Radio pulsars around intermediate mass black holes in super stellar clusters

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ABSTRACT
We study accretion in binaries hosting an intermediate mass black hole (IMBH) of $\sim 1000 M_\odot$, and a donor star more massive than $15 M_\odot$. These systems experience an active X-ray phase characterized by luminosities varying over a wide interval, from $<10^{36}$ erg s$^{-1}$ up to a few $10^{40}$ erg s$^{-1}$ typical of the ultra luminous X-ray sources (ULXs). Roche lobe overflow on the zero-age main sequence and donor stars above $20 M_\odot$ can maintain a long-lived accretion phase at the level required to feed a ULX source. In wide systems, wind transfer rates are magnified by the focusing action of the IMBH yielding wind luminosities $>\sim 10^{38}$ erg s$^{-1}$. These high mass-IMBH binaries can be identified as progenitors of IMBH-radio pulsar (PSR) binaries. We find that the formation of an IMBH-PSR binary does not necessarily require the transit through a ULX phase, but that a ULX can highlight a system that will evolve into an IMBH-PSR, if the mass of the donor star is constrained to lie within 15 to 30 $M_\odot$. We show that binary evolution delivers the pre-exploding helium core in an orbit such that after explosion, the neutron star has a very high probability to remain bound to the IMBH, at distances of 1-10 AU. The detection of an IMBH-PSR binary in the Milky Way has suffered, so far, from the same small number of statistics limit affecting the population of ULXs in our Galaxy. Ongoing deeper surveys or next generation radio telescopes like SKA will have an improved chance to unveil such intriguing systems. Timing analysis of a pulsar orbiting around an IMBH would weigh the black hole in the still uncharted interval of mass around 1000 $M_\odot$.

Key words: ULX — galaxies: neutron star — IMBH — X-rays: binaries — X-rays: galaxies

1 INTRODUCTION
Recent high resolution X-ray imaging and spectroscopic studies with Chandra and XMM, have led to the discovery of a large sample of a new class of compact sources with luminosities in the interval between $3 \times 10^{39}$ erg s$^{-1}$ and $10^{41}$ erg s$^{-1}$, that are in excess of the Eddington limit of a stellar-mass black hole of $20 M_\odot$ (Fabbiano 1989; see Mushotzky 2004 for a critical review). These sources can find a simple interpretation in the hypothesis that intermediate mass black holes (IMBHs) exist with mass $10^2 M_\odot - 10^4 M_\odot$ accreting from a companion star in binary systems (Fabbiano 1989; Mushotzky 2004; Miller & Colbert 2004). The detection of a cool-disc thermal spectral component in a number of ULXs (Miller et al. 2003; Zampieri et al. 2004; Eliasdóttir et al. 2004; Miller, Fabian & Miller 2004; Kaaret et al. 2004; Cropper et al. 2004; Dewangan et al. 2004), the properties of the optical and radio counterparts (Koerding, Colbert & Falcke 2005; Liu et al. 2004; Zampieri et al. 2004; Kaaret et al. 2004; Soria et al. 2005; Miller, Mushotzky & Neff 2005), and the timing behaviour of at least one source in the starburst galaxy M82 (Strohmayer & Mushotzky 2003; Fiorito & Titarchuk 2004), support this view. The IMBH hypothesis however does not represent the only possibility to explain the emission of ULXs, since mechanical beaming working in a thick disc around a conventional stellar-mass black hole, or Doppler boosting from a jet in a microblazar could produce the same range of observed luminosities (King et al. 2001; Koerding et al. 2002; Mushotzky 2004). Moreover, in a recent work of Rappaport, Podsiadlowski & Phpal (2005) the authors use binary evolution calculations to show how the largest part of the ULX population may be explained.

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with a stellar mass black hole emitting at a super Eddington rate of $\sim 10$ without the requirement of an IMBH (see also Podsiadlowski, Rappaport & Han 2003 and Pfahl, Podsiadlowski & Rappaport 2005 for an extended study on the evolution of stellar mass black hole binaries). This is also in agreement with another study of King & Dehnen (2005) where the authors claim that the luminosities of a large sample of ULXs could be explained using helium enriched matter and mechanical beaming with a stellar mass black hole. But, all the alternatives to the IMBH hypothesis meet with strong difficulties when the luminosity of a ULX is in excess of $\sim 10^{34}$ erg s$^{-1}$, since, in this case, beaming under rather extreme conditions should be at work to match with the observations, or super Eddington factors greater than $\sim 10$ could be difficult to achieve. On the other hand, although the hypothesis of an IMBH explains naturally many of the observational clues, it clashes with the problem of providing a viable mechanism of formation. Until now, two possibilities have been proposed: the formation of an IMBH through runaway collisions among massive stars undergoing fast dynamical segregation, in the core of a dense super star cluster (see Porteigies Zwart et al. 2004; Gurkan, Freitag & Rasio 2004), or the wandering of an IMBH, relic of a zero metallicity population III star (Abel et al. 2000). In the first case, the giant star that forms in the core of the dense star cluster, collapses into an IMBH. This can occur in a star-forming region, and the result is based on very large detailed N-body simulations (Portegies Zwart et al. 2004a). The case of wandering IMBHs relic of the early assembly of haloes in a currently starforming galaxy is uncertain, in particular the capture of gas or of a star to ignite accretion (Volonteri & Perna 2005).

In order to solve the controversy on the real existence of IMBHs in ULXs, the only secure route would be the determination of the optical mass function, similar to the procedure for the stellar-mass black holes in the Milky Way (Orosz et al. 2004). This is difficult however, since ULXs are distant sources hosted in external (starburst) galaxies for which the optical identification of the companion is troublesome, and even in the lucky circumstance of good identification (see Zampieri et al. 2004; Kaaret et al. 2004; Soria et al. 2004; Liu et al. 2004; Miller et al. 2004) the optical spectrum is too noisy to allow a mass estimate of the black hole.

