The ultraluminous X-ray source in M82: an intermediate-mass black hole with a giant companion

A. Patruno,1 S. Portegies Zwart,1,2 J. Dewi3 and C. Hopman4
1Astronomical Institute "A. Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ, the Netherlands
2Section Computational Science, University of Amsterdam, Kruislaan 403, 1098 SJ, the Netherlands
3Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA
4Faculty of Physics, Weizmann Institute of Science, PO Box 26, Rehovot 76100, Israel

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ABSTRACT
The starburst galaxy M82, at a distance of 12 million light years, is the host of an unusually bright 2.4–16 × 1040 erg s−1 X-ray point source, which is best explained by an accreting black hole 102 to 104 times more massive than the Sun. Though the strongest candidate for a so-called intermediate-mass black hole, the only support stems from the observed luminosity and the 0.05–0.1 Hz quasi-periodicity in its signal. Interestingly, the 7–12 Myr old star cluster MGG-11 which has been associated with the X-ray source is sufficiently dense that an intermediate mass black hole could have been produced in the cluster core via collision runaway. The recently discovered 62.0 ± 2.5 d periodicity in the X-ray source X-1 further supports the hypothesis that this source is powered by a black hole several hundred times more massive than the Sun. We perform detailed binary evolution simulations with an accreting compact object of 10–5000 M⊙ and find that the X-ray luminosity, the age of the cluster, the observed quasi-periodic oscillations and the now observed orbital period are explained best by a black hole of 200–5000 M⊙ that accretes material from a 22–25 M⊙ giant companion in a state of Roche-lobe contact. Interestingly, such a companion star is consistent with the expectation based on the tidal capture in a young and dense star cluster such as MGG-11, making the picture self-consistent.

Key words: black hole physics – galaxies: starbursts – X-rays: binaries.

1 INTRODUCTION
Ultraluminous X-ray sources (ULXs) are extragalactic off-nuclear X-ray point sources with an observed X-ray luminosity between 1039 and 1041 erg s−1, with a radiation pressure dominated disc that can reach luminosities & Markoff 2002; Mushotzky 2004). Another possibility could be a microblazar might produce an apparent super-Eddington emission with a giant companion in a state of Roche-lobe contact. Interestingly, such a companion star is consistent with the expectation based on the tidal capture in a young and dense star cluster such as MGG-11, making the picture self-consistent.

One of the best ULXs to search for an IMBH is the persistent source X-1 in the starburst galaxy M82 (Bode 1777) whose X-ray brightness can reach values as high as 2.4–16 × 1040 erg s−1 (Matsumoto & Tsuru 1999) that corresponds to bolometric fluxes larger than 5–20 × 1040 erg s−1, unexplainable with a stellar-mass black hole (Matsumoto et al. 2001; Kaaret et al. 2001; King & Dehnen 2005). The IMBH mass corresponding to the observed luminosity range lies between 400–1600 M⊙, assuming an isotropic sub-Eddington emission rate. The detection of a mHz quasi-periodic oscillation at a frequency of 54 mHz (Strohmayer & Mushotzky 2003) supports the hypothesis of an IMBH as massive as 1600 M⊙ as the compact accretor of M82 X-1 (Matucciarelli et al. 2006; Dewangan, Titarchuk & Griffiths 2006). A recent RXTE detection of an X-ray modulation with a period of 62.0 ± 2.5 d has been interpreted as the orbital period of the ULX with a donor star on the giant-supergiant phase with a mean density ρ ∼ 5 × 10−2 g cm−3 (Kaaret, Simet & Lang 2006). Remarkably, the position of M82 X-1
is coincident with that of MGG-11, a young dense cluster (YoDeC) with a mass of $\sim 3.5 \times 10^6 M_\odot$ and an age of $7$–$12$ Myr (McCrady, Gilbert & Graham 2003).

In recent N-body simulations of MGG-11 (Portegies Zwart et al. 2004a) it has been shown that in its first $3$ Myr, the cluster undergoes a runaway collisional merger of massive main-sequence stars leading to the formation of a giant protostellar object of several $1000 M_\odot$ in its core. The subsequent evolution of this supermassive star is still poorly known and probably can lead to the formation of an IMBH with a mass between several hundred and a few thousand solar masses. Once the IMBH is formed it might be fed by the mass transfer from a donor star captured via tidal interaction (Hopman, Portegies Zwart & Alexander 2004; Baumgardt et al. 2005), which fills its Roche lobe during the main sequence or at a later stage of the evolution.

