The gravitational wave signature of young and dense star clusters

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Abstract

Young star clusters are often born with such high stellar densities that stellar collisions play an important role in their further evolution. In such environments the same star may participate in several tens to hundreds of collisions ultimately leading to the collapse of the star to a black hole of intermediate mass. At later time the black hole may acquire a companion star by tidal capture or by dynamical 3-body capture. When this companion star evolves it will fill its Roche-lobe and transfer mass to its accompanying black hole. This then leads to a bright phase of X-ray emission but the binary may also be visible as a source of gravitational wave radiation in the LISA band. If the star captured by the intermediate mass black hole is relatively low mass ($\lesssim 2 \, M_\odot$) the binary will be visible as a bright source in gravitational waves and X-rays for the entire lifetime of the binary. The majority of compact binaries which formed from the population of primordial binaries in young and dense star clusters do not lead to detectable gravitational wave sources.

Key words: black holes, compact objects, simulation, star clusters, gravitational waves

PACS: code, code

1 Introduction

Dense and young star clusters are rather rare in our Galaxy. The six such star clusters that are currently known are: Arches [Figer et al.(2002)], IRS13 [Maillard et al.(2004)] and IRS16 [Portegies Zwart et al.(2003),Eckart et al.(2004)], NGC3603 [Brandl et al.(1999)], Quintuplet [Figer et al.(1999)] and Westerlund 1 [Vrba et al.(2000)]. The two IRS sources, however, can hardly be called a cluster as they look more like the debris of disrupted star cluster [Kim et al.(2000),McMillan and Portegies Zwart(2003)].
Young and dense star clusters (hereafter YDC, sometimes pronounced as Yo-DeC) are characterized by a stellar population which is younger than about 10 Myr.

The fact that these clusters are young means that stars of all masses are still present, offering critical insights into the stellar initial mass function and cluster structural properties at formation. The term “dense” means that dynamical evolution and physical collisional processes can operate fast enough to compete with and even overwhelm stellar evolutionary timescales; dense stellar systems are places where wholly new stellar evolution channels can occur, allowing the formation of stellar species completely inaccessible by standard stellar and binary evolutionary pathways.

There are no examples of the older ( $\gtrsim 10$ Myr) siblings of these clusters in the Milky Way Galaxy. For the Arches and Quintuplet this may not be so surprising, as they dissolve in the tidal field of the Galaxy in at most a few tens of million years [Kim et al.(2000),Portegies Zwart et al.(2002)], and even if they survive longer they will become hard to detect against the dense background stellar population [Portegies Zwart et al.(2001a)]. For the two rather isolated clusters, NGC 3603 and Westerlund 1, it is rather curious that there are no examples of their 10 to 100 Myr descendants in the Milky Way.

The other characteristic of YDCs is the high density. The few clusters near the Galactic center must have a high density, as otherwise they would be disrupted easily by the strong tidal field. The clusters further out however, do not have this constraint and it is interesting to note that clearly these clusters were born without much knowledge of the local potential of the Galaxy, i.e: they behave as isolated clusters.

In this paper, we discuss the formation and evolution of gravitational wave sources in the form of compact binaries in YDCs, but for convenience we extend our definition to star clusters of 100 Myr. The basis of this study is the star cluster MGG11 [McCrady et al.(2003)] at about 200 pc from the nucleus of the starburst galaxy M82 at a distance of about 3.6 Mpc.

The star cluster MGG-11 has an age of about 7–12 Myr [McCrady et al.(2003)], a line-of-sight velocity dispersion of $\sigma_r = 11.4 \pm 0.8$ km s$^{-1}$ and a projected half-light radii, $r = 1.2$ pc. The cluster mass then totals $\sim 3.5 \times 10^5 M_\odot$. The cluster mass function seems to be deficient of stars below about $1 M_\odot$, but follow a Salpeter slope for the higher masses.