In this paper we propose an alternative way to discover and weigh a IMBH: it uses the detection of a young radio pulsar around an IMBH. If ULXs are indeed accreting IMBHs in binaries, their evolution would end with a radio pulsar around the IMBH, if the mass of the donor star is in the range which avoids the formation of a stellar-mass black hole or of a white dwarf. The detection of a radio pulsar orbiting around an IMBH would provide, through timing, an unambiguous measure of its mass.

At present, no young radio pulsars have been seen orbiting a heavy invisible companion, but in the near future the search of these hypothetical IMBH-pulsar systems (IMBH-PSR hereon) can be extended to nearby galaxies, with LOFAR (Röttgering 2003) and SKA (Cordes et al. 2004). An IMBH-PSR system would lead to the discovery of black holes in the still uninvestigated interval of masses between $100 M_\odot$ \textendash $10^4 M_\odot$. Stellar-mass black holes around pulsars have long been considered to be the “holy grail” of compact star binaries. The systems studied here are even more intriguing, given their importance in discovering a new unexplored mass range crucial for cosmology (Madau & Rees 2001). The discovery of a pulsar orbiting around a stellar-mass black hole is expected in the next years, on the basis of theoretical considerations concerning their population, and on the observability of the radio pulsar signal (Lipunov et al. 1994, Sigurdsson 2003, Lipunov et al. 2005). On similar lines, there is also the hope of detecting, despite the large interstellar electron densities, a radio pulsar orbiting around the massive black hole of $\sim 3 \times 10^6 M_\odot$ hosted in the core of our Galaxy (Pfahl & Loeb 2004). Thus, the issue of pulsars around black holes is becoming of paramount importance.

In this paper we will assume the hypothesis of the formation of IMBHs in young dense star clusters, and will start our evolution study just after the formation/capture of a high mass star around the IMBH, which could be the progenitor of an IMBH-PSR system. In this framework, Hopman et al. (2004) considered the possibility that a passing star is tidally captured by the IMBH in a stable, close, not plunging orbit. Mass transfer may initiate, after circularization, while the star is on the main sequence or evolving away from it. Dynamical capture of a massive star by an IMBH is a further possibility, as shown by Baumgardt et al. (2004). In an exchange interaction of a binary star, the IMBH can acquire a companion, likely a massive star, given that the IMBH forms in a mass-segregated environment, where stellar encounters play an important role.

The observational appearance of binaries hosting an IMBH has only been partly explored, and mainly in the context of ULXs. Portegies Zwart et al. (2004b) studied the evolution of an IMBH of 1000 $M_\odot$ accreting from a donor star of mass between 5 to 15 $M_\odot$ (see also Kalogera et al. 2004 for another binary evolutionary study). Typically, light donors ($\lesssim 5 M_\odot$) do not transfer mass at a sufficiently sustained rate to produce sources as bright as ULXs; only the high mass stars ($\gtrsim 10 M_\odot$) on the main sequence or beyond can provide luminosities in excess of $10^{38}$ erg s$^{-1}$. Thus, IMBHs cannot easily be identified on the basis of their X-ray activity: they can display a rather wide range of luminosities, depending on the mass of the donor star, and on the mass transfer mechanism, as it will be shown in this paper. Only when they outshine as bright ULXs can they become visible over the stellar-mass black holes.

In this paper we address a number of issues, in the hypothesis that an X-ray and/or a ULX phase preceeds the one in which the system appears as an IMBH-PSR binary:

- What are the characteristics of the X-ray phase and of mass transfer when considering massive donors around an IMBH?
- Is the formation of a radio pulsar likely?
- What is the probability that an asymmetric kick imparted to the neutron star at birth, will unbind the system?
- On which orbits the radio pulsar is released after the supernova explosion? Can Doppler effects hamper the detection of the radio signal?

In order to address these questions, we explore in §2 wind fed accretion (WFA), and accretion through Roche lobe overflow (ROLF), when considering donor stars with masses in excess of 15 $M_\odot$. We infer the typical luminosities of these high-mass IMBH binaries and the fate of the mass transferring star. In §3 we explore natal kicks in such exotic massive
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2 ACCRETION ONTO IMBHs

Here we explore the evolution of binaries with an IMBH of 1000 M⊙ and stars having mass M heavier than 15 M⊙, so that we can be confident that, despite mass loss, the donor star does not evolve into a white dwarf. The helium core mass necessary to form a neutron star is in the range 2.8 M⊙ < Mhel < 8 M⊙, although some uncertainties exist in these upper and lower limits (Tauris & van den Heuvel 2004). In each evolutionary sequence, obtained by varying the mass and the initial orbital separation, the star is evolved until carbon ignition. The mass transfer episodes are either driven by RLOF during the main sequence phase; by RLOF during the rapid expansion of the star when ascending the giant branch; or by WFA when the system is detached. This third possibility has always been overlooked in previous studies, though it seems relevant to understand the different phases of an accreting IMBH.

The evolution equations for the binary systems are solved using an updated version of the Eggleton code (Eggleton 1976; Pols et al. 1995) with a modified mass transfer rate for the WFA case, as explained later in the text. All the stars considered have Population I chemical composition (Y=0.28, Z=0.02), radii R and wind losses ˙Mw obtained according to de Jager et al. (1988). The mixing length parameter is set to α = 2.0, and the overshooting constant δov = 1.2 (Pols et al. 1998). Using general arguments, we then focus attention on the remnant left in the evolution to study the detectability of a young neutron star revolving around an IMBH.

