*Highlights of Astronomy, Volume 14*
*IAU XXVI General Assembly, 14-25 August 2006*
*Karel A. van der Hucht, ed.*

doi:10.1017/S1743921307010265

# Joint Discussion 6
# Neutron stars and black holes in star clusters

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## 1. Introduction

This article was co-authored by all invited speakers at Joint Discussion 6 on *Neutron Stars and Black Holes in Star Clusters*, which took place during the IAU General Assembly in Prague, Czech Republic, on August 17 and 18, 2006. Each section presents a short summary of recent developments in a key area of research, incorporating the main ideas expressed during the corresponding panel discussion at the meeting.

Our meeting, which had close to 300 registered participants, was broadly aimed at the large community of astronomers around the world working on the formation and evolution of compact objects and interacting binary systems in dense star clusters, such as globular clusters and galactic nuclei. The main scientific topics cut across all traditional boundaries, including Galactic and extragalactic astronomy, environments from young starbursts to old globular clusters, phenomena from radio pulsars to gamma-ray bursts, and observations using ground-based and space-based telescopes, with a significant component of gravitational-wave astronomy and relativistic astrophysics.

Great advances have occurred in this field during the past few years, including the introduction of fundamentally new theoretical paradigms for the formation and evolution of compact objects in binaries as well as countless new discoveries by astronomers that have challenged many accepted models. Some of the highlights include: a nearly complete census of all the millisecond pulsars in 47 Tucanae; first detections of many new radio pulsars in other clusters, particularly Terzan 5; detailed studies of X-ray binary populations and their luminosity functions in many galaxies and extragalactic globular clusters; increasing evidence for intermediate-mass black holes in clusters and greatly improved theoretical understanding of their possible formation processes.

The next few years will prove at least as exciting, with many more data sets coming from recently or soon-to-be launched satellites, many new objects found in extensive deep radio and X-ray surveys, and follow-up spectroscopy and photometry with optical telescopes. On the theoretical side, advances in computer codes and special-purpose hardware will allow for more and more realistic modeling of whole large clusters including fairly complete treatments of all the relevant physics.

## 2. Direct $N$-body simulations

Direct $N$-body simulations follow stars individually. This is important when modeling star clusters, where specific interactions between single stars and binaries, as well as more complex multiple systems, play a central role (Aarseth 2003; Heggie & Hut 2003). In contrast, for larger-scale simulations of encounters between galaxies, and cosmological simulations in general, the stars are modeled as a fluid in phase space, and the individual properties of the stars are no longer important.

Traditionally, the term 'collisionless stellar dynamics' has been used for the latter case, and 'collisional stellar dynamics' for the former case. When these terms were coined in the nineteen sixties, they were perhaps appropriate, but now that we have started to simulate physical collisions between stars in a serious way, the use of the word 'collision' in the old sense has become rather confusing, since it was meant to denote relatively distant encounters that contribute to the two-body relaxation of a system.

It may be useful to introduce a new expression for the study of star clusters, shorter than 'collisional stellar dynamics,' and broader in the sense of including stellar evolution and hydrodynamics as well. One option would be to use *smenology*, or in Greek $\sigma\mu\eta\nu o\lambda o\gamma\iota\alpha$, after $\sigma\mu\eta\nu o\sigma$ (*smenos*), swarm, which is the word in use in modern Greek for a cluster; a star cluster is called $\sigma\mu\eta\nu o\sigma$ $\alpha\sigma\tau\epsilon\rho\omega\nu$ (*smenos asteroon*), literally a swarm of stars (Dimitrios Psaltis, personal communication).

Simulations of dense stellar systems, such as globular clusters (hereafter GCs) and galactic nuclei, have never yet been very realistic. Simplifying assumptions, such as those used in gas models or Fokker-Planck and Monte Carlo codes, have allowed us to model large particle numbers at the expense of a loss of detail in local many-body interactions and the imposition of global symmetry constraints. Conversely, direct $n$-body integration, while far more accurate, has labored under a lack of computer speed needed to model a million stars.

The good news is that we will soon be approaching effective computer speeds in the Petaflops range (Makino 2006), which will allow us to model the gravitational million-body problem with full realism, at least on the level of point particles. Adding equally realistic stellar evolution and hydrodynamics will be no problem as far as the necessary computer speed is concerned.

When the hardware bottleneck will thus be removed, the software bottleneck for realistic cluster simulations will become painfully obvious (Hut 2007). This is the bad news. While some serious uncertainties remain in the science needed to improve the software, currently the main bottleneck is neither science nor computer speed, but rather a sufficiently robust implementation of already available knowledge.

The main two codes currently being used for direct $N$-body simulations, `NBODY4` and `Kira`, are both publicly available: `NBODY4` at `<www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm>`, and `Kira` at `<www.ids.ias.edu/~starlab/>`.

`NBODY4` and other related codes form the results of a more than forty-year effort by Sverre Aarseth, as documented in Aarseth (2003). These codes are written in Fortran and they can be run stand-alone. A parallel version has been developed, named `NBODY6++` (Spurzem 1999; Spurzem & Baumgardt 2003), publicly available at `<ftp://ftp.ari.uni-heidelberg.de/pub/staff/spurzem/nb6mpi/>`. In addition to stellar dynamics, the version of NBODY4 developed by Jarrod Hurley and collaborators (see Hurley *et al.* 2005 and references therein) includes a treatment of stellar evolution for both single stars (named SSE) and binary stars (named BSE), using fitting formulae and recipes (Hurley *et al.* 2002).

The Kira code forms an integral part of the Starlab environment (Portegies Zwart *et al.* 2001). Kira and Starlab are written in C++. The basic data structure of Kira consists of a flat tree containing leaves representing single stars as well as nodes that hold center of mass information for small clumps of interacting stars. Each clump is represented by a binary tree, where each node determines a local coordinate system. The Kira code has built-in links to Seba, a stellar evolution module using fitting formulae developed by Tout *et al.* (1996) and recipes developed by Portegies Zwart & Verbunt (1996). In addition to Kira and Seba, the Starlab environment contains tools for setting up initial conditions for star clusters, using various models, and for analyzing the results of $N$-body simulations. Starlab also contains packages for binary–single-star and for binary–binary scattering.

Within the next ten years, multi-Petaflops computers will enable us to follow the evolution of star clusters with up to a million stars (Makino 2006). To make efficient use of this opportunity, while including increasingly realistic treatments of stellar evolution and stellar hydrodynamics, a number of new developments are required.

On the purely stellar dynamics level, some form of tree code may be useful for speeding up the long-range force calculations, as pioneered by McMillan & Aarseth (1993). In addition, guaranteeing accurate treatments of local interactions will become more challenging, especially for extreme mass ratios; designing good algorithms for following the motions of stars in the neighborhood of a massive black hole is currently an area of active research.

The largest challenge, however, will be to develop robust stellar evolution and stellar hydrodynamics codes, that can interface reliably with stellar dynamics codes, without crashing. The MODEST initiative (for MOdeling DEnse STellar systems) was started in 2002 with the intention to provide a forum for discussions concerning this challenge (Hut *et al.* 2003). A pilot project, MUSE (for MUlti-scale MUlti-physics Scientific Environment), was initiated recently to develop a modular software environment for modeling dense stellar systems, allowing packages written in different languages to interoperate within an integrated software framework (see the MODEST web site at <www.manybody.org/modest.html> and click on "projects").

Finally, for any large software project that involves a team of code developers, good documentation is essential. For most astrophysical simulation codes, documentation has come mainly as an afterthought. An attempt to develop a new code for modeling dense stellar systems, using an almost excessive amount of documentation can be found at <www.ArtCompSci.org>, the web site for ACS (the Art of Computational Science).

## 3. Monte Carlo methods

Hénon's Monte Carlo method has given rise to an industry in the business of simulating the evolution of dense stellar systems, providing fast and accurate simulations of large-$N$ systems. Its computational speed, coupled with the physical assumptions it requires (notably spherical symmetry and dynamical equilibrium) make it a very natural complement to 'direct' $N$-body simulations (Sec. 2), which are computationally much more expensive (or, equivalently, allow for smaller $N$) and generally require the use of special-purpose (GRAPE) hardware. Here we briefly discuss the method and the primary Monte Carlo

**Table 1.** Comparison of the capabilities of different methods for simulating the evolution of dense stellar systems. The first column lists the different physical processes at work in stellar systems, column 'NB' lists the capabilities of the $N$-body method, column 'MC' lists what the Monte Carlo method is in principle capable of, columns 'NU', 'F', 'G', and 'GS', list the current capabilities of the Northwestern, Freitag, and Giersz Monte Carlo codes, as well as the Giersz & Spurzem hybrid gas/Monte Carlo code. A filled circle means the code is fully capable of treating the physical process, while an open circle means it is capable subject to some limitations.

| **Physics** | **NB** | **MC** | **NU** | **F** | **G** | **GS** |
|---|---|---|---|---|---|---|
| two-body relaxation | ● | ● | ● | ● | ● | ● |
| stellar evolution | ● | ● | ○ | ○ | ○ | |
| stellar collisions | ● | ● | ● | ● | | |
| binary interactions | ● | ● | ● | | ○ | ● |
| external effects | ● | ○ | ○ | ○ | ○ | ○ |
| central BH | ● | ● | | ● | | |
| rotation | ● | | | | | |
| violent relaxation | ● | | | | | |
| large-angle scattering | ● | ● | | | | |
| three-body binaries | ● | ● | | | ● | ● |
| large $N$, $f_b$ | | ● | ● | ● | ● | ● |

codes before focusing on recent progress on the technique and recent contributions to the study of dense stellar systems made by those codes.

At the core of the modern Monte Carlo method is the Hénon technique, which amounts to the following. The evolution of each particle's orbit in a dense stellar system is influenced by all other particles in the system, although one cannot realistically sum all two-body scattering interactions and achieve reasonable computational speed on standard hardware. Instead, for each particle one performs a 'super'-encounter with a nearby particle, with the deflection angle chosen so as to represent the effects of relaxation due to the whole cluster (see Freitag & Benz 2001 for a pedagogical discussion and original references). This 'trick' makes the Monte Carlo method scale with particle number as $N \log N$ per time step, instead of $N^2$ with direct $N$-body methods.

There are currently three primary Monte Carlo evolution codes in use, along with a fourth hybrid gas model/Monte Carlo code. The Northwestern code uses the Hénon technique with a timestep shared among all particles (Fregeau & Rasio 2006, and references therein). Notably, it incorporates dynamical integration of all binary interactions in a cluster, allowing for the study of the long-lived binary-burning phase. The Freitag code uses the Hénon technique with a radius-dependent timestep (Freitag *et al.* 2006b, and references therein). It is notable for its inclusion of physical stellar collisions drawn from a library of SPH simulations, as well as a treatment of loss cone physics. The Giersz code uses the Hénon technique with radial timestep zones (Giersz 2006, and references therein), and includes stellar evolution of single stars. The Giersz & Spurzem hybrid code couples a gas dynamical model for the single star population with a Monte Carlo treatment of binary interactions (Giersz & Spurzem 2003, and references therein). Table 1 lists the capabilities of the Monte Carlo codes just discussed, as well as those of the direct $N$-body method.

