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

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ABSTRACT

The starburst galaxy M82 at a distance of 12 million light years, is the host of an unusually bright $2.4 - 16 \times 10^{40}$ erg/s X-ray point source, which is best explained by an accreting black hole $10^{2}$ to $10^{4}$ 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 $62.0 \pm 2.5$ day 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 $10 - 5000$ $M_\odot$ 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 $200 - 5000$ $M_\odot$ that accretes material from a $22 - 25$ $M_\odot$ 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 like MGG-11, making the picture self-consistent.

1 INTRODUCTION

Ultra Luminous X-ray sources (ULXs) are extra galactic off nuclear X-ray point sources with an observed X-ray luminosity between $10^{39}$ and $10^{44}$ erg s$^{-1}$, well in excess of the Eddington limit for a stellar mass black hole ($L_{\text{Edd}} = 1.25 \times 10^{38}(M_{\text{bh}}/M_\odot)$ erg s$^{-1}$, with $M_{\text{bh}}$ the mass of the accretor). While there is evidence of a binary nature of these sources, e.g. in M51, in IC342 and in Circinus (Ward 2004; Kuntz et al. 2005), the nature of their compact accretors remains somewhat controversial. A possibility is represented by beamed models with stellar mass black holes where a mechanical collimation in a thick disc or a Doppler boosting from a jet in a microblazar might produce an apparent super Eddington emission up to a factor $\sim 10$ explaining the nature of some ULXs with luminosities below $\sim 10^{40}$ erg s$^{-1}$ (King et al. 2001; K"ording et al. 2002; Mushotzky 2004). Another possibility can be a genuine super Eddington emission from a stellar mass black hole with a radiation pressure dominated disc that can reach luminosities as high as $10^{40}$ erg s$^{-1}$ (Begelman 2002). However all these models cannot easily explain those sources with luminosities above $\sim 4 \times 10^{40}$ erg s$^{-1}$ (King & Dehnen 2005). The presence of an Intermediate Mass Black Hole (IMBH) with a mass around $10^2 - 10^4$ $M_\odot$ represents an exciting possibility to naturally explain at least the most luminous sources. However its existence has not yet been demonstrated.

One of the best ULX 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 $2.4 - 16 \times 10^{40}$ erg s$^{-1}$ (Matsumoto & Tsuru 1999) that corresponds to bolometric fluxes larger than $5 - 20 \times 10^{40}$ erg s$^{-1}$, unexplainable with a stellar mass black hole (Matsumoto et al. 2001; Kaaret et al. 2001; King & Dehnen 2005). The detection of a millihertz quasi periodic oscillation at a frequency of 54 mHz (Strohmayer & Mushotzky 2003) supports the hypothesis of an IMBH as the compact accretor of M82 X-1 (Mucciarelli et al. 2005; Dewangan et al. 2005). A recent RXTE detection of an X-ray modulation with a period of 62.0 $\pm$ 2.5 days has been interpreted as the orbital period of the ULX with a donor star on the giant/ supergiant phase with a mean density $\rho \approx 5 \times 10^{-5}$ g cm$^{-3}$ (Kaaret 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 7–12Myr (McCray et al. 2003).

In recent N-body simulations of MGG-11 (Portegies Zwart et al. 2004) 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⊙ 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 thousands 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) that fills its Roche lobe during the main sequence or on 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 to solve the controversy about the origin of the compact accretor (Portegies Zwart et al. 2004). 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 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 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 donor mean density observed implies that the companion star has already left the main sequence, limiting the mass to be \( M > 17 M_\odot \).

In this paper 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 (\( 2.4 - 16 \times 10^{40} \text{erg s}^{-1} \)), the orbital period of M82 X-1 (62.0 ± 2.5 days), the age of MGG-11 (7-12 Myr), the mean density of the donor of M82 X-1 (\( \sim 5 \times 10^{-5} \text{g cm}^{-3} \)). Assumption that the system has been formed via tidal interaction we can add a few more constraints on the binary since the mass transfer cannot start before the time required to form an IMBH (\( t \sim 3 \text{Myr} \), Portegies Zwart & Mc Millan 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, Portegies Zwart & Alexander 2004). Subsequent tidal dissipation in the tidally captured star causes the orbit to circularize to an orbital separation in the range of \( 2r_t < a_t < 5r_t \) (Baumgardt et al. 2005), with \( r_t = (M_{bh}/M)^{1/3}R \) the tidal radius of the black hole, where \( M \) and \( R \) are the mass and the radius of the donor star. Larger orbital separations are hardly realizable as those 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 timescales 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 intermediate mass black hole and the initial orbital separation. We assume that mass transfer on 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 (1), including the modified recipe for the wind accretion onto 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⊙, which includes the possibility that the accreting object is a stellar mass black hole. The donor mass is varied between 18 and 26 M⊙. 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 \( a \sim 0.2 - 0.5 \text{AU} \), according to the tidal capture scenario. For the stellar mass black hole we used an initial value of the semi-major axis \( a \lesssim 0.2 \text{AU} \), typical of normal black hole binaries, to start the RLOF phase after \( 3 - 4 \text{Myr} \) when the star is still on the main sequence or just at the beginning of the giant branch.

3 RESULTS

In fig. 1 we present the result of these simulations. The extend to which the simulated binaries comply with the observed X-ray source is coded in the various symbols. The close circles in fig. 1 identify those initial conditions for our binary evolution simulations which satisfactorily reproduce the observations (period and luminosity).