2.1 Wind Fed Accretion

Consider a donor main sequence star of mass M above 15 M⊙, moving on a circular orbit around an IMBH of mass M_{BH}. Let a be the relative separation,

\[ V_{orb} \simeq 950 \left( \frac{M_{BH} + M}{1015 M_\odot} \right)^{1/2} \left( \frac{a}{1 \text{AU}} \right)^{-1/2} \text{ km s}^{-1} \] (1)

the relative orbital velocity, and

\[ V_w \simeq 1070 \left( \frac{M}{15 M_\odot} \right)^{1/2} \left( \frac{R}{5 R_\odot} \right)^{-1/2} \text{ km s}^{-1} \] (2)

the stellar wind velocity, set equal to the escape velocity from the stellar surface.

WFA dominates when the star is underfilling its Roche lobe radius, i.e., when the binary separation a exceeds a_{RL}, defined as

\[ a_{RL} = \frac{R [0.6 q^{2/3} + \ln (1 + q^{1/3})]}{0.49 q^{2/3}} \] (3)

where q = M/M_{BH}.

In high mass X-ray binaries, the mass of the donor usually exceeds the mass of the black hole, hence, the wind particles mainly accrete onto the black hole from unbound orbits, since V_{orb} ≪ V_w. Capture occurs within a cylinder of radius comparable to a_{BH} ~ 2GM_{BH}/V_w^2 ≈ (M_{BH}/M) R. In the fluid approximation, this leads to an accretion rate onto the hole of

\[ \dot{M}_{BH} \approx \frac{1}{4} (a_{BH}/a)^2 \left( \frac{V_{rel}/V_w}{\dot{M}_w} \right) \] (4)

(Shapiro & Lightman 1976, Shapiro & Teukolsky 1983), where \dot{M}_w is the wind speed relative to the black hole

\[ V_{rel} = V_w^2 + V_{orb}^2 + 2 V_{orb} V_w \cos \alpha, \] (5)

with \alpha ∈ [0, π] the angle between the directions of V_{orb} and V_w. Equation (4) is valid when a ≫ a_{BH}, and V_{orb} ≪ V_w, so that V_{rel} ≈ V_w.

In a binary with an IMBH, we may have a_{BH} ≫ a (or equivalently V_{orb} ≪ V_w), i.e., the particles released from the donor star surface can have kinetic energies such to be bound to the IMBH. This effect may lead to an accretion rate \dot{M}_{BH} comparable to the wind mass loss rate \dot{M}_w. In particular, if all the wind particles are deep in the potential well of the IMBH, their total energy K + U = V_{rel}^2/2 - GM_{BH}/a is negative. This implies a full wind gravitational focussing by the IMBH, and an X-ray luminosity at its highest value. The limiting orbital separation for this to occur corresponds to the case K + U = 0 for the most energetic wind particles, i.e., the ones having α = 0. This yields V_{orb} = (1 + \sqrt{2}) V_w, and accordingly, a binary separation

\[ a_{min} = \frac{G M_{BH}}{(1 + \sqrt{2}) V_w^2} \approx 0.1 \frac{M_{BH}}{M} R \] (6)

Below a_{min} the wind is entirely accreted. When α = π, the condition K + U = 0 corresponds to those particles having the minimum relative speed to remain bound to the IMBH. This defines a critical orbital velocity V_{crit} = (\sqrt{2} - 1) V_w and in turn a limiting orbital separation

\[ a_{max} \approx \frac{G M_{BH}}{(\sqrt{2} - 1) V_w^2} \approx 3 \frac{M_{BH}}{M} R \] (7)

above which all wind particles are unbound. In the interval a_{min} < a < a_{max} wind particles with K + U > 0 escape the gravitational field of the IMBH and this defines a loss cone of solid angle Ω = 2π(1 - cos \tilde{\alpha}), with \tilde{\alpha} = cos^{-1}[(V_{orb}^2 - V_w^2)/(2V_w V_{orb})]. Under these conditions, the accretion rate onto the IMBH can be approximated as

\[ \dot{M}_{BH} \sim \text{Max} \left[ \left( 1 - \frac{\Omega}{4\pi} \right) \dot{M}_w; \frac{a_{RL}^4}{M_{BH}} \right] \] (8)

For the mass transfer rate of eq. (8) even a very high mass star can provide the ULX luminosities during the main sequence, without the requirement that the donor is crossing the supergiant phase. In Figure 1 we illustrate this effect, plotting accretion rates \dot{M}_{BH} and \dot{M}_{BH}^{rel} for an IMBH of 1000 M⊙ and a donor star of 30 M⊙ during the main sequence. The probability to observe this system is strongly increased due to the larger time spent by the star on the main sequence.
In Figure 2, we show $a_{\text{min}}$ and $a_{\text{max}}$ as a function of the mass of the IMBH, compared to $a_{\text{RLOF}}$, i.e., the distance at which the donor star overfills its Roche lobe. The light gray area corresponds to orbital separations where WFA is in the Shapiro-Lightman limit, while in the middle gray area, the wind is enhanced by the action of gravitational focussing by the IMBH, and in the heavy gray area, it is fully captured, leading to a conservative system. The black area is the RLOF zone.

In our WFA model, the possible formation of a circumbinary disc around the donor star might change the quantity of wind accreted, although the order of magnitude remains unchanged (see van den Heuvel 1994). We have followed the evolution of the binary under WFA, starting from a separation of 1 AU, imposing angular momentum and mass loss from the fraction of the wind escaping from the binary. The star is non rotating and the wind leaves the donor isotropically, carrying away, in the centre mass reference frame, a specific angular momentum $J = h(M_\odot - M_{\text{BH}})$ with $h$ the specific angular momentum of the orbit (see Soberman, Phinney & Van den Heuvel 1997 for a detailed discussion). We have computed the accretion rate onto the IMBH using eq. (8) and a WFA luminosity adopting an efficiency factor of $\sim 0.1$ characteristic of disc accretion, since the captured wind has high enough angular momentum to form a disc.