We simulate this cluster by integrating the equations of motion for all stars and follow the evolution of stars and binaries in the cluster using the starlab$^1$ [Portegies Zwart et al.(2001b)] direct N-body package. We start our simula-

$^1$ [http://www.ids.ias.edu/~starlab/](http://www.ids.ias.edu/~starlab/)
tions with 144179 stars, 13107 of which are in binaries totaling a binary fraction of about 10%. The binary parameters were selected as follows: first we chose a random binding energy between a minimum of 10kT and a maximum, and we chose the orbital eccentricity from the thermal distribution. The maximum binding energy was selected such that the distance at pericenter exceeded four times the radius of the primary star. For the initial density profile we adopt a King model with \( W_0 = 12 \) [King(1966)]. We ignored an external tidal field, but stars are removed from the simulation if they are more than 10 tidal radii (about 80 pc) away from the density center of the cluster.

2 Global cluster evolution

2.1 Early core collapse and the growth of an intermediate mass black hole

Driven by the massive stars, the cluster experiences an early core collapse [Portegies Zwart et al.(2004), Gürkan et al.(2004)], which leads to subsequent collisions between massive stars. The result of this is the growth of one of the initially most massive stars through repeated collisions, to a total mass of about 1000-3000 \( M_\odot \). The evolution of the mass of this designated target is illustrated in figure 1, where we show the range in masses acquired by the star that experiences repeated collisions. In the end the massive star may collapse to an intermediate mass black hole [Portegies Zwart et al.(2004)]\(^2\).

In a recent model Hopman et al. [Hopman et al.(2004)] proposed that an intermediate mass black hole can capture a companion star in a tight orbit. Further tidal interaction between the black hole and the captured star then circularize the orbit. They further assume that the captured star is on the main-sequence, but the same argument can be made for evolved stars. By the time the orbit has been fully circularized the captured star under-fills its Roche-lobe only slightly. During the remainder of the main-sequence lifetime of the captured star, it grows in size by about a factor of two and gravitational wave radiation reduces the orbital separation. Ultimately the star fills its Roche lobe and starts to transfer mass to the intermediate mass black hole.

We do not further consider the details of tidal capture, nor do we assess the probability of forming the type of binary systems discussed in this paper, as we mainly concentrate on the phase in the lifetime of the intermediate mass black hole at which it is visible as a source for gravitational waves.

\(^2\) Several alternative theoretical models exist for producing black holes of \( \sim 10^2 - 10^4 M_\odot \); Portegies Zwart & McMillan 2002; Miller & Hamilton 2002; Madau & Rees 2001).
The shaded area indicates the range in mass for the designated target \( M_{\text{tot}} \) as a function of time for simulations which resemble the star cluster MGG 11 (see §1). This area is calculated with a large variety in initial conditions, and computed with two independently developed N-body codes NBODY4 and starlab (see [Portegies Zwart et al. (2004)] for details). The hashed area indicates the moment in time where the collision runaway typically collapses to a black hole of intermediate mass. The age range for the star cluster MGG 11 is given by the upper horizontal bar between 7 Myr and 12 Myr. Its neighboring cluster, MGG-9, is not expected to have experienced a collision runaway and the evolution of the mass of the most massive star in this cluster is indicated by the lower solid line. The horizontal dotted curve indicates the mass of the most massive star initially present in the calculations.

### 2.2 The further evolution of the intermediate mass black hole

After tidal capture we evolved the binary through various stages using the binary evolution code of Eggleton (Pols et al. 1995 and references therein), assuming a population I chemical composition \((Y = 0.98, Z = 0.02)\), mixing-length parameter of \(\alpha = 2.0\) and with convective overshooting constant \(\delta_{ov} = 0.12\) (Pols et al. 1998). Results on such evolution are published by Portegies Zwart et al [Portegies Zwart et al. (2004)]. They calculated the orbital evolution of the binary systems, as they are affected by the emission of gravitational waves (Landau & Lifshitz, 1958), Roche-lobe overflow and by non-conservative mass transfer or by mass loss via a wind (Soberman et al. 1997) [Soberman et al. (1997)]. Matter was assumed to leaves the system carrying the specific angular momentum of the donor. During mass-transfer the black
hole was assumed to accrete matter up to its Eddington limit (see e.g. King 2000).

