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COMPACT BINARIES IN GLOBULAR CLUSTERS

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RESUMEN

En sistemas estelares densos, las frecuentes interacciones dinámicas entre estrellas juegan un papel importante en la formación y evolución de las binarias compactas. Estudiamos esos procesos utilizando una nueva aproximación que combina los códigos de síntesis de población de binarias con un tratamiento simple de interacciones dinámicas en centros de cúmulos estelares densos. Nos enfocamos en los procesos dinámicos y evolutivos que llevan a la formación de binarias compactas que contienen enanas blancas en cúmulos globulares densos. Demostramos que la dinámica puede incrementar en un factor de $\sim 2-100$ los ritmos de producción de binarias, tales como variables cataclísmicas, "nonflickerers" (enanas blancas con una compañera oscura más pesada), objetos resultantes de la fusión de enanas blancas binarias con masas totales por encima del límite de Chandrasekhar, y enanas blancas binarias que emiten ondas gravitacionales en la banda de LISA.

ABSTRACT

In dense stellar systems the frequent dynamical interactions between stars play a crucial role in the formation and evolution of compact binaries. We study these processes using a novel approach combining a state-of-the-art binary population synthesis code with a simple treatment of dynamical interactions in dense star cluster cores. Here we focus on the dynamical and evolutionary processes leading to the formation of compact binaries containing white dwarfs in dense globular clusters. We demonstrate that dynamics can increase by factors $\sim 2-100$ the production rates of interesting binaries such as cataclysmic variables, "nonflickerers" (He white dwarfs with a heavier dark companion), merging white dwarf binaries with total masses above the Chandrasekhar limit, and white dwarf binaries emitting gravitational waves in the LISA band.

Key Words: **BINARIES: CLOSE — GALAXY: GLOBULAR CLUSTERS: GENERAL — WHITE DWARFS**

1. INTRODUCTION

From the earliest observations of X-ray binaries in globular clusters it has always been clear that they must be very efficient factories for the production of compact binary systems (Clark 1975). The overabundance of compact binaries in clusters, as compared to the field, must be a result of close stellar encounters. The key processes that affect the binary population in dense cluster environments include the destruction of wide binaries, hardening of close binaries (following "Heggie's law" (Heggie 1975)), and exchange interactions, through which low-mass companions tend to be replaced by a more massive participant in the encounter. As a result of these processes, in the dense cores of globular clusters, binaries are strongly depleted and their period distribution is very different from that of a field population (Ivanova et al. 2004). These processes also lead to an interesting and complex interplay between dynamics and binary evolution. For example, exchange interactions involving compact objects often produce systems that will evolve through a common-envelope (CE) phase and form very short-period binaries, which are much less common in field populations (Rasio, Pfahl, & Rappaport 2000).

There are two possible approaches to the study of binary evolution and dynamics in globular clusters. One can start from N-body simulations and introduce various simplified treatments of binary star evolution. This has been the traditional approach for many years (for recent examples see Shara & Hurley 2002; Portegies Zwart, McMillan, Hut, & Makino 2001). Alternatively, one can start from a binary population synthesis code and add a treatment of dynamical interactions. This approach was pioneered by Portegies Zwart et al. (1997) and has been adopted in our recent work. It has the great advantage that it is computationally much less expensive than N-body simulations, so that more exploration of the (enormous) parameter space is possible, and more realistic simulations, using sufficiently large numbers of stars and binaries, are possible today. In contrast, even when using special-purpose GRAPE computers, N-body simulations are still limited to smaller systems like open clusters with limited cover-

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age of parameter space and with unrealistically small numbers of binaries (see Ivanova et al. 2004; Wilkinson et al. 2003).