The run of the WFA luminosity as a function of time is shown in Figure 3 for an IMBH of 1000 $M_\odot$ in a binary with a 20-30-50 $M_\odot$ star, respectively. The luminosity is enhanced relative to the value that would be predicted from a stellar-mass black hole under equivalent conditions. With time the WFA luminosity rises mainly because of the intrinsic increase of the wind mass loss rate when the star is transiting through the Shapiro-Lightman limit, while in the middle gray area, it is mild gray refers to a partial focussing of the wind, while the light gray area is for accretion of the entire wind lost by the donor star.

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2.2 Accretion through Roche lobe overflow

Accretion via RLOF occurs during the main sequence when the star is close enough to the IMBH to fill its Jacobi surface, or during the rapid expansion of the star when ascending the giant or supergiant branch. In this section we explore the evolution for the former case, i.e., for separations ranging between 0.18-0.25 AU for a 1000 $M_\odot$ IMBH, and 15-50 $M_\odot$ companion stars.

Roche lobe contact remains stable along the entire evolution and gives luminosities above $10^{39}$ erg s$^{-1}$ when the donor star has a mass $M \geq 15 M_\odot$. Luminosities of $10^{40}$ erg s$^{-1}$, typical of the brightest ULXs, need a star at least as massive as 20 $M_\odot$, as illustrated in Figure 4. Adopting the Dubus criterion for assessing the stability of the disc against the thermal ionization instability (Dubus et al. 1999), we find that RLOF onto an IMBH is stable, under our conditions. This ensures that high mass IMBH binaries can remain bright for a relatively long time, between a few million to ten million years. This is opposite to the case of IMBH binaries with donor stars having masses $\leq 10 M_\odot$ as pointed out by Portegies Zwart et al. (2004b), for which

![Figure 1](image1.png)

**Figure 1.** $\dot{M}_{\text{BH}}$ (solid line) and $\dot{M}_{\text{BH}}^{\text{SL}}$ (dashed line) versus $a$ for a donor of $30 M_\odot$ and an IMBH of 1000 $M_\odot$. The mass transfer rates are in units of the wind mass loss rate. The accretion rate onto the IMBH is the highest value between the two. The figure is explained in the text.

![Figure 2](image2.png)

**Figure 2.** $a_{\text{RLOF}}$ (dashed line), $a_{\text{min}}$ (lower solid line) and $a_{\text{max}}$ (upper solid line) versus $M_{\text{BH}}$ for a donor of $30 M_\odot$ on the ZAMS. WFA prevails above the dashed line. If the donor star is inside the gray shaded area, WFA is enhanced by the gravity of the IMBH. Black area ($a_{\text{min}} > a_{\text{RLOF}}$) corresponds to RLOF, while the heavy gray area is for accretion of the entire wind lost by the donor star. Mild gray refers to a partial focussing of the wind, while the light gray is the Shapiro-Lightman regime. The condition $a_{\text{min}} = a_{\text{RLOF}}$ defines a minimum IMBH mass for which WFA occurs under full capture of the stellar wind, giving maximum WFA luminosities. For a $30 M_\odot$ donor this minimum IMBH mass corresponds to $\sim 3000 M_\odot$.

from the zero age to the terminal age main sequence. Only very massive stars can provide mean luminosities in excess of $3 \times 10^{39}$ erg s$^{-1}$, the threshold defining ULX sources.
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Figure 3. From the top to the bottom lines: WFA luminosity against time for donors with masses of $50 \, M_\odot$, $30 \, M_\odot$, and $20 \, M_\odot$ respectively, and a black hole’s mass of $1000 \, M_\odot$. The initial orbital separation is $1 \, AU$. The dashed line is the limit to obtain an ULX. The mass transfer begins near the ZAMS and the integration is stopped when the star reaches the giant branch. At this point a RLOF phase starts, producing the sharp spikes in the plot, with the exception of the donor of $50 \, M_\odot$ for which the code is stopped at the end of the main sequence.

The luminosities are transient and the X-ray phases last for a longer time, comparable with the donor lifetime. Within the limits of the available time span coverage of ULX observations, the apparent persistency in their emission may be an indication that donor stars have masses in the range considered in this paper.

Figure 4. Luminosity against time, for donors with masses of $15, 20, 25, 30, 50 \, M_\odot$, respectively, and for an IMBH of $1000 \, M_\odot$. The mass transfer begins near the zero age main sequence and the integration is stopped before carbon ignition. Stellar masses in excess of $\sim 20 \, M_\odot$ can produce luminosities above $10^{40} \, erg \, s^{-1}$ during the main sequence. All binaries appear to be persistent sources. The dashed line represents the ULX limit. Note that there is only one spike for each donor, corresponding to the giant phase. The envelope of the donor is almost completely depleted during this phase and the re-expansion after the helium burning is too small to produce another contact phase.

The high mass transfer rates that establish during RLOF dramatically change the mass of the star. Figure 5 shows the donor mass as a function of time. At the end of the stellar evolution, the core mass is almost equal to the mass of the whole star, since the mass transfer strips almost completely the entire stellar envelope during the RLOF phase. Donors with mass between $15 \, M_\odot$ and $\sim 25 \, M_\odot$ on the zero age main sequence likely end their lives with a core mass between $3.3$ and $7 \, M_\odot$, probably producing a neutron star. The case of a $30 \, M_\odot$ could be considered the mass limit between the neutron star and the black hole formation, since its final core mass is $\sim 9 \, M_\odot$. The fate of the heaviest star here considered ($M \gtrsim 30 \, M_\odot$) is to collapse into a stellar-mass black hole.