In the past year or so, six papers relying on the Monte Carlo codes mentioned above have been published. Gürkan *et al.* (2006) studied the process of runaway collisional growth in young dense star clusters, and found the exciting new result that, when the runaway process operates in young clusters with primordial binaries, generally two very massive stars (VMSs) are formed. The VMSs formed may quickly undergo collapse after formation to become intermediate-mass black holes (IMBHs), yielding the exotic

https://doi.org/10.1017/S1743921307010265 Published online by Cambridge University Press

possibility of IMBH–IMBH binaries forming in young clusters. Giersz (2006) performed simulations of clusters with $N = 10^6$ stars subject to the tidal field of their parent galaxy. The large particle number allowed a detailed study of the evolution of the cluster mass function. Freitag *et al.* (2006c) performed a comprehensive study of the process of mass segregation in galactic nuclei containing supermassive black holes, with implications for the distribution of X-ray binaries (XRBs) at the Galactic Center. Freitag *et al.* (2006a) and Freitag *et al.* (2006b) studied in great detail the process of runaway collisional growth in young dense star clusters. Their study yielded several key results. First, a comparison of approximate physical stellar collision prescriptions with the detailed results of SPH simulations showed that the simple 'sticky-star' approximation – in which stars are assumed to merge without mass loss when their radii touch – is sufficiently accurate for clusters with velocity dispersions less than the typical stellar surface escape velocity to faithfully model the physics of runaway collisions. Second, runaway collisional growth of a VMS to $\sim 10^3\,\mathrm{M}_\odot$ is generic for clusters with central relaxation times sufficiently short ($\lesssim 25\,\mathrm{Myr}$) and for clusters which are initially collisional. Fregeau & Rasio (2006) presented the first Monte Carlo simulations of clusters with primordial binaries to incorporate full dynamical integration of binary scattering interactions (the work of Giersz & Spurzem (2003) performed integration of binary interactions, but used a gas dynamical model for the single star population). They performed detailed comparisons with direct $N$-body calculations, as well as with semi-analytical theory for cluster core properties as a function of the binary population, and found good agreement with both. They then simulated an ensemble of systems and compared the resulting cluster structural parameters ($r_c/r_h$ and the concentration parameter, for example) during the binary burning phase with the observed Galactic GC population. The interesting result is that the values of $r_c/r_h$ predicted by the simulations are roughly a factor of 10 smaller than what is observed. The most likely explanation is that physical processes ignored in the simulations (such as stellar evolution and collisions) are at work in the Galactic sample, generating energy in the cores and causing them to expand. However, more detailed simulations should be performed to test this hypothesis.

## 4. Stellar and binary evolution in globular clusters

Much of the recent work in the area of stellar evolution in GCs has concentrated on the evolution of low-mass X-ray binaries (LMXBs) and their likely remnants, the millisecond pulsars (MSPs). In particular, several new studies have considered the possible effects of a 'radio-ejection phase' initiated when the mass transfer temporarily stops during the secular evolution of the systems.

The much larger fraction of binary MSPs and LMXBs in GCs, with respect to their fraction in the Galactic field, is regarded as a clear indication that binaries containing neutron stars (NSs) in GCs are generally not primordial, but are a result of stellar encounters due to the high stellar densities in the GC cores. On the other hand, it is still not clear how the LMXBs are formed in the Galactic field, as the result of a supernova explosion in a binary in which the companion is a low-mass star will generally destroy the binary. Many possible processes have been invoked to explain LMXBs: (*i*) accretion-induced collapse of a white dwarf primary into a neutron star; (*ii*) supernova kicks due to asymmetric neutrino energy deposition during the supernova event; (*iii*) formation of LMXBs as remnants of the evolution of binaries with intermediate-mass donors; (*iv*) LMXBs formed by capture in the dense environment of GCs and later released when the GC is destroyed. This last hypothesis, originally due to Grindlay *et al.* (1984), was recently re-evaluated in the literature (Podsiadlowski *et al.* 2002; see also Sec. 11).

https://doi.org/10.1017/S1743921307010265 Published online by Cambridge University Press

The 'standard' secular evolution of LMXBs as progenitors of binary MSPs is reasonable in the context of the evolution of binaries above the so-called 'bifurcation period' $P_{\rm bif}$ (Tutukov *et al.* 1985; Pylyser & Savonije 1988), in which the donor star begins the mass transfer phase after it has finished the phase of core hydrogen burning, and the system ends up as a low-mass white dwarf (the remnant helium core of the donor) in a relatively long or very long period orbit with a radio MSP (e.g., Rappaport *et al.* 1995. Some of these systems may also be the remnants of the evolution of intermediate-mass donors, with similar resulting orbital periods (Rasio *et al.* 2000; Podsiadlowski *et al.* 2002. Recently, D'Antona *et al.* (2006) showed that the secular evolution at $P > P_{\rm bif}$ may need to take into account the detailed stellar evolution of the giant donor, in order to explain the orbital period gap of binary MSPs between $\sim 20$ and $\sim 60$ days. During the evolution along the RGB, the hydrogen burning shell encounters the hydrogen chemical discontinuity left by the maximum deepening of convection: the thermal readjustment of the shell causes a luminosity and radius drop, which produces a well known 'bump' in the luminosity function of the RGB in GCs. In semi-detached binaries, at the bump, the mass transfer is temporarily stopped, following the sudden decrease in radius. We consider it possible that, when mass transfer starts again, a phase of 'radio-ejection' begins (Burderi *et al.* 2001; Burderi *et al.* 2002), in which mass accretion onto the NS is no longer allowed because of the pressure from the radio pulsar wind. In this case, the matter is lost from the system at the inner lagrangian point, carrying away angular momentum and altering the period evolution. This will occur for magnetic moments of the NS in a range $\sim 2-4 \times 10^{26}$ G cm$^3$, which is the most populated range for binary MSPs.

Turning now to the evolution below $P_{\rm bif}$, it is well known that, if the secular evolution of LMXBs is similar to that of cataclysmic variables (CVs), one should expect many systems at $P \lesssim 2$ hr, and a minimum orbital period similar to that of CVs, namely $\sim 80$ min. On the contrary, there are very few of these systems, and instead several 'ultrashort' period binaries. In particular, three LMXBs in the field (which are also X-ray MSPs) and one in a GC (X1832−330 in NGC 6652) are concentrated near $P_{\rm orb} \simeq 40$ min. In addition there are two other ultrashort period systems in GCs. While for GCs we may think that these systems were formed by capture of a white dwarf by the NS, the field systems should have arrived at this period by secular evolution. Models have been constructed by Nelson & Rappaport (2003) and Podsiadlowski *et al.* (2002), and all imply that the donors began Roche lobe overflow at periods just slightly below $P_{\rm bif}$, so that the donor evolved to become a degenerate dwarf predominantly composed of helium, but having a residual hydrogen abundance $< 10\%$. Until hydrogen is present in the core of the donor star, in fact, the evolution proceeds towards short $P_{\rm orb}$ (convergent systems). If the hydrogen content left is very small, the mass radius relation when these objects become degenerate is intermediate between that of hydrogen-dominated brown dwarfs and that of helium white dwarfs, so that smaller radii and shorter $P_{\rm orb}$ will be reached before radius and period increase again.

One problem of this scenario is that *there is a very small interval of initial* $P_{\rm orb}$ which allows this very peculiar evolution: in most cases, either a helium core is already formed before the mass transfer starts, and the system evolves towards long $P_{\rm orb}$, or there is enough hydrogen that the system is convergent, but the minimum period is similar to that of CVs, and cannot reach the ultrashort domain. Podsiadlowski *et al.* (2002) notice that, for a 1 M$_\odot$ secondary, the initial period range that leads to the formation of ultracompact systems is 13 − 18 hr. Since systems that start mass transfer in this period range might be naturally produced as a result of tidal capture, this could perhaps explain the large fraction of ultracompact LMXBs observed in GCs. However, quantitatively, this appears highly unlikely (van der Sluys *et al.* 2005).

In any case, this does not apply to LMXBs in the field. In her PhD thesis, Anamaria Teodorescu (2005) derived the period distribution expected for LMXBs from convergent systems under several hypotheses, and compared it with the available observed period distribution. An expected result was that the range $P_{\rm orb} < 2\,{\rm hr}$ is very populated and the distribution is inconsistent with observations, unless we can suppress the secular evolution of all the systems below the 'period gap', which should occur at about the same location as in CVs. One can consider several different possibilities to do this:

($a$) The lack of systems at $P_{\rm orb} < 2\,{\rm hr}$ is again a consequence of radio-ejection: after the period gap is traversed by the detached system, when the mass transfer resumes, it is prevented by the pulsar wind pressure, the matter escapes from the system with high specific angular momentum, and the evolution is accelerated. Indeed, this is probably occurring in the system containing pulsar W in 47 Tucanae, which has $P_{\rm orb} = 3.2\,{\rm hr}$. This system exhibits X-ray variability which can be explained by the presence of a relativistic shock within the binary that is regularly eclipsed by the secondary star (Bogdanov *et al.* 2005). The shock can then be produced by the interaction of the pulsar wind with a stream of gas from the companion passing through the inner Lagrange point (L1), a typical case of what is expected in radio-ejection (Burderi *et al.* 2001). This mechanism could affect all the systems which enter a period gap. Notice that only systems which end up at ultrashort periods *do not* detach during the secular evolution, and they only might have a 'normal' secular evolution. Thus both the lack of systems at $P_{\rm orb} < 2\,{\rm hr}$ and the presence of ultrashort periods could be due to this effect.

($b$) 'Evaporation' of the donor, due to the the pulsar wind impinging on, and ablating material from, the surface of the companion (Ruderman *et al.* 1989) is another possible mechanism, with results not so different from the previous case.

($c$) It is possible that the secular evolution almost never begins when the donor is not significantly evolved. This can be true only if binaries are mostly formed by tidal capture, in which the NS captures a main-sequence star only at separations $\lesssim 3\,R_*$ (Fabian *et al.* 1975). This might happen in GCs, but we need to explain the $P_{\rm orb}$ distribution of *all* the LMXBs in the Galaxy. We could then reconsider the possibility that *most* of the field LMXBs were in fact formed in GCs, which were later destroyed (e.g., by tidal interactions with the Galactic bulge; but see Sec. 11).