If the apparent coincidence of M82 X-1 with MGG-11 connotes that the source X-1 is located in MGG-11, this coincidence can be considered to be the key-point in solving the controversy about the origin of the compact accretor (Portegies Zwart et al. 2004a). In the here-proposed scenario, an estimate of the age is crucial in determining the mass of the possible donor star in an X-ray binary with a black hole as a compact object. This drastically limits the various possibilities, and allows us to perform detailed, pin-pointed simulations to constrain the other observables with our binary evolution simulations. In Section 2 we describe the evolution and the initial conditions used for our binary simulations. In Section 3 we present our results, and we discuss them in Section 4.

2 INITIAL CONDITIONS AND EVOLUTION OF THE BINARY

At an age of $t \sim 7$ Myr, all the stars with an initial mass $M > 26 M_\odot$ have experienced a supernova explosion and can therefore be excluded as possible donors to a black hole. Given the upper age limit of $12$ Myr, the low mean density of donors that is observed implies that the companion star has already left the main sequence, limiting the mass to $M > 17 M_\odot$.

In this Letter we aim to investigate the binary nature of this ULX using very stringent limits on the parameters of the binary: the X-ray luminosity of M82 X-1 ($2.4 \times 10^{36}$ erg s$^{-1}$), the orbital period of M82 X-1 (62.0 $\pm$ 2.5 d), the age of MGG-11 (7–12 Myr) and the mean density of the donor of M82 X-1 ($\approx 5 \times 10^{-5}$ g cm$^{-3}$).

Assuming that the system has been formed via tidal interaction, we can add a few more constraints on the binary because the mass transfer cannot start before the time required to form an IMBH ($t > 3$ Myr, Portegies Zwart & McMillan 2002). The tidal capture process itself also puts an interesting constraint to the initial conditions, as capture can only be successful in a rather narrow range of impact parameters (Hopman et al. 2004). Subsequent tidal dissipation in the tidally captured star causes the orbit to circularize to an orbital separation in the range of $2 r_t < a_t < 5 r_t$ (Baumgardt et al. 2005), with $r_t = (M_{\text{bd}}/M)^{1/3} R$ the tidal radius of the black hole, where $M$ and $R$ are the mass and the radius of the donor star, respectively. Larger orbital separations are hardly realizable, as they can only result from an encounter with a larger impact parameter, and those are unable to dissipate sufficient energy in the tidal interaction (Press & Teukolsky 1977). On the other hand, an encounter which brings the star too close to the IMBH will result in the destruction of the incoming star, leaving only a disc of stellar debris (Rees 1988; Alexander & Morris 2003). After the tidal capture, the binary continues to evolve on nuclear time-scales of the captured star and by the emission of gravitational radiation. We adopted an updated version of Eggleton’s binary evolution code (Eggleton & Kiseleva-Eggleton 2002; Pols et al. 1995) to perform a large number of simulations in which we vary the mass of the stellar donor (i.e. the captured star), the mass of the IMBH and the initial orbital separation. We assume that mass transfer on to the IMBH is Eddington-limited and that the excess mass is lost from the system with the specific angular momentum of the accretor. For mass loss by the stellar wind we adopt a de Jager like wind (de Jager, Nieuwenhui & van der Hucht 1988), including the modified recipe for the wind accretion on to the IMBH during the detached phase (Patruno et al. 2005). We assume that all the stars have Population I chemical composition, mixing length parameter $\alpha = 2.0$ and overshooting constant $\delta_{ov} = 0.12$. We then explored black hole masses between 10 and 5000 $M_\odot$, which includes the possibility that the accreting object is a stellar mass black hole. The donor mass is varied between 18 and 26 $M_\odot$. The IMBHs were assumed to acquire their stellar remnant still on the main sequence at an age of $\sim$4 Myr in a circular binary with a semi-major axis $a \approx 0.2$–0.5 au, according to the tidal capture scenario. For the stellar-mass black hole, we used an initial semi-major value axis of $\leq 0.2$ au, typical of normal black hole binaries, to start the Roche-lobe overflow (RLOF) phase after 3–4 Myr when the star is still on the main sequence or is just at the beginning of the giant branch.