If RLOF is the mechanism leading to a ULX during the main sequence phase, the donor star is expected to lie at an initial distance of $a < \sim 1 \, AU$ from the IMBH. After leaving the main sequence, the star ascends the giant branch, while keeping on overflowing its Roche lobe. This generate the spikes in Figure 4 giving very high luminosities. The typical values of $a$ reached at the end of the evolution are in the range of $\sim 2 - 5 \, AU$.

If the initial orbital separation of a donor star is $a \gtrsim 1$ AU, RLOF is avoided on the main sequence phase. The star, in exiting the terminal age main sequence, may later overfill its Roche lobe due to the sizable increase of its radius when ascending the giant branch, initiating a phase of accretion. Mass transfer and angular momentum conservation will drive the star further away from the IMBH, up to typical distances of $8 - 10 \, AU$.

3 NEUTRON STAR KICKS AND THE SURVIVAL OF THE IMBH-PSR BINARY

In the RLOF case, the continuous increase of $a$, implied by conservative mass transfer, would bring the donor to distances of several astronomical units. We may ask whether the explosion and the asymmetric kick that accompanies the formation of the neutron star can unbind the system. Given the high inertia of the IMBH, a neutron star has a greater chance to remain bound than in the case of a lighter black hole companion.

To keep a binary bound, we need a kick velocity below the limit given by the equation (Brandt & Podsiadlowski 1994, Willems, Kalogera & Henninger 2004)

$$V_{k,l} = \left[ \frac{G \left( M_{BH} + M \right)}{a_0} \right]^{1/2} \left[ 1 + \left( \frac{M_{BH} + M_{NS}}{M_{BH} + M} \right)^{1/2} \right]$$ (9)

where $M_{NS}$ is the mass of the neutron star formed after.
the supernova explosion, and $M$ and $a_0$ are the mass of the donor star and binary separation, just prior the supernova explosion. In the presence of the IMBH, the total mass remains almost constant before and after the explosion, and so the most important parameter is the orbital separation $a_0$. To obtain a conservative estimate, we use our largest value of $a_0$ which is about 10 AU. The kick velocity limit is around 700 km s$^{-1}$.

To calculate the probability of survival of the IMBH-PSR system, we adopt an analytical expression for the distribution of the kick magnitudes (Hansen & Phinney 1997, HP distribution)

$$p(V_k) = \sqrt{\frac{2 V^2_k}{\pi \sigma^2}} e^{-V^2_k/\sigma^2}, \quad (10)$$

where $\sigma$ is the velocity dispersion of each of the components of the kick velocity.

Although there is not full agreement on the form of the kick magnitude distribution, it is rather well established that speeds larger than $\sim 700$ km s$^{-1}$ are attained only in extreme rare cases (see also Lyne & Lorimer 1994, Arzoumanian et al. 2002, Hobbs et al. 2005). Therefore we are confident that our calculations are not strongly affected by the particular choice of the distribution, since what is interesting here is the existence of a cutoff at high velocities more than the specific form of the distribution itself.

We use the following equation to calculate the probability of survival of our system, obtained by integrating the HP distribution between zero and our kick velocity limit:

$$\frac{\int_{0}^{V_{k,l}} p(V_k) dV_k}{\int_{0}^{\infty} p(V_k) dV_k} = \text{Erf} \left( \frac{V_{k,l}}{\sigma} \right) - \frac{2V_{k,l}}{\sqrt{\pi} \sigma} e^{-2V_{k,l}^2/\sigma^2} \quad (11)$$

Using a value for $V_{k,l}$ of 700 km s$^{-1}$ and a value for $\sigma$ of 152 km s$^{-1}$ (Hobbs et al. 2005), we infer a probability of survival greater than 99%. Therefore after the supernova explosion we can be confident that the system is still bound.

After the explosion the orbital parameters change. To obtain the distribution of post-supernova orbital separations and eccentricities, we introduce, following Kalogera (1996), the three dimensionless parameters that are necessary to constrain the properties of the binary after the explosion:

$$\alpha = \frac{a_f}{a_0} \quad (12)$$

$$\beta = \frac{M_{BH} + M_{NS}}{M_{BH} + M} \quad (13)$$

$$\xi = \frac{\sigma}{V_{orb}} \quad (14)$$

where $a_0$ is the pre-explosion binary separation and $a_f$ its post-explosion value, $\beta \approx 1$ the binary total mass ratio, after and prior explosion.

Typical pulsar 1D speeds peak at 152 km s$^{-1}$ (Hobbs et al. 2005). Given the high relative orbital velocity (eq. 1) with respect to $\sigma$, $\xi \ll 1$ in our case. Figure 6 shows the probability distribution over $\alpha$ and post-encounter eccentricity $e$, computed for $\beta \sim 1$ and $\xi = 0.3$, while Figure 7, and Figure 8 give the distribution over $e$ (integrated over $\alpha$) and $\alpha$ (integrated over $e$) respectively, for selected values of $\xi$.

Post-supernova binaries populate only a restricted area of the $\alpha$$-$$e$ plane giving minimum acceptable post-supernova separations $a_f = (1/2)a_0$ for $\xi \sim 1$ and $a_f = a_0$ for $\xi < 1$ according to the fact that the post-supernova orbit must include the position of the two stars just prior to explosion. Because we have found in Section 2.2 that the likely pre-supernova orbital separation falls in the range 2-10 AU, final values of $a_f$ range between $\sim 1 - 10$ AU.