In our code we combined `StarTrack`, a state-of-the-art binary population synthesis code (Belczynski et al. 2002) and `FewBody`, a small-N-body integrator that we use to compute 3-body and 4-body interactions (Fregeau et al. 2004; Fregeau & Rappaport 2004). Currently we adopt a simple two-zone model, in which the cluster is partitioned into an inner core and an outer halo, with all interactions assumed to take place in the core. This background cluster model remains unchanged throughout the evolution (Hut, McMillan, & Romani 1992). In particular, the core density is assumed constant. However, our ultimate aim is to incorporate full dynamical Monte Carlo models (Fregeau et al. 2003). In a typical simulation we start with $N \sim 10^5$ stars, with between 50% and 100% binaries. This high primordial binary fraction (much higher than assumed in all previous studies) is needed in order to match the observed binary fractions in globular cluster cores today (Ivanova et al. 2004).

2. COMPACT BINARIES AND MERGERS

Consider the evolution of a typical dense cluster with central velocity dispersion $\sigma = 10\,\mathrm{km\,s^{-1}}$ and core density $n_c = 10^5\,\mathrm{pc^{-3}}$. Dynamical interactions lead to greatly enhanced numbers of compact binaries containing white dwarf (WD) and neutron star (NS) components, and, in particular, to much larger numbers of heavier compact binaries (Fig. 1). Here we focus in particular on the fate of WDs involved in CE events leading to compact binary formation or mergers of WDs driven by gravitational wave emission. Our simulations confirm that the formation rate of compact binaries containing a Helium WD with a heavier companion via CE events is increased significantly in dense clusters. The brighter Helium WDs in these binaries could be detectable as "nonflickerers." These were observed for the first time in the core of NGC 6397 (Cool et al. 1998) and are indeed thought to be double WD binaries containing a young Helium WD with an older and heavier WD companion (Hansen, Kalogera, & Rasio 2003).

We can also examine the rate of double WD mergers, and, in particular, those for which the total mass is $\geq M_{\rm Ch} \simeq 1.4 M_{\odot}$). These so-called supra-Chandrasekhar mergers could lead either to a Type Ia supernova, or to a "merger-induced" collapse of the remnant to form a NS (and perhaps a millisecond radio pulsar). It is possible that the NS in this case is formed without a significant kick

