relative importance of the three processes and found that it is
the short lifetime of an ULX that mostly reduces the rate of occurrence of ULXs (by four
orders of magnitude alone). The necessity to capture a stellar component at the particular
evolutionary stage reduces the ULX occurrence rate by three orders of magnitude. The
dynamical capture probability causes another two orders of magnitude reduction.

Suppose that in every passage through the galactic plane an IMBH always captures a
star through exchange interactions with binaries. Not all of the binaries formed this way
can later appear as ULXs. Let us forget about this for a moment and assume that the
initial binary system always provides the IMBH with a stellar companion with appropriate
properties. Then let us assume that once an ULX is formed, it is visible for a very long time.
Only under such overly optimistic assumptions the number of IMBHs formed in 3\sigma halos
(126 per galaxy) would be sufficient to produce the observed \sim 0.1 ULX per galaxy.
We conclude that the mechanisms of exchange interaction and of tidal capture cannot explain the observed population of ULXs under the assumption that they are related to IMBHs wandering in the galactic halos or formed in situ from zero-metallicity stars in galactic discs. We have showed that the formation rate of accreting systems with IMBHs is very low even for smaller luminosities. For $L > 10^{36}$ erg s$^{-1}$ we obtain only $< 0.01$ accreting IMBH per galaxy. Hence we conclude that dynamical captures of companions by IMBHs remnants of zero metallicity stars do not lead to a potentially interesting number of observable sources.

A much more promising way of forming ULXs from IMBHs can be achieved in a scenario in which the formation of IMBHs derives from runaway merging of stars in dense star clusters. In this case the probability of capturing a companion is very large. The formation of persistent ULXs is however not granted. Blecha et al. (2006) find that IMBH binaries reach a steady ULX luminosity only for a short period of time ($\sim 10^5$ years), making their detection improbable. Hopman et al. (2004), Baumgardt et al. (2006) find more optimistic results for more massive IMBHs, when companion stars are captured through tidal heating from a mass-segregated population.

Another possibility, which would bypass the need for a stellar companion, is that the fuel for the IMBHs is provided by a baryonic remnants that they carry with themselves (see e.g. Volonteri & Perna 2005)). These IMBHs, however, are not to be confused with "naked" IMBHs ejected from galaxy centers by, e.g., the gravitational rocket mechanism. IMBHs accreting from baryonic remnants are instead associated with inefficient galaxy mergers, where the IMBHs was hosted by a small satellite falling into the halo of a large galaxy. Such light satellites seem to be almost unaffected by orbital decay, and they are left on peripheral orbits. The IMBHs hosted in the satellite cores, if accreting, would be found in the outskirts of a galaxy. Swartz (2006), however, notices that the most (or even all), of ULXs are found located within the optical extent of their host galaxies.

ACKNOWLEDGMENTS

We thank the referee for useful comments. The work of A.K. and K.P. was partially supported by the RFBR grants 04-02-16720 and 06-02-16025, S.P. is the INTAS and Cariplo Foundation Fellow.
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