3 RESULTS

In Fig. 1 we present the result of these simulations. The extent to which the simulated binaries comply with the observed X-ray source is coded in the various symbols. The filled circles in Fig. 1 identify those initial conditions for our binary evolution simulations which satisfactorily reproduce the observations (period and luminosity). The crosses identify those initial conditions that fail to reproduce the observations. The conditions illustrated by the open circles give

![Figure 1](https://example.com/figure1.png)

Figure 1. Grid of binaries used for the simulations. The dots represent those systems that are in total agreement with the observations. The filled dots represent those binaries that match with the luminosity of M82 X-1 without any super-Eddington or beamed emission. The empty circles represent those binaries where a good agreement is reached with the need of beaming or super-Eddington emission. When the parameters of the binary are within 1 $\sigma$ from the observed period, the dots are bigger; the small dots are for parameters that are in total disagreement with the observations. The filled circles in Fig. 1 identify those binaries that are in total agreement with the observed X-ray source.
comparable orbital separation in the observed age interval of 7 to 12 Myr, but require super-Eddington accretion on the black hole to comply with the observed X-ray luminosity. This happens for black holes of $M_{bh} < 400 M_{\odot}$. The simulation with a 18- $M_{\odot}$ donor and a $\sim 25-M_{\odot}$ black hole (indicated with the open circle in the lower left-hand corner of Fig. 1) is able to reach the observed orbital period and mass accretion rate at an age of 11.5 Myr. This binary started the RLOF, at the age of $\sim 4$ Myr with the donor still on the main sequence. However, in order to comply with the observed X-ray luminosity the emission has to be beamed with an angular diameter of between 4' and 20' which cannot easily explain the X-ray modulation observed (Kaaret et al. 2006). Moreover the collimation factor is 2–10 times smaller than the maximum collimation reached in the mechanical beaming model (King et al. 2001). In the case of isotropic emission, the super-Eddington factor must be as high as $\sim 100$ times the value obtainable in a standard accretion disc. These initial conditions also happen to be highly unstable, as a slight variation in black hole mass and/or donor mass makes the comparison with the observations unsatisfactory (indicated with the crosses in Fig. 1).

If the initial period of binaries with a stellar mass black hole is increased to 3–4 d, the mass transfer rate becomes very violent in the beginning of the contact phase, leading to rates of $\gtrsim 10^{-2}$–$10^{-4} M_{\odot}$ yr$^{-1}$. This is a consequence of both the very rapid expansion of the donor on the giant branch and of its mass, which is often larger than the mass of the black hole. The orbital period changes quickly, surpassing the correct range in a few $\sim 10^3$ yr, after which the mass of the black hole is larger than the donor and the evolution proceeds in a stable way with a period of about 100 d. Because the observed period is achieved for a very brief time during the evolution of these binaries, we consider them too unstable to reproduce the observations.

The largest area of the parameter space that satisfactorily reproduces the observations are found for binaries with a donor of 22–25 $M_{\odot}$ and a 200–5000 $M_{\odot}$ IMBH. The initial orbital separation for these binaries is 2–3 tidal radii, which is consistent with the tidal capture of the donor by the IMBH (Hopman et al. 2004; Baumgardt et al. 2005). The donor in these binaries starts to transfer mass to the IMBH on the main-sequence at the age of about 4 Myr. By this time the rate of mass transfer is still rather low ($\dot{M} \lesssim 2 \times 10^{-6} M_{\odot}$ yr$^{-1}$), though sufficient to power a bright X-ray source with $L_x \lesssim 10^{39}$ erg s$^{-1}$ (Portegies Zwart, Dewi & Maccarone 2004b; Patruno et al. 2005). After tidal capture however, the main-sequence phase lasts for 3–4 Myr. In Fig. 2 we show the evolution of the mass-transfer rate as a function of the orbital period. The binaries are initialized at a short orbital period (in the lower left-hand corner of the figure) and evolve to a higher mass transfer rate and larger orbital period. The small feature in the lower left-hand corner, until an orbital period of about 10 d, is the main-sequence evolution. The broad shoulder is caused by the evolution of the donor on the giant branch.

As soon as the donor ascends the giant branch, the mass transfer rate increases by about two orders of magnitude to $\dot{M} = 10^{-5}$–$10^{-3} M_{\odot}$ yr$^{-1}$, giving rise to a very bright phase, with $L_x \sim 10^{41}$–$10^{42}$ erg s$^{-1}$. This phase, however, only lasts for 1–2 $\times 10^4$ yr. Near the end of this phase, the rate of mass transfer drops as the orbital period increases. At an age of 7.2–9.0 Myr the binaries reach an orbital period within 3r of the observed range of 57–67 d and with a mass transfer rate of $\dot{M} = 1 \times 10^{-3} M_{\odot}$ yr$^{-1}$. In addition, the mean density of the donor in this time interval is $\rho = 3.5 \times 10^{-2}$ g cm$^{-3}$, also consistent with the observations.