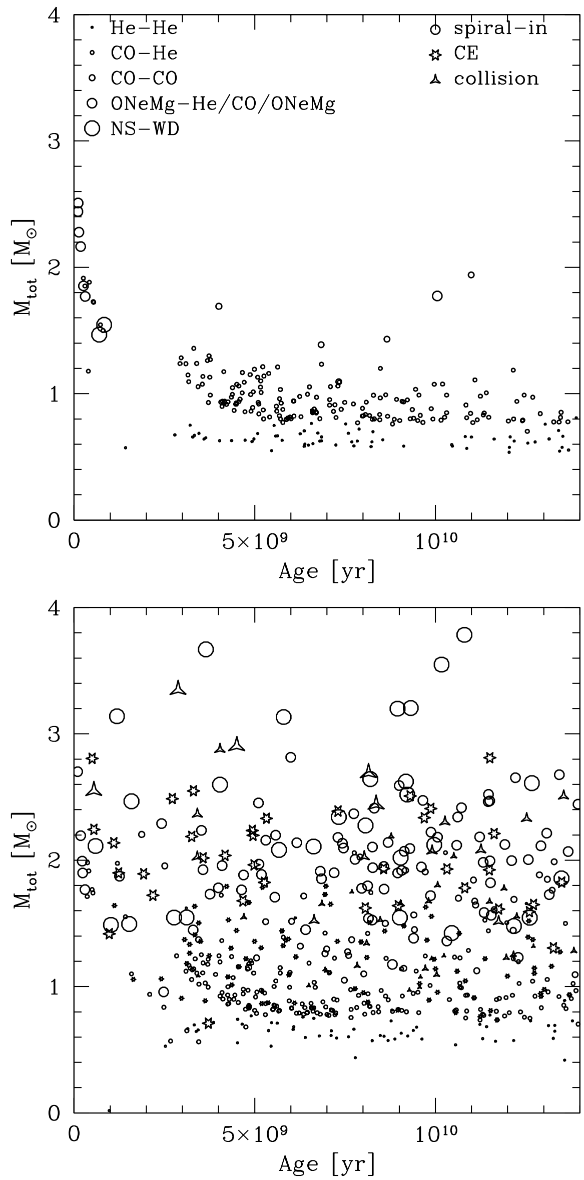

Fig. 1. Mergers and dynamical formation of compact binaries containing white dwarfs (WD) or neutron stars (NS). The horizontal axis gives the cluster age when the event occurred and the vertical axis gives the total mass of the binary. The top panel shows a population evolved without dynamical interactions, while the bottom panel shows the same initial population evolved in a dense cluster with core density $n_c = 10^5\,\mathrm{pc^{-3}}$. The size of each symbol indicates the types of stars involved, while the shape indicates the type of event: binary merger (round dots; usually driven by gravitational radiation or spiral-in during a common envelope phase), compact binary formation following a common envelope phase (stars), or merger following a physical collision (triangles). It is clear that dynamics increases both the total number of events and the typical mass of mergers and compact binaries.

(see the article by Podsiadlowski in this volume). An increased rate of Type Ia supernovae from star cluster dynamics would likely be redshift-dependent (as more stars are formed in starburst environments — which favor star cluster formation — at higher redshifts) and this has important potential consequences for their use in cosmology (for a review see Leibundgut 2001). Alternatively, merger-induced collapse could lead to the formation of neutron stars and millisecond pulsars in clusters, thereby alleviating or perhaps eliminating the NS "retention problem" (the ejection of most NS from the shallow cluster potentials if they are born with the natal kicks expected from asymmetric supernova explosions; see, e.g., Chen & Leonard 1993; Pfahl, Rappaport, & Podsiadlowski 2002)

The enhanced production rate of double WD mergers in dense stellar clusters was first discussed in detail by Shara & Hurley (2002). They estimated that, for stars born in open clusters (which can be simulated directly using their N-body code), the supra-Chandrasekhar WD merger rate can be increased by an order of magnitude. The results of Shara & Hurley (2002) are based on N-body simulations for a typical open cluster containing $\sim 10^4$ stars with 10% primordial binary fraction, and with $\sigma = 2\,\mathrm{km\,s^{-1}}$ and $n_{\mathrm{c}} = 10^3\,\mathrm{pc^{-3}}$. Our simulations are for much denser and massive star clusters with a primordial binary fraction of 100%. Not surprisingly, we find an even larger number of supra-Chandrasekhar WD mergers, with an enhancement factor (compared to a field population) closer to ~ 100 for a typical dense globular cluster. In contrast, the *total* number of double WD mergers (of all types) is typically increased by a factor of a few only. The majority of these mergers are driven ultimately by gravitational radiation, although a few come from physical collisions of WDs during hard binary encounters (Fregeau et al. 2004).

3. LISA SOURCES

Our results show that compact double WD binaries are mainly formed dynamically and have typically experienced multiple hardening encounters before merging. Prior to merger, these systems may be detectable as gravitational wave sources by LISA, when their orbital period becomes smaller than about 2000 s (Benacquista, Portegies Zwart & Rasio, 2001). This limit on the orbital period is imposed by the background noise from Galactic binaries. At the same time, the positional accuracy of LISA is much greater for binaries with these shorter periods, so that the sources can then be associated with specific globular clusters in our Galaxy.