There are other specific cases that we must take into account when discussing evolutions starting close to $P_{\rm bif}$. The famous interacting MSP binary in NGC 6397, PSR J1740−5340 is such a case. At $P_{\rm orb} = 35.5\,{\rm hr}$, it is in a radio-ejection phase and the companion has certainly not been captured recently in a stellar encounter: it is an evolved subgiant, as predicted by the secular evolution models (Burderi *et al.* 2002), and as confirmed by the CN cycled chemistry of the donor envelope, observed by Sabbi *et al.* (2003b) and predicted by Ergma & Sarna (2003). We suspect that PSR J1748−2446ad in Terzan 5 is also in a radio-ejection phase (Burderi *et al.* 2006), but the lack of information on the donor precludes a very secure interpretation. At $P_{\rm orb} = 26.3\,{\rm hr}$, again, the donor should be in an early subgiant stage, and have evolved very close to $P_{\rm bif}$.

Finally, the whole period distribution of binary MSPs in GCs is consistent with a very high probability of the onset of mass transfer being close to $P_{\rm bif}$. In fact, there is a large group having $P_{\rm orb}$ from 0.1 to 1 day, a range not covered at all by the 'standard' evolutions in Podsiadlowski *et al.* (2002), but which results easily from the range of initial periods between those leading to ultrashort period binaries and those above the bifurcation (Teodorescu 2005). In addition, there are several binary MSPs in GCs for which the white dwarf mass is very low ($0.18 - 0.20\,{\rm M}_\odot$), close to the minimum mass which can be formed by binary evolution (Burderi *et al.* 2002), indicating again evolution starting at a period slightly larger than $P_{\rm bif}$.

## 5. Population synthesis with dynamics

Ivanova and collaborators have developed a new simulation code to study the formation and retention of NSs in clusters, as well as the formation and evolution of all compact binaries in GCs. This code is described in Ivanova *et al.* (2005) and Ivanova *et al.* (2006). The method combines the binary population synthesis code `StarTrack` (Belczynski *et al.* 2002; Belczynski *et al.* 2007) and the `Fewbody` integrator for dynamical encounters (Fregeau *et al.* 2004). Compared to other numerical methods employed to study dense stellar systems, this method can deal with very large systems, up to several million stars, and with large fractions of primordial binaries, up to 100%, although the dynamical evolution of the cluster is not treated in a fully self-consistent manner.

In addition to the formation of NSs via core collapse, these simulations take into account NSs formed via electron-capture supernovae (ECS). When a degenerate ONeMg core reaches a mass $M_{\rm ecs} = 1.38\,{\rm M}_\odot$, its collapse is triggered by electron capture on $^{24}$Mg and $^{20}$Ne before neon and subsequent burnings start and, therefore, before the formation of an iron core (see, e.g., Nomoto 1984). The explosion energy of such an event is significantly lower than that inferred for core-collapse supernovae (Dessart *et al.* 2006), and therefore the associated natal kick velocities may be much lower. There are several possible situations when a degenerate ONeMg core can reach $M_{\rm ecs}$:

• During the evolution of single stars: if the initial core mass is less than that required for neon ignition, $1.37\,{\rm M}_\odot$, the core becomes strongly degenerate. Through the continuing He shell burning, this core grows to $M_{\rm ecs}$. The maximum initial mass of a single star of solar metallicity that leads to the formation of such a core is $8.26\,{\rm M}_\odot$, and the minimum mass is $7.66\,{\rm M}_\odot$. This mass range becomes 6.3 to 6.9 ${\rm M}_\odot$ for single stars with a lower GC metallicity $Z = 0.001$. The range of progenitor masses for which an ECS can occur depends also on the mass transfer history of the star and therefore can be different in binary stars, making possible for more massive progenitors to collapse via ECS (Podsiadlowski *et al.* 2004).

• As a result of accretion onto a degenerate ONeMg white dwarf (WD) in a binary: accretion-induced collapse (AIC). In this case, a massive ONeMg WD steadily accumulates mass until it reaches the critical mass $M_{\rm ecs}$.

• When the total mass of coalescing WDs exceeds $M_{\rm ecs}$: merger-induced collapse (MIC). The product of the merger, a fast rotating WD, can significantly exceed the Chandrasekhar limit before the central density becomes high enough for electron captures on $^{24}$Mg and $^{20}$Ne to occur, and therefore more massive NSs can be formed through this channel (Dessart *et al.* 2006).

Both metal-poor ($Z = 0.001$) and metal-rich ($Z = 0.02$) stellar populations have been studied by Ivanova *et al.* (2005) and Ivanova *et al.* (2006), who find that the production of NSs via core-collapse SNe (CC NSs) is 20% lower in the metal-rich population than in the metal-poor population. In a typical cluster (with total mass $2 \times 10^5\,{\rm M}_\odot$, age $\sim 10$ Gyr, 1-dimensional velocity dispersion $\sigma = 10$ km/s and central escape velocity 40 km/s), about 3000 CC NSs can be produced, but less than 10 will typically be retained in the cluster.

ECS in single stars in a metal-rich population are produced from stars of higher masses, but the mass range is the same as in metal-poor populations. As a result, the number of ECS from the population of single stars in the metal-rich case is 30% smaller than in the metal-poor population, in complete agreement with the adopted initial mass function (IMF). The total number of NSs produced via this channel is several hundreds (and depends on the initial binary fraction), but the number of retained NSs is higher than in the core-collapse case: about 150 NSs in a typical cluster. The binarity smoothes the mass range where ECS could occur, and there are fewer differences between the production of

NSs via ECS in binary populations of different metallicity. The number of retained NSs produced via AIC and MIC is comparable to the number of ECS, about 100 in a typical metal-poor cluster. Overall, one finds that, if a metal-rich GC has the same IMF and initial binary properties as a metal-poor GC, it will contain 30 – 40% fewer NSs.

These simulations can also be used to examine the spatial distribution of pulsars and NSs in clusters, although the present method only distinguishes between a central 'core' (where all interactions are assumed to take place) and an outer 'halo'. For a typical half-mass relaxation time $t_{\rm rh} = 10^9$ yr, about 50% of all NSs and 75% of pulsars should be located in the core, and for a longer $t_{\rm rh} = 3 \times 10^9$ yr, these fractions decrease to about 25% and 50% respectively. Such predicted spatial distributions are in good agreement with observations of pulsars in many GCs (Camilo & Rasio 2005).

Ivanova *et al.* analyzed three main mechanisms for the formation of close binaries with NSs: tidal captures, physical collisions with giants, and binary exchanges. Very few primordial binaries with a NS can survive, except for those that were formed via AIC. Typically $\sim 3\%$ of all NSs in a metal-poor GC can form a binary via physical collision and $\sim 2\%$ via tidal captures, while 40% of dynamically formed binary systems will start mass transfer (MT) in a Hubble time. These number are slightly higher in the case of a metal-rich cluster, and can be as much as two times higher in a cluster of the same metallicity but with a lower velocity dispersion, down to $\sigma = 5$ km/s. The binary exchange channel is more important for binary formation, as up to 50% of all NSs will be at some point members of binary systems, but only about 8% of these systems will start MT.

Overall, taking into account the formation rates of MT binaries with a NS and a MS star, and the duration of the MT phase, the probability that a cluster contains a NS-MS LMXB is almost unity, although most of them will be in quiescence. For NS-WD binaries, the probability is $\sim 50\%$, but only a few percent of these will be in the bright phase, when $L_{\rm x} > 10^{36}$ erg/s. More LMXBs per NS are formed in metal-rich clusters, but since fewer NSs are produced and retained, no significant difference in the resulting LMXB formation rate is found.

Finally, we note that if all ECS channels indeed work, too many NSs and pulsars (more than observed) are produced in these models. Therefore, either one or more of the ECS channels (standard ECS, AIC or MIC) does not work, or they have smaller allowed physical ranges where they can occur, or the kick associated with ECS could be larger. Our current understanding of stellar evolution and NS formation and retention in GCs of different metallicities, coupled with the dynamical formation of mass-transferring binaries with NSs, cannot explain the statistically significant overabundance of LMXBs in more metal-rich clusters. Instead, different physics for the MT with different metallicities or different IMFs are required (Ivanova 2006).

## 6. Green Bank observations of millisecond pulsars in clusters

Since its first scientific observations five years ago, the Green Bank Telescope (GBT), has uncovered at least 60 GC pulsars, almost doubling the total number known†. Almost all of these systems are MSPs, and the majority are members of binaries. Incredibly, 30 of these new MSPs, including many strange systems, are in the dense and massive bulge GC Terzan 5 (with a total of 33), while another 10 are in the bulge cluster M 28 (for a total of 11). Other clusters with new pulsars (and the numbers new/total) are M 30

† There are at least 133 known GC pulsars, of which 129 are currently listed in Paulo C.C. Freire's catalog at `<http://www2.naic.edu/~pfreire/GCpsr.html>`. For a recent review of GC pulsars, see Camilo & Rasio (2005).

https://doi.org/10.1017/S1743921307010265 Published online by Cambridge University Press

(2/2), M 62 (3/6), NGC 6440 (5/6), NGC 6441 (3/4), NGC 6522 (2/3), NGC 6544 (1/2), and NGC 6624 (4/5).

Most of the GCs with new pulsars are in the Galactic bulge, with large columns of ionized gas along the lines of sight. Almost all of the new pulsars have been found using wide bandwidth (600 MHz) observations centered near 2 GHz, a relatively high radio frequency for pulsar searches. Such observations are much less affected by interstellar dispersion and scattering than traditional searches (at 1.4 GHz or 430 MHz), resulting in greatly improved search sensitivities, particularly for the fastest MSPs.

Pulsar timing solutions using the GBT now exist for almost 50 of the new MSPs, as well as for an interesting binary MSP found with the GMRT (NGC 1851A; Freire *et al.* 2004). These timing solutions provide precise spin and orbital parameters, which are useful for probing many aspects of NS physics, binary evolution, and cluster dynamics. In addition, the highly precise astrometric positions (with typical errors of $\lesssim 0.1''$) allow additional probes of cluster dynamics and possible identification of pulsar companions at optical or X-ray wavelengths.

Using the ensemble of 32 Terzan 5 (Ter 5) MSP timing solutions, the positions of the pulsars with respect to the cluster center allow a statistical measurement of the average NS mass ($\sim 1.35 - 1.4\,M_{\odot}$). Similarly, the pulsar positions and dispersion measures (DMs; the integrated electron column density along the line of sight to the pulsar) provide a unique probe of interstellar medium electron density variations over $0.2 - 2$ pc scales and show that they are not inconsistent with Kolmogorov turbulence. Several of the brighter Ter 5 pulsars with timing solutions encompassing older Parkes observations are beginning to show evidence for proper motions. Average proper motion values from GC MSPs may provide the best proper motion measurements of highly reddened clusters like Ter 5. Finally, comparisons of the spin-period and luminosity distributions of the 33 pulsars in Ter 5 and 22 in 47 Tuc show that they are significantly different, and hence may be related to the properties and dynamics of the GCs.