The binary emits gravitational waves, and as long as the stars are far apart we can assume that they behave as point masses. Note, however, that the donor star fills its Roche-lobe and can hardly be described as a point mass. The amplitude of the gravitational wave signal is given by (Evens et al. 1987)

\[ h \simeq 6 \times 10^{-23} \left( \frac{M}{M_\odot} \right)^{5/3} \left( \frac{P_{\text{orb}}}{\text{1 days}} \right)^{-2/3} \left( \frac{d}{1\text{kpc}} \right)^{-1}. \]  

(1)

Here \( M \) is the chirp mass. The gravitational wave frequency is twice the orbital frequency. The resulting gravitational wave signal is presented in Fig. 2, for binaries which started Roche-lobe overflow on the zero-age main-sequence. Binaries which do not stars RLOF during the main-sequence phase of the donor will not become detectable gravitational wave sources.

At the onset of Roche-lobe overflow the wave strain is \( \log h \gtrsim -19.2 \) for a 1000\( M_\odot \) black hole with a \( \gtrsim 5 M_\odot \) Roche-lobe filling main-sequence companion at a distance of 1\( \text{kpc} \). While mass transfer proceeds the binary system becomes wider, resulting in an increase of the orbital period and consequently in a decrease of the wave strain. A binary at a distance of \( \sim 1\text{kpc} \) is then visible for about \( 1/10^{th} \) of its main-sequence lifetime, which, for an \( \gtrsim 5 M_\odot \) donor is at most a few million years.

Figure 2 shows the expectation of the LISA noise curve (diagonal solid curve from top left to bottom right. Sources to the right and above this curve are expected to be detectable by the LISA satellite. Main-sequence stars of 5\( M_\odot \) and 15\( M_\odot \) which ware born in Roche lobe contact to a 1000\( M_\odot \) black hole are visible between the two diagonal dashed curves, assuming a distance of 1\( \text{kpc} \). Note that the star cluster Westerlund 1 is at a distance of 1.1\( \text{kpc} \).

The \( \lesssim 10 M_\odot \) donors turn into a white dwarfs after their entire hydrogen envelope has been transferred to the black hole. After that, the emission of gravitational waves brings the two stars back into the relatively high frequency regime and it becomes detectable again for the LISA antennae. This process, however takes far longer than a Hubble time, unless the orbit has an eccentricity \( e > 0.97 \). Such high eccentricities, after the phase of mass transfer, can only be achieved in the cases where the donor collapses to a compact object in a supernova explosion, or if the binary is perturbed by external influences. Note that the kick velocity due to a possible asymmetry in the supernova in which the neutron star forms is not sufficient to unbind the binary system. The supernova may induce a high eccentricity, leading to a relatively quick merger due to the emission of gravitational waves. Such a post-supernova system can be seen by LISA over a much larger distance, enhancing the available volume.
within which such event can occur. We conclude that the here discussed class of binaries with relatively massive donors $\gtrsim 5 M_\odot$ in a state of Roche-lobe contact are probably not important sources of gravitational waves, because this phase is short lived and the gravitational wave radiation emitted is relatively weak. If the donor collapses to a neutron star, however, the binary can be seen to a much larger distance and this may result in an appreciable detection rate.

The binary in which a $2 M_\odot$ main-sequence star starts to transfer mass to a $1000 M_\odot$ black hole, however, remains visible as a bright source of gravitational waves for its entire lifetime (see Figure 2). The reason for this striking result is the curious evolution of the donor. During RLOF, the hydrogen content in the star is continuously fully mixed, and as a consequence the star remains rather small in size, causing the mass transfer rate to remains roughly constant. By the time the hydrogen fraction drops below $\sim 0.66$, the central temperature becomes so low that thermonuclear fusion stops: this happens at about $t = 630$ Myr. At that point the system is detached for about 8 Myr before it undergoes another phase of mass transfer until $t = 1.2$ Gyr, at which point the donor turns into a $0.011 M_\odot$ (about $10 m_{\text{Jup}}$) brown dwarf. The brown dwarf ultimately merges with the black hole due to the emission of gravitational-waves [Portegies Zwart et al.(2004)].