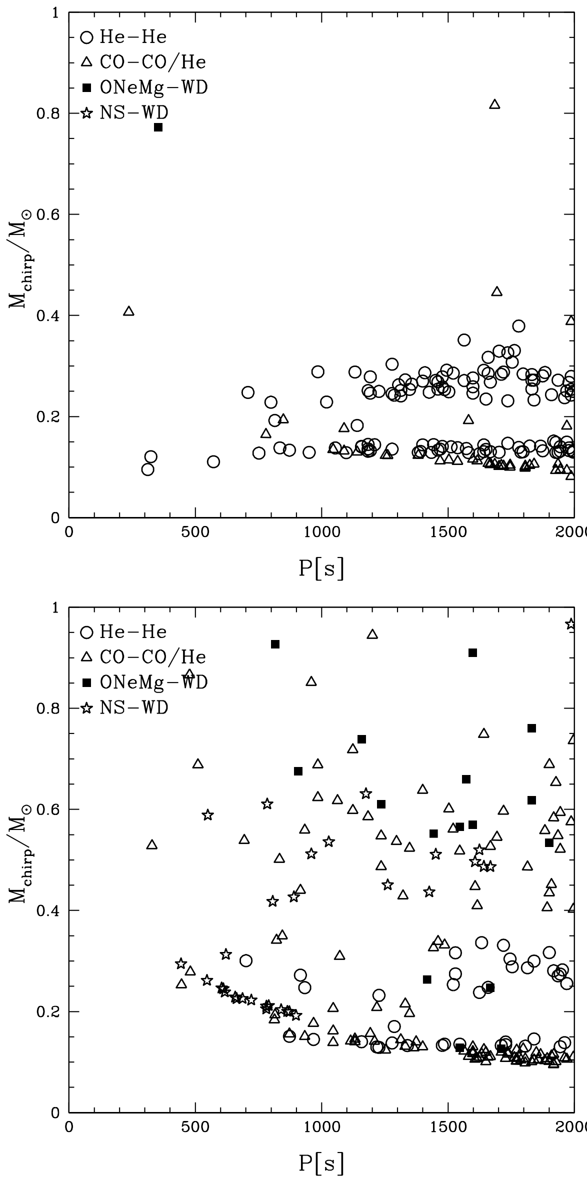

Fig. 2. All LISA-detectable binaries during the last Gyr of evolution for a typical dense cluster model with core density $n_c = 10^6\,\mathrm{pc^{-3}}$. Each source is shown only once, at a randomly chosen moment in its evolution across the LISA band. Here P is the binary orbital period and $M_{\mathrm{chirp}} = (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5}$ is the chirp mass. The different symbols indicate binaries with different types of components. We again compare a field population (top) to our cluster model including dynamical interactions (bottom).

Figure 2 shows all LISA-detectable sources (chirp masses and periods) that appeared during the last Gyr of our simulation for a typical dense cluster. For this model, where the total cluster mass today is about $2 \times 10^5\,M_\odot$, at least one LISA source is present at any given time. On average, there are ~ 5 LISA sources at any given moment, about twice the number predicted for a field population. In addition to this rise in the number of sources, we also note changes in their typical properties: in particular, the number of sources with chirp mass above $0.4\,M_\odot$ is increased significantly in the cluster model. We also find that NS-WD binaries represent about 20% of all LISA sources. Therefore, the number of LISA-detectable NS-WD binaries in all Galactic globular clusters ($M_{\rm tot} \sim 10^{7.5} M_\odot$) could be as high as $\gtrsim$ 100, while the total number of detectable WD-WD binaries could be $\gtrsim 500$. However, since the cluster models we have used so far in our simulations are denser than average, these numbers should be taken as upper bounds.

4. MASS TRANSFER SYSTEMS

As they spiral in and evolve across the LISA band, WD-WD and NS-WD binaries will eventually come into contact around a period $P \sim 100\,$s. At first the binary orbit shrinks as it loses angular momentum to gravitational radiation. However, during stable mass transfer, the orbit will evolve towards a larger period. During this mass transfer phase the binary can also appear as an ultracompact X-ray binary (NS-WD) or an AM CVn type cataclysmic variable (WD-WD). As expected, we find that the population of these mass transfer binaries is also increased significantly by dynamical interactions. For example, for our typical cluster model with $n_c = 10^5\,{\rm pc}^{-3}$, we predict about 50 AM CVn binaries, roughly twice the number obtained without dynamics.

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