Among the interesting new pulsars are Ter 5E, a 2.2 ms pulsar in a 60 d orbital period (the 2$^{\rm nd}$ longest of any cluster MSP, the longest is in the low-density cluster M53); Ter 5N, an 8 ms pulsar with a likely CO white dwarf companion, the first known in a GC; five 'black-widow'-like systems (M 62E, Ter 5O, Ter 5ae, M 28G, and M 28J) with few-hour circular orbits and $\sim 10 - 40\,M_{\rm Jupiter}$ companions; and at least seven eclipsing binaries (M 30A, Ter 5O, Ter 5P, Ter 5ad, NGC 6440D, NGC 6624F, and M 28H).

Several of the above systems hint at production mechanisms involving stellar interactions. But there are two other classes of very interesting pulsars that are almost certainly produced via exchange interactions: pulsar-'main-sequence' binaries, and highly eccentric ($e > 0.25$) binaries. Recent 2-GHz GBT searches have uncovered at least two of the former, and (amazingly) nine of the latter.

Ter 5ad is the fastest MSP known ($P$=1.396 ms; Hessels *et al.* 2006) and finally beats the 23-yr-old 'speed' record established by the first MSP discovered Backer *et al.* (1982). Ter 5P is the 5$^{\rm th}$ fastest MSP known. Both systems are in circular binaries ($P_{\rm orb} = 26$ hr for Ter 5ad and 8.7 hr for Ter 5P) with companions of mass $\gtrsim 0.14\,M_{\odot}$ for Ter 5ad and $\gtrsim 0.36\,M_{\odot}$ for Ter 5P. Both systems are eclipsed for $\sim 40\%$ of their orbit, yet on some occasions the eclipses appear to be irregular (of different duration or possibly of variable depth). These systems appear to be very similar to the fascinating MSP J1740$-$5340 in NGC 6397 (D'Amico *et al.* 2001b).

Timing solutions for Ter 5ad and P associate both pulsars with hard X-ray point sources detected in a *Chandra* observation of the cluster. In addition, both systems exhibit extremely large orbital period derivatives ($\dot{P}_{\rm orb} \simeq 7 \times 10^{-9}$) and numerous (4 or more) higher-order period derivatives, likely due to tidal interactions with the companion stars. Upcoming *HST*-ACS and near-IR VLT adaptive-optics observations may identify 'bloated' companions, as for PSR J1740−5340 (Ferraro *et al.* (2001)).

These two systems raise many questions: Why has it taken so long to find a new 'fastest MSP'? Do faster systems exist? Why does Ter 5 have 5 of the 10 fastest MSPs known in the Galaxy and *the* 5 fastest-spinning pulsars known in the GC system? Can the large orbital period variations constrain tidal circularization theory? Is the X-ray emission from magnetospheric pulsations, an intra-binary shock, or some combination of both?

The second class of exchange products are the highly eccentric binaries. M 15C, a double NS system, was the first highly-eccentric binary discovered in a GC (Anderson *et al.* 1990), but it took ten years to find the next, NGC 6441A (Possenti *et al.* 2001). Soon afterwards, M 30B (found with the GBT; Ransom *et al.* 2004) and then NGC 1851A (currently being timed with the GBT; Freire *et al.* 2004) were detected. The recent GBT 2-GHz surveys, though, have uncovered *nine* additional highly-eccentric binaries: six in Terzan 5 (I, J, Q, U, X, and Z), two in M28 (C and D), and one in NGC 6440 (B).

Eccentric MSP binaries systems can be important probes of NS physics, as they provide a way to constrain (or even directly measure) the masses of fully-recycled pulsars. Given the angular reference that an ellipse provides, pulsar timing can easily measure the orbital advance of periastron. If the companion star is compact, the advance is dominated by general relativistic effects and determines the total system mass ($M_{\rm tot}$). The amount of mass required to spin-up a MSP is currently unknown: the double NS systems with precisely determined masses are only partially recycled, and there are only a handful of mass measurements for fully recycled pulsars ((Stairs *et al.* 2004; Lattimer & Prakash 2004). Since the recycling scenario in general creates binary MSPs in circular orbits (due to tidal circularization during the accretion phase), these systems are *only* produced during interactions in dense stellar systems (Rasio & Heggie 1995).

Timing solutions from the GBT are now available for all of the known highly eccentric binaries except for M 15C (although, see Jacoby *et al.* 2006), M 30B (which has only been detected once, likely due to strong scintillation effects), and Ter 5U (a very strange system with $P_{\rm orb} = 1.8$ d, $e \simeq 0.27$, and a minimum companion mass of only 25 $M_{\rm Jupiter}$). From these 10 timing solutions, the advance of periastron is highly significant in 9, indicating total system masses between 1.6 - 2.5 $M_\odot$. Such values are expected for recycled pulsars (with the NS mass being 1.4 - 2 $M_\odot$) with white-dwarf-like companions, indicating that the periastron advance is likely dominated by general relativity and not by classical effects.

Two of these systems (Ter 5I and J) appear to have 'massive' NSs ($\sim 1.7\,M_\odot$), which constrain the equation of state (EOS) of matter at nuclear densities, possibly ruling out very soft EOSs or those with strange-matter components (Ransom *et al.* 2005). Over the next couple of years, measurements of the relativistic $\gamma$ parameter for Ter 5I and possibly of the Shapiro delay for M 28C are likely. These measurements, if the companions are white dwarfs, will provide accurate masses for the NSs. Several of the other eccentric binaries are interesting as well: Does Ter 5Q (with $P = 2.8$ ms and $P_{\rm orb} = 30$ d) have a NS companion? How do you create a highly eccentric binary like Ter 5U with a 25 – 30 $M_{\rm Jupiter}$ companion? Why was Ter 5Z not ejected from the core when the interaction that made it eccentric occurred? Why does M28D (with $P = 79.8$ ms and $P_{\rm orb} = 30$ d) appear to be a 'young' pulsar (characteristic age $t_c \simeq 1 \times 10^7$ yr)? Was it really formed (and possibly partially-recycled) only recently?

Timing observations are ongoing for most of the new pulsars mentioned here, and will continue to refine known parameters, to allow searches for planetary companions, to measure secular effects possibly due to unseen companions or stellar encounters, and likely to determine the proper motions of the clusters. In addition, searches of all timing data and GBT observations of other clusters are underway. We fully expect the GBT to uncover many more GC MSPs, including some new surprises, in the coming years.

## 7. Parkes observations of radio pulsars in clusters

The Parkes Globular Cluster Pulsar Search is a project started in the mid 1990s as a side search project of the Parkes Multibeam Pulsar Survey. Observations with the Parkes radio telescope have been extensively performed with the central beam of the multibeam receiver and the collected data have been processed with dedicated algorithms. This project has so far led to the discovery of twelve new MSPs in six GCs for which associated pulsars were previously unknown. This section summarizes some recent results obtained from timing these sources.

### 7.1. *NGC 6266*

The cluster NGC 6266 hosts six MSPs. The first three of them, PSR J1701−3006A, B and C, have been discovered in the framework of the Parkes Globular Cluster Pulsar Search by D'Amico *et al.* (2001a), while the other three have been discovered with further GBT observations by Jacoby *et al.* (2002).

All six pulsars in this cluster are members of binary systems (D'Amico *et al.* 2001a; Possenti *et al.* 2003; Jacoby *et al.* 2002). This unusual occurrence is very unlikely to be due to chance. It is possible that the absence of isolated pulsars in this cluster is related to the peculiar dynamical state of the cluster that lowers the rate at which binaries are disrupted via dynamical encounters.

A peculiar object in this cluster is the MSP PSR J1701−3006B (Possenti *et al.* 2003). It is in the emerging family of eclipsing MSPs with relatively massive companions. Several observations of this pulsars as it transits at the superior conjunction show distortions in the signal that can be ascribed to the pulsar motion through the companion wind matter. The ablation timescale for the companion is compatible with the pulsar's age only if less than 10% of the released mass is ionized, which appears unlikely. The alternate possibility is that mass loss is due to nuclear evolution of the companion, analogous to the case of the eclipsing system in NGC 6397 (Possenti *et al.* 2003).

### 7.2. *NGC 6397*

PSR J1740−5340 is a peculiar MSP in NGC 6397 (D'Amico *et al.* 2001a; D'Amico *et al.* 2001b). It is a binary source, whose radio signal suffers eclipses as the pulsar approaches superior conjunction (D'Amico *et al.* 2001b). The extent of the eclipses strongly depends on the observing frequency. At 1.4 GHz eclipses last up to 40% of the orbit, and signal distortion is observed at all orbital phases. Such distortions become less prominent at an observing frequency of 2.3 GHz and become nearly absent at 3.0 GHz.

Optical observations of the companion have revealed several phenomena that occur as the pulsar emission interacts with the companion surface:

(*i*) The study of H$\alpha$ lines indicates that matter is swept away in a cometary tail by a radio ejection mechanism (Sabbi *et al.* 2003a);

(*ii*) The presence of He lines in absorption may indicate that hot barbecue-like strips on the companion surface are heated by a highly anisotropic pulsar flux (Sabbi *et al.* 2003b);

(*iii*) The signature of an enhanced lithium abundance on the companion surface may be perhaps ascribed to lithium production from nuclear reactions triggered by accelerated particles flowing from the pulsar (Sabbi *et al.* 2003b).

The strong distortion suffered by the radio signal from the pulsar makes it very difficult to obtain a fully coherent timing solution for the pulses. This is illustrated by a recent optical determination of the companion position (Bassa & Stappers 2004), which is inconsistent with the previous determination obtained from the pulsar timing (D'Amico *et al.* 2001b). The measurement of the companion position by Bassa & Stappers (2004) allowed the determination of a new timing solution (Possenti *et al.* 2005), which will be updated with timing observations at 3.0 GHz.

### 7.3. *NGC 6441*

The cluster NGC 6441 hosts PSR J1750−3703 (D'Amico *et al.* 2001a), a binary pulsar in a highly eccentric orbit ($e = 0.712$) with a relatively massive companion. Since a data span of about five years is now available, the periastron advance for this system is actually measured with a precision of about $20\,\sigma$ (Possenti *et al.* 2006), which gives a total mass for this binary $M_{\rm tot} = 2.20 \pm 0.17\,{\rm M}_\odot$. This result can be combined with the mass function for this system and the minimum measured mass for a NS to obtain a range for the mass of the companion $0.6\,{\rm M}_\odot \leqslant M_{\rm C} \leqslant 1.17\,{\rm M}_\odot$ (Possenti *et al.* 2006). This makes it unlikely that the companion is another NS.

### 7.4. *NGC 6752*

NGC 6752 contains five known MSPs. The discovery of PSR J1910−5959A as a binary pulsar (D'Amico *et al.* 2001a) allowed the subsequent discovery of four more isolated pulsars (D'Amico *et al.* 2002).