This binary remains visible in the LISA frequency regime for its entire lifetime, only the gravitational wave strain drops as the donor is slowly consumed by the intermediate mass black hole. Mass transfer in this evolutionary stage is rather slow causing the X-ray source to be transient, being bright for a few days every other month. We argue that such a transient could result in an interesting synchronous detection of X-rays and gravitational waves [Portegies Zwart et al.(2004)].

The solid curve in the middle of the diagram gives the gravitational wave radiation emitted by a $2 M_\odot$ star transferring mass to a $1000 M_\odot$ black hole. This binary has a rather peculiar evolution [Portegies Zwart et al.(2004)]. Such binaries may remain visible in X-rays and as a source of gravitational waves for their entire main-sequence lifetime. The gravitational waves, however will only be visible by the LISA antennae do a distance of at most a few kpc.

The other symbols in figure 2 give the location of the compact binaries in the frequency–strain diagram for the simulated cluster at an age of 100 Myr. The large $\star$ identifies the location of an intermediate mass black hole formed in the simulations, which, at that moment had a mass of about $1130 M_\odot$ and had a $1.4 M_\odot$ main-sequence star companion in a 0.6 day orbit. This binary was captured by a three-body process.

Stellar-mass black holes, neutron stars and white dwarfs are represented in
Fig. 2. A selected sample of binaries in the gravitational wave strain and frequency domain. The LISA noise curves is over plotted as a reference. For all sources we assumed a distance to the source of 1kpc. The two diagonal dashed curves indicate the range of parameters (wave strain and frequency) between which a $5 \, M_\odot$ (lower) and $15 \, M_\odot$ (upper) main-sequence star which transfers mass to a $1000 \, M_\odot$ black hole is visible. The solid curve gives the evolution of the $2 \, M_\odot$ main-sequence star which transfers mass to a $1000 \, M_\odot$ black hole. The other symbols indicate the position of compact binaries from the in this paper described N-body simulation of MGG-11 at an age of 100 Myr. The large $\ast$ gives the position of the $\sim 1130 \, M_\odot$ intermediate mass black hole, which happens to have acquired a $1.4 \, M_\odot$ main-sequence companion star in a tight orbit. Each binary with two compact objects in this simulation (at an age of 100 Myr) is indicated with a single symbol or with a combination of symbols. Each symbols stands for either a stellar mass black hole (bullet), a neutron star (large circle) or a white dwarf (small circle). Some of the bullets to the left (binaries with two black holes) will eventually evolve through the LISA detection limit and become visible as gravitational wave sources.

figure 2 by bullets, large circles and small circles, respectively. All objects are binaries, and a single large circle therefore represents a binary consisting of two neutron stars, of which there are a couple. The few large circles with an inner smaller circle (near $\log f \sim -7$ and $\log h \sim -23.7$) are binaries with a neutron star and a white dwarf. The majority of objects contain black holes or white dwarfs; binaries with neutron stars are rare because of the large kick velocities they receive upon birth.
3 Summary

Young and dense star clusters are promising sources for gravitational wave radiation. Especially when they get older than \( \gtrsim 50 \) Myr as white dwarf binaries start to form. But also at younger age the presence of an intermediate mass black hole may provide an important source of gravitational waves.

An interesting possibility is provided by a \( \sim 2 \, M_\odot \) donor which starts to transfer mass to an intermediate mass black hole at birth. Such a binary may be visible as a bright transient X-ray source and simultaneously as gravitational wave source in the \( LISA \) band to a distance of a few kpc.

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