The small eccentricity of these systems is a direct consequence of the very high mass of the IMBH, which produces higher orbital velocities than in normal binaries, and a value of $\xi < 1$ also for the largest orbital separations. Another consequence of the large mass of the black hole is that the binary can be always defined as an hard one (Heggie 1975).
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and thus the dynamical interactions in the star cluster tend to decrease the orbital separation of the system, although there are some uncertainties in the real effect of this process as stated by Hopman & Portegies Zwart (2005).

Neglecting this uncertain effect, the production of gravitational waves seems to be unimportant, because the pulsar is revolving on a mildly eccentric orbit at a large separation. The in-spiral time for emission of gravitational waves is extremely large: \( t_{GW} \gtrsim 3 \times 10^{10} \) yrs for \( e = 0.4 \), and only for very high eccentric systems (\( e = 0.9 \)) it is \( t_{GW} \sim 6 \times 10^7 \) yrs.

The lifetime of a super star cluster is about \( 10^8 \) yrs (see Hopman & Portegies Zwart 2005), which is comparable to the lifetime of the binary even if the eccentricity produced by dynamical interactions becomes \( \sim 0.9 \). Thus we have a very small probability of a merger in a super star cluster by gravitational waves emission, and the observability in the radio band of our system is not compromised by this effect. This is in agreement with the results of Hopman & Portegies Zwart (2005) which found that with an IMBH of \( \sim 1000 \, M_\odot \), only a fraction around 2% would merge in an Hubble time.

4 SIMULATING PULSARS AROUND IMBH

The search of pulsars in binary systems is more difficult than for isolated pulsars, because of changes in the line-of-sight velocity due to orbital motion cause varying observed pulse periods. Most of the algorithms for searching for periodicities in a time series use a Fast Fourier Transform (FFT) to produce a frequency spectrum; a varying received pulsation frequency spreads the detection over many spectral bins. This reduces the signal-to-noise ratio \( (s/n) \) of a detection with respect to that of an isolated pulsar with the same intrinsic flux and rotational period.

We have investigated the consequences of this effect on the probability of detecting a pulsar orbiting an IMBH during the Parkes Pulsar Multibeam survey (Manchester et al. 2001), i.e. the deepest and most successful large scale survey for pulsars in the Galactic disc completed so far, resulting in the discovery of more than 700 new sources (Faulkner et al. 2004). We have generated many sets of simulated time series containing a pulsating signal (with a duty cycle of 5%, as statistically appropriate for non-recycled pulsars) of a pulsar of \( 1.4 \, M_\odot \) orbiting an IMBH of \( 1000 \, M_\odot \). The other binary parameters have been chosen to span the most likely values of the distribution plotted in Figure 6, i.e. orbital separations in the range 1-10 AU (corresponding to orbital periods from \( \sim 10 \) days to \( \sim 1 \) yr) and eccentricity from 0 to 1 in steps of 0.05. The sampling time (0.25 ms) and the total number of samples \( (2^{23}) \) are the same as the observations of the Parkes Pulsar Multibeam survey. Spin periods have been chosen to be 1000 ms, 100 ms and 10 ms (the latter being a rather extreme case for typical non-recycled pulsars, which would be expected to be hosted in a binary with an IMBH). For each of the parameters, we have produced eight time series, spanning four different values of the longitude of the periastron of the elliptical orbit (0, 90, 180 and 270 deg) and two values of the orbital phase (quadrature or conjunction) for simulated observation.

After creating this large set of time series, we first applied the standard search (which maximizes the sensitivity for detecting isolated pulsars) and, later, the “stack search”, which involves splitting each time series into 16 segments, performing an FFT on each of them. Then the resulting spectra are summed applying a constant shift between fre-
quency bins of adjacent spectra, the shift corresponding to the change in the apparent spin frequency between one segment of observation and the next (Faulkner et al. 2004). Many different bin shifts are explored in order to find the ones which maximize the spectral signal-to-noise of a given periodicity in the whole time series. At the sacrifice of a certain loss of sensitivity (due to the incoherent sum of spectra) this algorithm considerably improves the possibility of detecting Doppler distorted signals at a reasonable computational cost.

For each simulated time series, we finally compared the signal-to-noise ratio \( (s/n)_{\text{obs}} \) at which the simulated pulsed period has been recovered by the search analysis with the signal-to-noise ratio \( (s/n)_{\text{sr}} \) of the same signal if it were been emitted by a solitary pulsar. For spin period \( P > 100 \) ms, it results that \( \eta = (s/n)_{\text{obs}}/(s/n)_{\text{sr}} > 0.8 \) for all cases, but those involving \( \varepsilon > 0.7 \) and the closest orbital separations. The application of the stack search allows to maintain a relatively good sensitivity (\( \eta > 0.6 \)) at most orbital phases and eccentricities even for a 10 ms pulsars. In summary, only the combination of very extreme eccentricities and eccentricities even for a 10 ms pulsars. In summary, only the combination of very extreme eccentricities and eccentricities even for a 10 ms pulsars.

For a disc structure with thickness much smaller than its radial extension, \( \eta \) roughly represents the ratio between the galactic volumes explored to search for the two types of sources; thus, assuming a disc-like and uniform distribution for both pulsars, i.e., those in IMBH-PSR systems and the isolated pulsars, \( \eta \) indicates approximately the relative detection efficiency. In summary, given the orbital parameters of the putative pulsars orbiting IMBHs, under the conditions explored, we conclude that their detectability by the Parkes Multibeam Pulsar survey has only been modestly affected by their orbital motion. Other biases related to large-scale pulsar surveys (discussed in §5.2) play the major role in selecting the observed population from the intrinsic population of IMBH-PSR systems.