All five pulsars in this cluster show peculiar features. PSR J1910−5959B and E, located within a few arcseconds from the cluster center, show a large negative value for the spin period derivative (D'Amico *et al.* 2002). These negative values are ascribed to the motion of these objects inside the cluster potential well. PSR J1910−5959D is also located close to the cluster core (D'Amico *et al.* 2002). Its spin period derivative is positive and of the same order of magnitude as the values for PSR J1910−5959B and PSR J1910−5959E, implying that, for this pulsar as well, the spin period derivative is affected by the cluster potential (D'Amico *et al.* 2002). These measurements allow us to investigate the mass-to-light ratio in the central region of the cluster. A lower limit $M/L_V \geqslant 5.5\,{\rm M}_\odot/{\rm L}_\odot$ has been obtained by Ferraro *et al.* (2003). Such a high value indicates the presence of a large number of low-luminosity objects in the cluster core.

PSR J1910−5959A and C are located in the outskirts of the cluster, namely $\theta_{\perp,{\rm PSR\,A}} = 6.3'$ and $\theta_{\perp,{\rm PSR\,C}} = 2.7'$ (D'Amico *et al.* 2001a; D'Amico *et al.* 2002; Corongiu *et al.* 2006), values that put these two objects in first and second place, respectively, among GC pulsars that show a large offset from the cluster center. These unusual positions have been investigated in detail by Colpi *et al.* (2002) and Colpi *et al.* (2003). The most probable explanation invokes the ejection of these objects from the cluster core by dynamical interactions with a central massive object that may be either a single massive black hole or a binary black hole of intermediate mass (Colpi *et al.* 2003).

The recent measurement of proper motions for the pulsars PSR J1910−5959A and PSR J1910−5959C (Corongiu *et al.* 2006) shows that they are compatible with each other, but they are not in agreement with the proper motion of the cluster as determined from optical observations. Further observations of this cluster will soon allow us to determine the proper motion of the pulsars in the cluster core (certainly belonging to the cluster) and the comparison between these proper motions and those of pulsars A and C will then establish whether the more distant pulsars are truly associated with the cluster.

## 8. *Chandra* observations of X-ray sources in clusters

The *Chandra X-ray Observatory* has provided fundamental new insights into the nature of faint ($L_x \simeq 10^{30-34}$ ergs/s) GC X-ray sources, through its superb spatial resolution and moderate spectral resolution. See Verbunt & Lewin (2006) for a fuller (but dated) review, and the next section for some *XMM-Newton* results. The best-studied cluster (and the main focus in this section) is 47 Tucanae (47 Tuc), which has been well observed with *Chandra* (detecting 300 X-ray sources), *HST* in the optical and UV, and Parkes for pulsar timing observations (detecting 22 pulsars; see Sec. 7).

### 8.1. *Low-mass X-ray binaries*

The bright sources in GCs have long been known to be accreting neutron stars; X-ray bursts have now been detected from all Galactic GCs hosting luminous X-ray sources (in't Zand *et al.* 2003). *Chandra*'s resolution resolved a longstanding puzzle about the M 15 LMXB: the optically identified LMXB in M 15 is seen edge-on, not allowing direct view of the accreting (likely) neutron star; and yet X-ray bursts from a neutron star surface have been seen from M 15. This puzzle is resolved by the identification of a second LMXB in M 15 (White & Angelini 2001). This second LMXB has a period of 22.6 min (Dieball *et al.* 2005); this is the third neutron star accreting from a white dwarf (an ultracompact XRB; see Sec. 4) known in a GC.

### 8.2. *Transient LMXBs*

*Chandra* has allowed the identification of the quiescent counterparts to three transient LMXBs. Quiescent LMXBs, at $L_x \simeq 10^{32-34}$ ergs/s, tend to show soft spectra, dominated by a $\sim 0.3$ keV blackbody-like spectrum. This component can be fit with a neutron star hydrogen atmosphere model, with implied radius of 10 - 15 km (Rutledge *et al.* 2002a). This radiation is commonly thought to be produced by heating of the core during accretion, which will slowly leak out over $10^4$ yr (Brown *et al.* 1998). A second harder component (of unknown origin) is often required above 2 keV, typically fit by a power-law with photon index 1 - 2. Two of the transient LMXBs observed in quiescence fit this model; those in NGC 6440 (in't Zand *et al.* 2001) and Terzan 1 (Cackett *et al.* 2006). In contrast, the spectrum of the transient in Terzan 5 requires only a power-law component, with a photon index of $1.8^{+0.5}_{-0.4}$, indicating that quiescent LMXBs may also have relatively hard spectra (Wijnands *et al.* 2005).

### 8.3. *Quiescent LMXBs*

In addition to the known quiescent counterparts of transient LMXBs, additional X-ray sources are seen in clusters with spectra and luminosities characteristic of quiescent LMXBs. Spectral fitting of the brightest of these with neutron star atmosphere models gives inferred radii consistent with 10 - 12 km (Rutledge *et al.* 2002b). Two such systems in the cluster 47 Tuc show regular eclipses at periods of 8.7 and 3.1 hr (Heinke *et al.* 2005a), and two systems have faint optical counterparts (Haggard *et al.* 2004). Pooley *et al.* (2003) and Heinke *et al.* (2003) showed that the numbers of quiescent LMXBs in different clusters scaled with the stellar interaction rate in those clusters, implying they are formed dynamically.

If the distance to the GC is reasonably well-known, then it is possible to constrain the radius (or a combination of radius and mass) of the glowing neutron star through fits to hydrogen atmosphere models. This has the potential to improve our understanding of the composition of neutron star interiors, and thus the behavior of matter at high density. In units of $R_\infty (= R*(1+z))$, constraints have been placed on the neutron star in $\omega$ Cen ($R_\infty = 14.3 \pm 2.1$ km, Rutledge *et al.* 2002b), and on X7 in 47 Tuc ($R_\infty = 18.3^{+3.8}_{-1.2}$ km, Heinke *et al.* 2006b); see below for *XMM-Newton* results. Perhaps the largest remaining source of uncertainty in these calculations is the distance to the GCs; recent authoritative determinations of the distance to 47 Tuc by the subdwarf main-sequence fitting method and direct geometry give results which differ by 20% (Gratton *et al.* 2003; McLaughlin *et al.* 2006).

## 8.4. *Cataclysmic Variables*

Optical counterpart searches using *HST* have identified 22 cataclysmic variables (CVs) in 47 Tuc through blue optical/UV colors and variability, eight of which have secure orbital periods (Edmonds *et al.* 2003a). Ten CVs have also been identified in NGC 6752 (Pooley *et al.* 2002) and nine in NGC 6397 (Grindlay *et al.* 2001b). These CVs have blue $U-V$ colors, but $V-I$ colors that are on or near the main sequence. This indicates that the secondaries dominate the optical light, which is in agreement with the identification of ellipsoidal variations in several of these systems. Comparison of these and other cluster CVs with Galactic CVs shows that cluster CVs have fainter accretion disks than Galactic CVs with similar periods (Edmonds *et al.* 2003b). This suggests that cluster CVs have relatively low mass transfer rates. However, the lack of dwarf nova outbursts from cluster CVs (Shara *et al.* 1996) may be an indication that cluster CVs tend to be strongly magnetic (e.g., Dobrotka *et al.* 2006).

CVs may be formed in GCs either dynamically or from primordial binaries. Several *Chandra* observational studies (Pooley *et al.* 2003; Heinke *et al.* 2003; Pooley & Hut 2006; Heinke *et al.* 2006b; Kong *et al.* 2006) as well as population synthesis studies (Ivanova *et al.* 2006) point to contributions by both mechanisms to the existing CV population in clusters.

## 8.5. *Active binaries*

Numerous chromospherically active binaries (mostly close main-sequence binaries) have been identified in several GCs. Sixty have been identified with *Chandra* sources in 47 Tuc alone (Heinke *et al.* 2005b). Bassa *et al.* (2004) and Kong *et al.* (2006) have recently shown that the population of active binaries in clusters, unlike CVs and LMXBs, is produced from primordial binaries; in the densest clusters (such as NGC 6397), these binaries have been largely destroyed (Cool & Bolton 2002).

## 8.6. *Radio millisecond pulsars*

MSPs have been detected in X-ray in several GCs (e.g., Bassa *et al.* 2004). The deep observations of 47 Tuc have detected all 19 MSPs with known positions (Bogdanov *et al.* 2006), showing that in most cases their X-ray spectra are dominated by thermal emission from their hot polar caps. Comparison of the X-ray spectra of unidentified sources in 47 Tuc with known MSPs and active binaries reveals that the majority of the unknown sources are active binaries, and constrains the total number of MSPs in 47 Tuc to $<60$, most likely $\leqslant 30$ (Heinke *et al.* 2005b). This helps to resolve a suggested discrepancy between the birthrates of LMXBs and MSPs in Galactic GCs.

A few of the MSPs in 47 Tuc (and elsewhere) show harder X-ray spectra, suggestive of nonthermal synchrotron or shock emission. One of these, 47 Tuc-W, shows long X-ray eclipses, indicating the X-rays are produced in a shock near the companion from matter that continues to overflow the companion's Roche lobe (Bogdanov *et al.* 2005) – making this a 'missing link' between LMXBs and MSPs. These discoveries have greatly improved our understanding of the evolution of LMXBs into MSPs in clusters.

## 9. *XMM-Newton* observations of X-ray sources in clusters

Observations of Galactic GC faint X-ray sources made with the two X-ray satellites *XMM-Newton* (e.g., Webb *et al.* 2006; Webb *et al.* 2004; Gendre *et al.* 2003a; Gendre *et al.* 2003b; Webb *et al.* 2002) and *Chandra* (Heinke *et al.* 2006a; Heinke *et al.* 2006b; Pooley *et al.* 2003; see Sec. 8) have revealed that 25 are neutron star XRBs. *XMM-Newton* spectra of these systems are of sufficiently high quality, even with only 30 ks observations, to well constrain the mass and radius of the neutron star, using neutron star atmosphere models (e.g., Zavlin *et al.* 1996; Heinke *et al.* 2006a; Heinke *et al.* 2006b) and taking advantage of the fact that their distances and interstellar absorptions are well constrained due to their situation in a GC (Servillat *et al.* in preparation; Gendre *et al.* 2003a; Gendre *et al.* 2003b). The masses and radii are essential for constraining the (poorly known) equation of state of the nuclear matter in these very compact stars.

Gendre *et al.* (2003b), Pooley *et al.* (2003) and Heinke *et al.* (2003) have also used the GC observations of faint X-ray sources, coupled with the result that the bright X-ray sources ($L_{\rm x} > 10^{36}$ erg s$^{-1}$; Hertz & Grindlay 1983) are also neutron star XRBs (see Verbunt & Hut 1987 and references therein), to confirm, through observations, the theory that these objects are formed mainly through dynamical encounters. This implies a total population of approximately 100 neutron star XRBs distributed throughout the 151 Galactic GCs (Pooley *et al.* (2003)). This population is wholly insufficient to slow down the inevitable core collapse of these self-gravitating stellar clusters if the energy liberated by binaries interacting with other cluster stars is indeed the internal energy source necessary to counter the tendency of clusters to collapse (see Hut *et al.* 1992 for a review).