The crosses fail to reproduce the observations. The open circles give 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⊙ donor and a \( \sim 25 M_\odot \) black hole (indicated with the open circle in the lower left corner of fig. 1) is able to reach the observed orbital period and mass accretion rate at an age of \( 11.5 \text{Myr} \). This binary started the Roche-lobe overflow (RLOF) at the age of \( \sim 4 \text{Myr} \) 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 between 4 and 20 degrees which cannot easily explain the X-ray modulation observed (Kaaret 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 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 around 3 – 4 days, the mass transfer rate become very violent in the beginning of the contact phase leading to rates of \( \lesssim 10^{-2} - 10^{-4} \text{M}_\odot \text{yr}^{-1} \). This is both a consequence of 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 above 100 days. 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 \( \text{M}_\odot \) and a 200-5000 \( \text{M}_\odot \) 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, Portegies Zwart & Alexander 2004, Baumgardt & Alexander 2005). The donor in these binaries start 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 (\( \dot{M} \lesssim 2 \times 10^{-5} \text{M}_\odot \text{yr}^{-1} \)), though sufficient to power a bright X-ray source with \( L_x \lesssim 10^{40} \text{erg/s} \) (4; Patruno et al. 2005). After tidal capture however, the main-sequence phase lasts for 3-4 Myr in figure 2 we show the evolution of the mass-transfer rate as a function of the orbital period.

The binaries are initialized at short orbital period (in the lower left corner of the figure) and evolve to higher mass transfer rate and larger orbital period. The small feature in the lower left corner, until an orbital period of about 10 days, is the main-sequence evolution. The broads 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 \( \dot{M} = 10^{-5} - 10^{-3} \text{M}_\odot \text{yr}^{-1} \), giving rise to a very bright phase, with \( L_x \sim 10^{41} - 10^{42} \text{erg/s} \). This phase, however, only lasts for 1-2 \( \times 10^4 \) years. 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 2\( \sigma \) of the observed range of 57-67 days and with a mass transfer rate of \( \dot{M} = 1-3 \times 10^{-5} \text{M}_\odot \text{yr}^{-1} \). In addition, the mean density of the donor in this time interval is \( \rho = 3-5 \times 10^{-5} \text{g cm}^{-3} \), 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 \( L_{bol} = 5-20 \times 10^{40} \text{erg/s} \) and their orbital period are within 2\( \sigma \) 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 \( \text{M}_\odot \) giant donor star transfers

**Figure 1.** Grid of binaries used for the simulations. The dots are those systems with total agreement with the observations. The close dots are those binaries that match with the luminosity of M82 X-1 without any super Eddington or beamed emission. The empty circles are 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\( \sigma \) form the observed period the dots are bigger, while the small one are those in agreement within 2\( \sigma \). The crosses are binaries with a discrepancy larger than 2\( \sigma \) from the observed values.

**Figure 2.** Evolution of the mass transfer rate as a function of the orbital period. The four small dashed straight lines creates a rectangle inside which the orbital period is within 2\( \sigma \) from the best value 62.0 \( \pm \) 2.5 days, and the mass transfer rate is in the correct range to produce bolometric luminosities in the range \( 5 - 20 \times 10^{40} \text{erg/s} \). The three curves are respectively binaries with a donor star of 24 \( \text{M}_\odot \) and a black hole of 15, 200 and 1000-5000 \( \text{M}_\odot \). The numbers in the plot give the age in Myr of the donor at several steps of the evolution assuming an IMBH mass of \( \sim 1300 \text{M}_\odot \). The small bump corresponds to a RLOF phase on the main sequence that lasts for 7.4 Myr until the donor reaches the terminal age main sequence (TAMS). The big bump is produced after the main sequence and lasts only for \( \sim 20000 \) yr.
mass via Roche-lobe overflow 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 2-8) to cope with the observations. 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_\text{bh} \gtrsim 1000 M\odot. If the initial orbital separation is wider (4r_2 < a_1 < 5r_2) 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 \gtrsim 5r_1 would result in significantly larger period than 62.0 days. A dynamical formation scenario of the binary such as dynamical friction or binary disruption (Blecha et al. 2005) 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 (McCrandy et al. 2003). If the cluster happens to be on the young side of this interval (\lesssim 9 Myr) we exclude the stellar mass black hole as accreting object since our binary evolution models systematically fails to reproduce the observed parameters.

The average time span over which a binary with an intermediate-mass black hole that accretes from a stellar wind. This will produce a donor under-filling its Roche lobe and transferring mass on to the black hole. The formation rate of x-ray sources with L_x > 10^{40} erg s^{-1} is then \dot{N} \simeq 0.3 \times 10^{-7} per year.

The average density of spiral galaxies, blue elliptical, starbursts and irregular galaxies is about 6.1 per Mpc\(^3\) (assuming h = 0.76) (van den Berg 1995; McLaughlin 1999). The observable lifetime of a radio pulsar is about 10^7 years (Lyne et al. 1985) which would allow the detection more than 5 to 17 binaries with an intermediate mass black hole and a observable radio pulsar within the 1.2 Mpc range of LOFAR (Leeuwen 2004). Finally we have to correct for the beaming of the radio pulsar which, with a beaming factor of 0.2 results in 1-3 potential detections with LOFAR.

The general consistency between the observations, the result of the detailed N-body simulations and our binary evolution calculations strongly constrains the nature of the ultra-luminous x-ray source in M82 X-1 to a 22-25 M\odot evolved donor star that transfers mass to a 200-5000 M\odot black hole.

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