5 DISCUSSION

5.1 The formation of an IMBH-PSR and its X-ray luminosity

The formation of an IMBH-PSR binary system relies mainly on four working hypothesis: that an IMBH (i) forms in a young core-collapsed dense star cluster, (ii) acquires, preferentially, a massive companion star (with \( M > 15 M_\odot \)), given the dense environment in which it is expected to form and live, (iii) experiences a phase of wind fed or RLOF accretion that terminates when the donor star ends its life, and that (iv) the donor star is sufficiently massive to explode leaving behind a radio pulsar, as a remnant.

Hypothesis (iii) implies that an X-ray active phase precedes the formation of the IMBH-PSR binary. Thus, IMBH-PSR progenitors can be identified as X-ray sources. The X-ray active phase is found to be characterized by luminosities that spread over a broad range, depending on the mass of the companion star and the initial orbital separations. Two possibilities may occur: (a) If the star on the ZAMS is underfilling its Roche lobe, WFA luminosities in excess of \( L_{\text{ULX}} \sim 3 \times 10^{39} \) erg s\(^{-1}\) are found only in presence of donors as massive as \( 30 M_\odot \). With lighter stars, WFA luminosities fall typically in the range between \( 10^{37} \sim 10^{39} \) erg s\(^{-1}\), with the highest values coming from transfer rates magnified by the focussing action of gravitational field of the heavy IMBH on wind particles. At separations up to several AU, typical WFA luminosities fall short below \( 10^{38} \) erg s\(^{-1}\) so that, based on luminosity arguments, it would be impossible to distinguish an accreting IMBH from a stellar-mass black hole, under WFA. WFA can last as long as the entire time spent by the star on the main sequence, \( \tau_{\text{MS}} \sim 1 \sim 10 \) Myrs. Expansion of the massive star during nuclear evolution leads inevitably to a phase where the star fills its Roche lobe. This occurs when the binary separation \( a \lesssim 10 \) AU at the time the star is transiting the Hertzsprung gap and/or ascending the giant branch. At this moment, one expects a dramatic increase of the mass transfer rate (see the spikes in Fig. 3 and 4, and also Portegies Zwart et al. 2004b). This is a short lived phase of a few \( 10^5 \sim 10^7 \) yrs that accounts only for \( \sim 5\% \) of \( \tau_{\text{MS}} \), in which the binary can emit luminosities in excess of \( 10^{39} \) erg s\(^{-1}\), characteristic of those bright ULXs in which we can be confident to find an IMBH. Thus, the lifetime of a ULX, progenitor of an IMBH-PSR system, \( \tau_{\text{ULX}} \) can be as short as a few \( 10^7 \) yrs.

(b) If, instead, the massive star overfills its Roche lobe near the zero age, contact is maintained stably in the binary, and mean transfer rates as large as \( 10^{-7} \sim 10^{-5} M_\odot \) yr\(^{-1}\) are found. These rates are large enough to guarantee the stability of the disc against thermal-ionization perturbations. For donors more massive than \( 15 M_\odot \) the mass transfer rate is higher than the Dubus’ critical value so that we argue in favor of persistent emission in binaries with an IMBH and massive donors. The accretion luminosities inferred at an averaged efficiency of 0.1, all exceed \( 10^{39} \) erg s\(^{-1}\), but only stars more massive than \( 20 M_\odot \) can guarantee luminosities above \( 10^{40} \) erg s\(^{-1}\) during the main sequence. RLOF with massive donors (\( > 20 M_\odot \)) at the ULX level lasts for a time \( \tau_{\text{ULX}} \) of few million years, while lighter donors are found to brighten at the level of a few \( 10^{39} \) erg s\(^{-1}\) for a time of \( \gtrsim 10 \) Myrs.

Concerning the ultimate fate of the donor star we have seen that RLOF on the ZAMS causes significant mass losses, so, one can estimate that only stars heavier than \( 15 M_\odot \) and lighter than \( 30 M_\odot \) may end their lives as neutron stars and thus turn on as radio pulsars. Lighter donors end probably their life as white dwarfs. These can still produce ULX activity under transient conditions.

With hypothesis (iv), the formation of an IMBH-PSR system requires that the supernova explosion of the companion to the IMBH does not end with the disruption of the binary. Symmetric mass loss would not unbind the system given the large inertia of the IMBH, but the occurrence of an asymmetric natal kick can place the neutron star in an unbound orbit. Considering the pre-explosion orbital parameters from our binary evolution models, we find that the probability of survival is very high, around 90%. The IMBH-PSR binary that survives disruption would have preferential separations between 1 and 10 AU, and a mild eccentricity.
5.2 Perspectives of detection of the radiopulsar

In our study we have shown that binaries hosting an IMBH and a donor star, massive enough to leave a pulsar as a relic, likely experience an X-ray phase characterized by accretion luminosities ranging from well below the Eddington luminosity of a one solar mass star, up to values characterizing the bright tail of the ULX window. The life time $\tau_{ULX}$ over which a ULX phase is observed falls in the range between 0.05 to 10 Myrs whereas $\tau_X \simeq 10$ Myrs is the characteristic lifetime of an accreting IMBH as “normal” X-ray source. While the formation of a binary IMBH-PSR system does not necessarily require a transit through a ULX phase, a ULX phase can inversely highlight a system that will evolve into an IMBH-PSR binary. From the knowledge of the distribution function $P(a)$ of the initial orbital separations we can calculate the ratio $\mathcal{R} > 1$ between the number of binaries hosting an IMBH-massive star system ending as an IMBH-PSR, to the number of binaries $N_{ULX}$ which experience a bright ULX phase before becoming an IMBH-PSR. $\mathcal{R}$ is:

$$\mathcal{R} = \frac{\int_{a_{ULX}}^{a_{max}} P(a) da}{\int_{a_1}^{a_{max}} P(a) da}$$

where $a_1$ is the tidal disruption radius of the IMBH, $a_{max}$ is the orbital separation at which an X-ray phase (of arbitrary low intensity) occurs ending with the formation of a pulsar bound to the IMBH, and $a_{ULX}$ is the initial orbital separation at which a ULX phase sets in during binary evolution. If we suppose $P(a)$ is uniform, and take $a_{max} \simeq 200$ AU as the limiting distance above which a natal kick would unbind the system (for a chance probability of 50%), and $a_{ULX} \simeq 1$AU (the distance for a RLOF phase during the main sequence), then we obtain an approximate estimate of $\mathcal{R} \sim 200$. This shows that the IMBH-PSR binaries whose progenitor experienced a ULX phase may well represent only the tip of the iceberg of the whole population of IMBH-PSR binaries. However, we note that the estimate of $\mathcal{R}$ is strongly affected by the uncertainty of the maximum orbital separation allowed by an exchange interaction (which corresponds to the cutoff of the distribution $P(a)$), and also by the real form of the distribution $P(a)$. Detailed stellar dynamical simulations are required to improve the knowledge of the crucial factor $\mathcal{R}$.

Provided $\mathcal{R}$ is known, we can estimate the number of IMBH-PSR binaries, from the simple formula $(\tau_{PSR}/\tau_X) \mathcal{R} f N_{ULX}$ where $\tau_{PSR} \sim 10$ Myr is the lifetime of a radiopulsar, $N_{ULX}$ the observed number of bright ULX sources and $f \leq 1$ is a fudge factor to compute $N_{ULX} = f N_{ULX}$ from the known number of ULXs. In order to calculate the number of potentially observable radiopulsars $N_{IMBH-PSR}$ orbiting an IMBH, one must also account for the strong anisotropy in pulsar emission. Introducing the pulsar beaming factor $b \sim 10$ (Lorimer 2001), and scaling the others quantities to the reference values, it turns out

$$N_{IMBH-PSR} \simeq 20 f \left( \frac{\tau_{PSR}}{10\text{ Myr}} \right) \left( \frac{10\text{ Myr}}{\tau_X} \right) \frac{\mathcal{R}}{200} b N_{ULX}$$

In section §4 we have shown that Doppler distortion of the radio signal should not have hampered the detection of a putative IMBH-PSR system by the Parkes Multibeam survey of the Galactic Disc (Manchester et al. 2001). However, other selection effects influence the detectability of a given radio pulsar during a survey, the most relevant being the pulsar intrinsic luminosity and the survey sensitivity limit for a source at the given position in the Galaxy, in turn depending on the pulsar spin period, duty cycle, dispersion measure, and amount of scattering smearing. A population synthesis analysis combined with a simulation, for the given survey, is necessary (e.g. Lorimer et al. 1993) for assessing the ratio $\chi \lesssim 1$ between the number of expected detections and the number of potentially observable radio pulsars (i.e. those having the radio beam sweeping the line of sight to the Earth). Putative pulsar companions to IMBH and typical isolated pulsars are populations of non-recycled pulsars born and still residing in the Galactic disc. Assuming, in first approximation, that the two populations both share the Galactic distribution and the same intrinsic properties (such as the luminosity function), we can apply to the pulsars orbiting an IMBH the “average” value of $\chi$ properly calculated for the Parkes Multibeam Survey (Manchester et al. 2001). In particular, $\chi$ is in the range 0.050 – 0.075 for pulsars with luminosity greater than 1 mJy kpc$^{-2}$ (Vranesevic et al. 2004), and is $\sim 3$ times smaller, when including fainter sources having minimum luminosity $\sim 0.2$ mJy kpc$^{-2}$.

Correcting for this factor, and adopting the reference values of equation (16), we expect that the Parkes Multibeam survey should have detected

$$N_{obs} = \chi N_{IMBH-PSR} \simeq f N_{ULX}$$

pulsars orbiting an IMBH. This estimate implies that the detection of a radio pulsar orbiting an IMBH in the Galaxy is subjected to the same small number statistics of the ULX population (whose detection in the X-ray band is free from biases), even for the most favorable case $f = 1$. In particular it is compatible with the current lack of observed pulsars of this type. More sensitive surveys of the Galactic disc (such as the ongoing P-Alpha survey at Arecibo) or targeted surveys (searching deeply for pulsars in the directions of young star clusters) may results in a improved value of $\chi$, enhancing the possibility of unveiling a pulsar orbiting an IMBH within few years. However another possibility is that the number of ULXs hosting an IMBH is not so high as supposed, since as previously discussed, these sources may be explained by simple stellar mass black holes, leaving only a few number of ULXs with a true IMBH. In this case we must rescale the value of the equation (16) to the unknown number $N_{ULX} < N_{ULX}$ of ULXs with a real IMBH, diminishing our chance of a successful detection. Next generation radio telescopes will be able to go well beyond the Magellanic Clouds and eventually reach all the galaxies in the Local Group (e.g. M31 with LOFAR, Röttgering 2003) or nearby galaxies (e.g. M82 with SKA, Cordes et al. 2004). The much larger volume of space explored will enclose some known bright ULX$^1$. If these future instruments will be able to sample a sizeable fraction of the total pulsar population in nearby external galaxies, they will greatly increase the chance of discovering objects belonging to the very intriguing class of binaries presented in this paper.

$^1$ The nearest known bright ULXs are at a distance of $\sim 2$–3Mpc, whereas the ULX reported in the spiral galaxy M33 seems to be an ordinary X-ray binary in a high state rather than a true ULX (Foschini et al. 2004).
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