Cataclysmic variables (CVs) exist in much greater numbers in GCs. Indeed Di Stefano & Rappaport (1994) predict of the order one hundred CVs in a single Galactic GC. This prediction is born out by observations, for example more than 30 CVs have been detected in 47 Tuc using X-ray observations (Heinke *et al.* 2005a; Heinke *et al.* 2005b) and approximately 60 candidate CVs have been identified in NGC 2808 using UV observations (Dieball *et al.* 2005). Thus, although we do not yet know the whole population size of CVs in the GCs observed (unlike for the brighter, soft neutron stars) with which to determine their formation mechanisms and numbers, it is apparent that they exist in large numbers and thus it is possible that they are important to the cluster's fate.

With more and more cataclysmic variables identified in Galactic GCs, one striking and unexplained difference has become clear between cluster CVs and field CVs. Cluster CVs show a distinct lack of outbursts (characterized by a steep rise in the flux by several orders of magnitude) compared to field CVs. Due to the proximity of the white dwarf and its companion in a CV, material is accreted from the companion star and stored in the accretion disk around the white dwarf whilst it loses sufficient angular momentum to fall onto the compact object. Outbursts are believed to occur when too much material builds up in the disc, increasing both the density and the temperature, until the hydrogen ionizes and the viscosity increases sufficiently for the material to fall onto the white dwarf (Osaki 1974; Meyer & Meyer-Hofmeister 1981; Bath & Pringle 1981. Many types of field CVs show such outbursts every few weeks to months. However, only very few GC outbursts have been observed (e.g., Paresce & de Marchi 1994; Shara *et al.* 1996; Shara *et al.* 1987) and it is unclear why this should be.

It was originally suggested that cluster CVs may be mainly magnetic (see the five CVs in Grindlay 1999). Magnetic CVs have accretion discs that are either partially or totally disrupted by the strong white dwarf magnetic fields and these two types are known as intermediate polars and polars, respectively. Material is channelled along the field lines

https://doi.org/10.1017/S1743921307010265 Published online by Cambridge University Press

onto the white dwarf, although in the case of intermediate polars, a truncated disk can exist and these systems can undergo a limited number of outbursts (e.g., Norton & Watson 1989). Recently it has been proposed that it may not simply be the magnetic field that is responsible for the lack of outbursts. Dobrotka *et al.* (2006) suggest that it may be due to a combination of low mass transfer rates ($\lesssim 10^{14-15}\,\mathrm{g\,s^{-1}}$) and moderately strong white dwarf magnetic moments ($\gtrsim 10^{30}\,\mathrm{G\,cm^3}$) which could stabilize the CV discs in globular clusters and thus prevent most of them from experiencing *frequent outbursts.* This result suggests that the brightest globular cluster CVs in Ter 5s should be intermediate polars. Ivanova *et al.* (2006) have also proposed that the lack of outbursts is due to higher white dwarf masses (higher mean masses are observed amongst strongly magnetic isolated white dwarfs; Wickramasinghe & Ferrario 2000). This is likely to be due to the difference in the formation mechanisms of GC and field CVs, since a substantial fraction of cluster CVs are likely to be formed through encounters, rather than from their primordial binaries (Ivanova *et al.* 2006).

Intermediate polars show modulation on the spin period (typically $\sim 10^{2-3}$ s) of the accreting white dwarf which can be detected through Fourier analysis. For example, Parker *et al.* (2005) showed that 70% of the intermediate polars that were observed with *ASCA* and *RXTE* showed this modulation. Thanks to the sensitivity of the *XMM-Newton* satellite, observations made with this observatory of the cluster NGC 2808 revealed that the brightest CV in this cluster shows evidence for a modulation with a 430 s period (Servillat *et al.*, in preparation). This is likely to be the modulation on the spin period, supporting an intermediate polar identification. Low-resolution spectra of the brightest CV (candidate) in the cluster M 22 (Webb *et al.* 2004; Webb *et al.* in preparation) also show some evidence for the He 4686 Å line in emission, indicative of a magnetic white dwarf (e.g., Szkody *et al.* 2005). As the CV has already been observed to outburst (Anderson *et al.* 2003; Bond *et al.* 2005; Pietrukowicz *et al.* 2005), it would indicate that this source is also an intermediate polar, again supporting the idea that cluster CVs have moderate magnetic field strengths, in part responsible for their lack of outbursts.

We now turn briefly to possible formation mechanisms for cluster CVs. It is now believed that there are two populations of CVs in GCs, those formed dynamically (as the neutron star LMXBs), thought to be located in the dense cluster cores, and those that have evolved from a primordial binary without undergoing any significant encounter. This latter population may reside outside the cluster core (Davies 1997), where the stellar density is much lower than near the center. Naturally we expect that the more concentrated GCs, which have higher core densities, have higher encounter rates, thus increasing the number of CVs formed through encounters. In addition, the timescales of encounters between primordial binaries and single stars are shortened, thus decreasing the number of primordial CVs. The GCs that have been observed with *XMM-Newton* are particularly well adapted to searching for a primordial binary population, as they are low-density clusters, chosen to ensure that we can resolve all the X-ray sources (the angular resolution of the *XMM-Newton*-EPIC cameras is approximately 6″ FWHM of the PSF). In addition, *XMM-Newton*'s large collecting area ensures that there are enough photons for a full spectral study of about 20% of the sources detected, advantageous for identifying CVs using X-ray data alone. Several CVs have already been detected in the cores of GCs, like AKO 9 in 47 Tuc (Auriére *et al.* 1989), which Knigge *et al.* (2003) state was almost certainly formed dynamically, either via tidal capture or in a three-body encounter. Such dynamically formed CVs exist in other GCs, like $\omega$ Cen (e.g., Carson *et al.* 2000; Gendre *et al.* 2003a) and M 22 (Webb *et al.* 2004).

Several X-ray sources in GCs studied with *XMM-Newton* lie outside the half-mass radius and have X-ray luminosities, spectra, colors, and lightcurves that indicate they may be CVs. Recently, Pietrukowicz *et al.* (2005) confirmed, using optical photometry, that one of these X-ray sources (Webb *et al.* 2004) lying at 3.9 core radii from the centre of M 22 is indeed a CV. It is possible that this CV was formed from a primordial binary. Ivanova *et al.* (2006) predict that as many as 37% of the CVs in a cluster like 47 Tuc should be formed from the primordial binaries, thus one would expect an even greater percentage for a lower-concentration cluster such as M 22, supporting the primordial formation mechanism.

## 10. X-ray luminosity functions

Populations of X-ray sources have been discovered with *Chandra* in all kinds of galaxies. These populations provide a novel approach to study the evolution of XRBs. This section summarizes recent results from the study of the X-ray Luminosity Functions (XLFs) in these extragalactic populations.

XLFs (in either differential or cumulative form) provide a useful tool for characterizing and comparing XRB populations. Cumulative XLFs are typically described by functional slope(s), breaks, and normalization. Each of these parameters is potentially related to the formation and evolution of XRBs in a given stellar population: the distribution of luminosities (slope) has been found to be related to the age of the population (see below); breaks in the XLF are a possible indication of multiple or evolving XRB populations in the same galaxy; the normalization is a measure of the total number of XRBs. Grimm *et al.*(2002) first reported differences in the XLFs of different types of binaries, by deriving the 'young-short-lived' high-mass X-ray binary (HMXB) and 'old LMXB' XLFs for the Milky Way. They found that the HMXB XLF is well fitted by a single power-law, while the LMXB XLF may show both high- and low-luminosity breaks. More recent studies, based on *XMM-Newton* and *Chandra* observations, are in general agreement with these early results, but also show a more complex reality (see review by Fabbiano 2006).

Early studies of the integrated X-ray luminosity of star-forming galaxies pointed to a tight connection between the number of XRBs and star formation activity (e.g., Fabbiano *et al.* 1988; Fabbiano & Shapley 2002)). More recently, comparisons of XLFs have suggested a dependence of the normalization on the star formation rate (SRF) of the galaxy ( Kilgard *et al.* 2002; Zezas & Fabbiano 2002; Grimm *et al.* 2003). Grimm *et al.* (2003), in particular, propose that all HMXB XLFs follow a similar cumulative slope of $-0.6$, and have normalization strictly proportional to the SFR. The XLFs of individual spiral galaxies (see Fabbiano 2006 and references therein) not always agree with this conclusion. However, deviations can be understood if the effect of XRB populations of different ages is considered. A particularly illuminating case is that of M83, a grand-design spiral with a nuclear starburst (Soria & Wu 2003). In M83, the XLF of the nuclear region is a power-law with a cumulative slope $-0.7$, reasonably consistent with Grimm *et al.* (2003); instead, the XLF of the outer disk is complex, suggesting several XRB populations. This XLF has a break (and becomes steeper) at luminosities above $8 \times 10^{37}$ erg/s, suggesting an older XRB population than that of the nuclear region; below the break it follows a $-0.6$ power-law, but this power-law is interrupted by a dip. Soria & Wu suggest that this complex disk XLF may result from the mixing of an older disk XRB population mixing with a younger (but aging) population of spiral-arm sources.

The best-studied example of an extreme young HMXB population so far is given by the deep *Chandra* study of Antennae galaxies (Fabbiano *et al.* 2003), which led to the discovery of 120 X-ray sources down to a limiting luminosity near $2 \times 10^{37}$ erg/s (Zezas *et al.* 2006), and including about 14 ultra-luminous X-ray sources (ULXs). The cumulative XLF is well fitted with a single power-law of slope of $\sim -0.5$. There is a small

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deviation from this power-law near $2 \times 10^{38}$ erg/s, suggesting a NS Eddington limit effect (however this result is not statistically significant; Zezas *et al.* 2007).

Two papers, reporting the analysis of samples of early-type galaxies, give a good picture of the LMXB XLF at luminosities greater than a few $10^{37}$ erg/s. Kim & Fabbiano (2004) analyzed 14 E and S0 XLFs, corrected each individual XLF for incompleteness by means of simulations, and found that the corrected XLFs could be fitted (above $6 \times 10^{37}$ erg/s) with similar steep power-laws. Given this similarity, the data were co-added resulting in a significantly higher signal-to-noise XLF, which shows a break, formally at $4.5 \times 10^{38}$ erg/s, and marginally consistent with the NS Eddington limit. Gilfanov (2004) using a sample of early-type galaxies and spiral bulges reached a similar conclusion.

Gilfanov (2004) suggested that the global stellar mass of the galaxy or bulge is the driving factor for the normalization of the XLF (the total number of slowly-evolving LMXBs in a given stellar population). A somewhat different conclusion was reached by Kim & Fabbiano (2004; see also Kim *et al.* 2006). They reported a correlation between the total LMXB luminosity of a galaxy and the $K$-band (stellar) luminosity, in agreement with the stellar-mass-normalization link, but the scatter of this correlation is large, and while independent of total $K$-band luminosity, is correlated with the specific frequency of GCs in the galaxies (a link previously suggested by White *et al.* 2002). The conclusion, similar to that suggested for Galactic LMXBs (Clark 1975), is that GCs have a special effect on the formation and evolution of LMXBs. These results, however, do not exclude the possibility that evolution of native field binaries is also important, a point stressed by Irwin (2005).