The binaries in this rather narrow window of initial conditions are consistent with the observed age of the star cluster MGG-11; they produce the observed luminosity of $L_{bol} = 5 \times 10^{40}$ erg s$^{-1}$ and their orbital periods are within 3$\sigma$ of the observed periodicity. We therefore firmly conclude that the X-ray source M82 X-1 is satisfactorily explained by a binary in which a 22–25 $M_{\odot}$ giant donor stars transfer mass via RLOF to a 200–5000 $M_{\odot}$ black hole. The lower limit of 200–400 $M_{\odot}$ still needs a mild beaming or super-Eddington isotropic emission (a factor of 2–8) to cope with the observations. With a mass between 400 and 1600 $M_{\odot}$, the IMBH still needs a small beaming or super-Eddington emission (a factor 1–4) to explain its maximum luminosity. The upper limit to the black hole mass is ill-constrained by the observed orbital period, because the orbital period in a state of mass transfer is rather insensitive for black holes of $M_{bh} \gtrsim 1000 M_{\odot}$. If the initial orbital separation is wider ($4r_1 < a_i < 5r_1$) the RLOF phase begins near the terminal age main sequence, or when the star is already ascending the giant branch. In this situation the final period is much larger than observed.

4 DISCUSSION

The range for the donor mass in our best range of parameters (22–25 $M_{\odot}$) agrees well with recent N-body simulation (Baumgardt et al. 2005). In these simulations the authors find that the typical mass of a captured star is 25 $M_{\odot}$ and that most tidal captures occur in the first few million years after the formation of the IMBH. We also note that even slightly larger initial separations $a > 5r_1$ would result in significantly larger period than 62.0 d. A dynamical formation scenario of the binary such as dynamical friction or binary disruption (Blecha et al. 2006) is therefore unlikely.

A better age estimate for the star cluster MGG-11 could further constrain our model. The observed range in cluster age is 7–12 Myr.
(McCready et al. 2003). If the cluster happens to be on the young side of this interval (≤9 Myr) we exclude the stellar mass black hole as an accreting object because our binary evolution models systematically fail to reproduce the observed parameters.

The average time-span over which a binary with an IMBH that accretes from a stellar donor less massive than 30 $M_{\odot}$ reaches luminosities in excess of $L_x > 10^{40}$ erg s$^{-1}$ is a few times $10^4$ yr. These binaries spend about 4 Myr as relatively low-luminosity X-ray sources (with $L_x \approx 10^{39}$−$10^{40}$ erg s$^{-1}$). We would therefore expect about 400 low luminosity sources on each bright ULX (with $L_x > 10^{40}$ erg s$^{-1}$). An additional channel to make bright sources but not the dim sources is the tidal capture, for stars more massive than 30 $M_{\odot}$. These sources spend their whole lifetime with luminosities larger than $10^{36}$ erg s$^{-1}$, increasing the expected fraction of bright over dim ULXs. On the other hand, a dynamical capture during a close encounter can be another mechanism to form a dim ULX. This process has a cross-section that is 50 times as large as tidal capture, and it may be that a large fraction of the bright ULXs we observe are formed by dynamical capture. This is consistent with various ULX catalogues (Liu & Mirabel 2005; Colbert & Ptak 2002), which give 198 relatively dim ($L_x < 10^{40}$ erg s$^{-1}$) versus 31 brighter sources. Moreover the dynamical capture scenario will also create a large fraction of detached systems with the donor underfilling its Roche lobe and transferring mass on to the black hole through the stellar wind. This will produce luminosities of between $10^{36}$ and $10^{39}$ erg s$^{-1}$, in the range of normal X-ray binaries.

The ULX formation rate is about one per million years per galaxy, given an average lifetime of $10^7$ yr and a present ULX population of ~0.1 per galaxy (Swartz et al. 2004). These estimates are based on all ULXs, which include the relatively dim $L_x \approx 10^{36}$−$10^{40}$ erg s$^{-1}$ X-ray sources. We adopt a donor of 20 $M_{\odot}$, which has a main-sequence lifetime of about 7 Myr. The first 3 Myr of the star cluster’s life is spent in forming an IMBH. The capture event is most likely to occur within about 1 Myr after the formation of the IMBH (Baumgardt et al. 2005), leaving about 3–4 Myr for the donor to transfer mass to the black hole. The formation rate of X-ray sources with $L_x > 10^{36}$ erg s$^{-1}$ is then $R \approx 0.3–1 \times 10^{-7}$ per year. In the Local Group there are 30 galaxies within 1.7 Mpc (Tully 1988). The observable lifetime of a radio pulsar is about $10^7$ yr (Lyne, Manchester & Taylor 1985) which would allow a possible detection of 1–3 pulsars within the LOFAR (LOw Frequency ARray) range, assuming a beaming factor of between 5 and 10 (Leeuwen 2004).

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