LMXBs as short-lived ultra-compact binaries formed in GCs, have been discussed by Bildsten & Deloye (2004) (; see also Ivanova *et al.* 2005), who point out that their model can reproduce the observed XLF. Disruption of (or expulsion from) GCs could then give rise to LMXBs in the stellar field. Alternatively, LMXBs may form and evolve in the field (Verbunt & van den Heuvel 1995; Kalogera 1998, and references therein). Field source evolution models (e.g., Piro & Bildsten 2002) have not set constraints on the XLF, but predict that most high-luminosity LMXBs should be detached binaries with large unstable disk, and therefore recurrent transients. While more time monitoring observations are needed, transients are indeed detected in some cases (e.g., in NGC 5128; Kraft *et al.* 2001).

A large body of work has addressed the association of individual X-ray sources with GCs in E and S0 galaxies, and the properties of observed field and GC LMXBs (Sec. 11). A particularly relevant result from the recent paper by Kim *et al.* (2006), based on the analysis of the LMXB populations of 6 galaxies observed with *Chandra*, is worth mentioning here: no significant difference can be seen in the XLFs of LMXBs with and without a GC counterpart. Moreover, both XLFs extend to luminosities above $5 \times 10^{38}$ erg/s, a regime where the accreting object is likely to be a black hole. Ivanova & Kalogera (2006) have pointed out that high-luminosity LMXBs are likely to be field transients populating the XLF in outburst, and that the XLF can be considered as the footprint of the black-hole mass function, with a differential slope of $-2.5$ and upper mass cut-off at $20\,M_{\odot}$. However, the field and cluster LMXB XLFs are similar and both extend to high luminosities. Are black-hole X-ray binaries therefore present in GCs, despite their very low expected formation probability (Kalogera *et al.* 2004)?

Very recent work (Kim *et al.* 2006), based on deep *Chandra* observations of two nearby elliptical galaxies with well studied old stellar populations, NGC 3379 and NGC 4278, is addressing the low-luminosity LMXB XLF, at luminosities below a few times $10^{37}$ erg/s, which are typical of the majority of LMXBs in the bulge of the Milky Way and M 31. The LMXB XLF of the Milky Way (Grimm *et al.* 2002) becomes flatter at these lower luminosities. Gilfanov (2004) suggested a significant 'universal' flattening below $5 \times 10^{37}$ erg/s in the LMXB XLF. This flattening is suggested by a number of models (see, e.g., Bildsten & Deloye 2004; Pfahl *et al.* 2003). Kim *et al.* (2006) demonstrate that there is no universal low-luminosity flattening of the LMXB XLF. The XLF of NGC 4278 is very well fitted with a continuous power-law with cumulative slope $-1$, down to $1 \times 10^{37}$ erg/s. The XLF of NGC 3379 (extending down to near $10^{36}$ erg/s) is also well represented by a similar power-law, but it presents a statistically marginal localized excess near $4 \times 10^{37}$ erg/s.

## 11. Extragalactic globular cluster X-ray sources

Other galaxies, particularly ellipticals, have proved to be excellent grounds for learning about what kind of GCs produce bright X-ray sources. These galaxies have GC systems up to two orders of magnitude larger than the Milky Way's. Furthermore, they often show much more diversity than the Milky Way in terms of metallicities and ages of the clusters. On top of this all, there are dozens of galaxies within 20 Mpc, so even if one galaxy fails to provide a sufficiently large or diverse population of clusters for studying a particular effect, one can co-add many galaxies. Studies of elliptical galaxies have been especially fruitful, since the specific frequencies of GCs are larger in more massive, later type galaxies. Additionally, the GC samples are better understood in elliptical galaxies than in spiral galaxies because of the smoother field star backgrounds in elliptical galaxies are easier to subtract off than the knotty emission in spiral galaxies.

It was determined early in the *Chandra* era that about half of all X-ray sources in elliptical galaxies are in GCs (see, e.g., Sarazin *et al.* 2001 and Angelini *et al.* 2001 for the first few studies, and Kim *et al.* 2006 for an analysis of an ensemble of galaxies). This compares with matching fractions of 10% in the Milky Way (van Paradijs & van den Heuvel 1995) or $\sim 20\%$ in M 31 (Supper *et al.* 1997). The fraction was found to increase continuously through the Hubble tuning fork diagram from spirals to lenticulars to ellipticals to cD galaxies (Maccarone *et al.* 2004). It has been suggested that a substantial fraction of non-GC X-ray sources were originally formed in clusters (e.g., White *et al.* 2002), but recent work has shown both that the fraction of X-ray sources in clusters increases with specific frequency of GCs (Juett 2005), and that the ratio of X-ray to optical luminosity increases more slowly than linearly with the specific frequency (Irwin 2005).

One of the key areas of interest for extragalactic GC studies is the determination of which cluster properties most affect the likelihood that a cluster will contain an XRB. The most significant parameter is the cluster mass (Kundu *et al.* 2002), with several studies finding that the probability a cluster will be an X-ray source scales in a manner consistent with $M^{1.1 \pm 0.1}$ (Kundu *et al.* 2003; Jordan *et al.* 2004; Smits *et al.* 2006).

The normalization in the number of XRBs per unit stellar mass is still considerably larger than in galaxies' field populations, where the number of LMXBs seems to be linearly proportional to the stellar mass as well (Gilfanov 2004; Kim & Fabbiano 2004), so clearly the number of XRBs must be related to the stellar interaction rates in the clusters. Determining the stellar interaction rate requires an understanding of the radial profile of the cluster as well as its total mass, and this is rather difficult to determine for most GCs at the $10-16$ Mpc distances of the best-studied elliptical galaxies. Kundu *et al.* (2002) found for NGC 4472 that the half-light radius of a cluster was a marginally significant parameter for predicting whether a GC would have an X-ray source. Jordan *et al.* (2004) attempted to fit King models to the GCs in M 87 and found no statistically significant difference between the predictive power of cluster mass and of inferred cluster collision rate for whether a cluster would contain an X-ray binary. There is only a weak correlation between cluster core radius and cluster half-light radius, except in the least concentrated clusters, and since the core radii of nearly all Milky Way GCs are too small to be resolved, even with the *Hubble Space Telescope*, at distances exceeding a few Mpc. It is thus not surprising that we cannot obtain any quantitative information about the relation between cluster collision rate and probability of containing an XRB by looking at Virgo Cluster elliptical galaxies.

It was found by Smits *et al.* (2006) that the observed $P(\mathrm{LMXB}) \propto M^{1.1}$ is consistent with bimodal pulsar kick-velocity distributions (e.g. Arzoumanian *et al.* 2002; Brisken *et al.* 2003), but not with a single Maxwellian kick-velocity distribution around 200 km/s (e.g., Hobbs *et al.* 2005). Because binary evolution effects can produce low kick-velocity pulsars (e.g., Pfahl *et al.* 2002; Dewi *et al.* 2005) it is not clear whether the cluster XRB results have direct implications for the controversies concerning isolated pulsar velocity distributions.

Aside from mass, the other key parameter which helps determine whether a cluster will contain an X-ray source is its metallicity. There were some indications from the pre-*Chandra* era that this was the case, based on the Milky Way and M 31 (Grindlay 1999), but the strong correlation in spiral galaxies between metallicity and galactocentric radius, along with the relatively strong tidal forces in the centers of spiral galaxies, left some doubt about which was the underlying physical cause of the enhancement of X-ray sources in metal-rich bulge GCs. It has since been proven clearly, in numerous elliptical galaxies, that metallicity really is a strong predictor of whether a cluster will have an X-ray source (Kundu *et al.* 2002; Di Stefano *et al.* 2003 ; Jordan *et al.* 2004; Minniti *et al.* 2004; Xu *et al.* 2005; Posson-Brown *et al.* 2006; Chies-Santos *et al.* 2006).

Attempts have also been made to determine whether cluster ages affect X-ray binary production, especially in light of theoretical suggestions that there should be a peak in the X-ray source production rate at ages of about 5 Gyr (Davies & Hansen 1998). In NGC 4365, which has a substantial sub-population of intermediate-age clusters (Puzia *et al.* 2002; Larsen *et al.* 2003; Kundu *et al.* 2005), it is clear that there is an effect of metallicity on the probability a GC will be an X-ray source (Kundu *et al.* 2003); roughly the same effect of metallicity is seen in NGC 3115 (Kundu *et al.* 2003), which has only old GCs (Puzia *et al.* 2002). This argues in favor of the idea that the metallicity effect is causual.

Two viable possibilites have been suggested for this effect. One is irradiation-induced stellar winds (Maccarone *et al.* 2004), which should be stronger in low-metallicity environments (Iben *et al.* 1997) since the energy deposited by irradiation in a low metallicity star cannot easily be dissipated by line cooling. As a result, the metal-poor stars will lose much of their mass to the interstellar medium, rather than to the accreting star, yielding effectively lower duty cycles as bright sources. The other model depends on the smaller convection zones of metal-poor stars compared with metal-rich stars (Ivanova 2006). This leads to reduced cross sections for formation of X-ray binaries through tidal capture, and to less efficient magnetic braking, and hence lower accretion rates. A distinguishing characteristic of the models is that the irradiation wind model should leave behind absorbing material which will leave an absorption signature in X-ray spectra, while the convection zone model should not. Spectra of M 31 clusters in the 0.1 – 2.4 keV *ROSAT* band are harder in the more metal-poor clusters (Irwin & Bregman 1999), while *Chandra* spectra showed no correlation between X-ray spectrum and cluster metallicity (Kim *et al.* 2006 Kim *et al.* 2006). It is thus not clear whether the M 31 results are a statistical fluke, or the *Chandra* data, with very little sensitivity to X-rays below 0.7 keV, are simply not sensitive to this effect.

## 12. Massive black holes in globular clusters

There has been considerable debate as to whether evidence supports the existence of massive central black holes in GCs. M15 has been the focus for decades, and the latest observational results by van den Bosch *et al.* (2006) show no significance for a black hole ($1000 \pm 1000\,\mathrm{M}_{\odot}$). The same is true of 47 Tuc where McLaughlin *et al.* (2006) report $700 \pm 700\,\mathrm{M}_{\odot}$. In both of these cases, the value reported, while not significant, is consistent with that mass expected from an extrapolation of the correlation between black hole mass and host dispersion as reported in Gebhardt *et al.* (2002) and Tremaine *et al.* (2002).

The case is different in G1, the largest cluster in M 31. In G1, Gebhardt *et al.* (2002) reported a mass of $2 \times 10^4\,\mathrm{M}_{\odot}$, which was subseqently challenged by Baumgardt *et al.* (2003), who argued against a central black hole. However, the latest observations by Gebhardt *et al.* (2005) continue to argue for a massive black hole using newer data. Whether GCs contain black holes has significant effects on both the evolution of the cluster and on how supermassive black holes grow. Thus it is very important to understand possible number densities for these black holes, and the current observational situation is not satisfying. Theoretically, there are reasons to expect massive black holes in clusters, although observations are required.

We now turn to very recent observations of $\omega$ Cen. This cluster is an ideal candidate to look for a central black hole. It has one of the largest velocity dispersions among GCs, implying it may have a large black hole mass. It is nearby both allowing for any black hole influence to be well resolved and allowing access to many stars used to trace the gravitational potential. With an integrated velocity dispersion of $18\,\mathrm{km\,s^{-1}}$, the expected black hole is $10^4\,\mathrm{M}_{\odot}$ which has a sphere of influence of $6''$ at the 4.8 kpc distance of the cluster. The issue with $\omega$ Cen is that it may not be a globular cluster, but has been suspected to be the nucleus of an accreted dwarf galaxy (Freeman 1993; Meza *et al.* 2005). Thus, while a massive black hole in $\omega$ Cen would not necessarily answer the question as to whether GCs contain black holes, it would help establish the existence and frequency of intermediate-mass black holes in general.

Kinematic data on the cluster come from two sources. Noyola *et al.* (2007) used Gemini/GMOS-IFU data to measure the integrated light in the central $3''$ and at $14''$ radius. Gebhardt & Kissler-Patig (2007) used individual velocities in the central $8''$ to measure the dispersion. Both observations are consistent, and, since one uses integrated light and the other individual velocities, argue for a robust central dispersion estimate. The central velocity dispersion for the cluster is $24 \pm 2\,\mathrm{km\,s^{-1}}$. The dispersion at $14''$ is $20\,\mathrm{km\,s^{-1}}$. Beyond $25''$, data have been compiled by van de Ven *et al.* (2006), coming primarily from radial velocities of Xie *et al.* (2007). Noyola *et al.* and Gebhardt & Kissler-Patig use orbit-based dynamical models and require a central black hole mass of $4(\pm 0.8) \times 10^4\,\mathrm{M}_{\odot}$.

The main arguments against having a black hole are allowing radial orbital anisotropy and having a significant population of heavy remnants. For the orbital anisotropy, there are two considerations. Van de Ven *et al.* (2006) model $\omega$ Cen using both radial velocities and proper motions, at radii beyond $25''$. They find a distribution function very close to isotropic. The amount of radial anisotropy required to increase the central dispersion is extreme (see Noyola *et al.*) and very inconsistent with the van de Ven *et al.* model. Furthermore, orbit-based models have been constructed which allow for any orbital distribution consistent with the Jeans equations. For these models, the no-black-hole model is radially biased in the central region, but not enough to make a significant improvement to the fit to the data. In other words, the black hole model is still a better fit even given

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the maximum radial bias that the radial velocities can tolerate. Presumably, including the proper motion will lead to an even poorer fit for the no-black-hole model

To have the increase be caused by heavy remnants, there are two main problems: having the required number of remnants in the first place, and having all remnants well within the observed core with a very steep density profile. The core radius of $\omega$ Cen is $50''$. The total mass inside $50''$ is $8 \times 10^4$ $M_\odot$. If the dispersion increase seen inside $10''$ is due to remnants, then for a cluster with a $r^{-2}$ profile all remnants would have to be inside $10''$; having $4 \times 10^4$ $M_\odot$ of material clustered inside $10''$ within a core of $50''$ would cause the cluster to evaporate on very short timescales (Maoz 1998). Furthermore, the total mass in heavy remnants (neutron stars and white dwarfs over 1 $M_\odot$) would require a very top heavy initial mass function, inconsistent with what is generally observed. The main problem with alternatives to a black hole is that the velocity dispersion rises inside the core of $\omega$ Cen.

The black hole model fits the $\omega$ Cen data the best and is consistent with an extrapolation of the black hole $M_{\rm bh}$ - $\sigma$ correlation. The same situation is true in G1. However, for M 15 and 47 Tuc, the black hole model is preferred but not statistically significant. A main observational point is that there is no black hole mass estimate for a GC that is below the expected value from the $M_{\rm bh}$ - $\sigma$ correlation.

## 13. *N*-body simulations of massive black hole formation

The first $N$-body simulations of the formation of IMBHs in young, dense clusters and their later interactions with passing stars have been performed recently. In some cases, it is found that a massive ($>1000$ $M_\odot$) object can form as a result of collisions between young stars and that, if turning into an IMBH, this star will capture passing stars through tidal energy dissipation. Gas accretion from circularized stars onto the IMBH may be sufficient to create ultra-luminous X-ray sources (ULXs) in the cluster. These simulations therefore strengthen the connection between ULXs and IMBHs.

ULXs are point-like X-ray sources with isotropic X-ray luminosities in excess of $L = 10^{40}$ erg s$^{-1}$. Since the Eddington luminosity of a star of mass $M$ is given by $L_{\rm Edd} = 1.3 \times 10^{38}$ erg s$^{-1}$($M/M_\odot$), where $M$ is the mass of the accreting object, most low-luminosity ULXs are probably stellar-mass black holes. However, there is mounting evidence that the brightest ULXs with luminosities exceeding $10^{40}$ erg s$^{-1}$ could be IMBHs.

The starburst galaxy M 82 for example hosts a ULX with brightness in the range $L = (0.5 - 1.6) \times 10^{41}$ erg s$^{-1}$ (Matsumoto *et al.* 2001; Kaaret *et al.* 2001), corresponding to a black hole with mass 350 - 1200 $M_\odot$ if emitting photons at the Eddington luminosity. The case for an IMBH in M 82 is supported by a 54 mHz quasi-periodic oscillation found in the X-ray flux (Strohmayer & Mushotzky 2003) and also by the soft X-ray spectrum of this source (Fiorito & Titarchuk 2004). Additional observational support for an IMBH comes from the observation of a 62-d period in the X-ray luminosity (Kaaret, Simet & Lang 2006; Patruno *et al.* 2006). The position of the ULX in M 82 coincides with that of the young star cluster MGG-11. Recent $N$-body simulations, summarized below, have showed how runaway merging of young stars could have led to the formation of an IMBH in MGG-11 and how this IMBH later could have captured passing stars to became a ULX.

The evolution of MGG-11 was simulated through $N$-body simulations of star clusters containing $N = 131{,}072$ (128K) stars using Aarseth's collisional $N$-body code NBODY4 on the GRAPE computers in Bonn and Tokyo (see Sec. 2). The initial set-up was given by King models with various central concentrations in the range $3 \leqslant W_0 \leqslant 12$ and half-mass radius $r_h = 1.3$ pc. The initial mass function of cluster stars was given by a Salpeter power-law between $1.0\,M_\odot \leqslant m \leqslant 100\,M_\odot$. These clusters have a projected half-mass radius,

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mass-to-light ratio and total cluster mass after 12 Myr (the age of MGG-11) that are consistent with the properties of MGG-11 as observed by McCrady *et al.* (2003). In the simulations, stars were merged if their separation became smaller than the sum of their radii. Orbital energy loss by tidal interactions between a star and the IMBH was implemented in the $N$-body simulations using the prescription of Portegies Zwart & Meinen (1993). More details on these simulations are presented in Portegies Zwart *et al.* (2004) and Baumgardt *et al.* (2006).

For low-concentration models ($W_0 < 8$), the core radii hardly change with time in the first few Myrs and expand at later times due to stellar evolution mass loss from massive stars. Few stellar collisions are observed in these models and no IMBH is formed. For clusters with higher concentration, the central relaxation time is short enough that massive stars spiral into the cluster core while still being in the hydrogen burning stage. Once in the cluster core, they can collide with each other due to the high central density and the large stellar radii of massive stars. Repeated collisions lead to the formation of a VMS with $m > 300\,\mathrm{M}_\odot$. Once such a VMS is produced, all further collisions are predominantly with this star and its mass grows up to $m = 500\,\mathrm{M}_\odot$ to a few $1000\,\mathrm{M}_\odot$ (see also Sec. 3). If this VMS collapses to an IMBH at the end of its lifetime, the presence of a ULX in MGG-11 could be explained by this IMBH. Furthermore, simulations of other young star clusters in M 82 show that runaway merging of stars can happen only in MGG-11 and in none of the other clusters, explaining why only MGG-11 hosts a ULX.

In another set of runs the further dynamical evolution of the IMBH in M 82 was studied. These simulations show that a cusp develops in the stellar density distribution around the IMBH. Inside this cusp, high-mass stars are enriched due to dynamical-friction-driven inspiral. Encounters of stars with the IMBH could lead to tidal capture of the star if its pericenter distance is only slightly larger than the tidal radius, $r_p/r_t \lesssim 3$. If the orbit is unperturbed by other stars, repeated pericenter passages will further decrease its orbital semimajor axis until it circularizes near the black hole. Angular momentum conservation requires this circularization to end at an orbital radius equal to twice the initial pericenter distance. Although perturbations by other stars can either scatter the inspiraling star away from the IMBH or onto an orbit with $r_p < r_t$ where it is destroyed, the simulations show that on average $\sim 3$ successful inspirals leading to circularization happen within the lifetime of MGG-11.

Once circularized, stars will sooner or later fill their Roche lobe due to stellar evolution and start to transfer mass onto the IMBH. The combined star-IMBH system will then become visible as a ULX. In total, in 10 out of the 12 performed runs a ULX source was produced at least once between 3 and 12 Myrs. Furthermore, 4 runs created an X-ray source brighter than $2 \times 10^{39}$ erg/s within the age range of MGG-11. Hence, the performed $N$-body simulations provide a good explanation for the ULX source seen in MGG-11 (cf. Blecha *et al.* 2006).

A further test of this scenario might come from the stellar and orbital evolution of the IMBH binaries. Since the runs show that mostly massive stars are captured and circularize near the IMBH, stellar-mass black holes or NSs will be formed out of the donor stars after they have undergone a supernova. The further evolution of the IMBH binaries will then be driven by encounters with cusp stars, which harden the binaries. In the later stages, emission of gravitational waves will also be important and will lead to the merger of the stars with the IMBH. Hopman & Portegies Zwart (2005) have shown that the event rate for this is likely to be high enough to be detectable by *LISA*, in particular if the IMBH mass is larger than $\sim 3 \times 10^3\,\mathrm{M}_\odot$. Observations of gravitational waves from such binaries would therefore give further support to the scenario discussed here.

https://doi.org/10.1017/S1743921307010265 Published online by Cambridge University Press

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## Acknowledgements

G.F. acknowledges support from NASA contract NAS8-39075 (CXC) and *Chandra* GO grant G06-7079A. J.M.F. acknowledges support from NASA Grant NNG06GI62G and a *Chandra* Theory grant. C.O.H. acknowledges support from the Lindheimer Fellowship at Northwestern University and thanks his many collaborators, especially J. Grindlay, P. Edmonds, and G. Rybicki. S.R. thanks the whole GBT cluster pulsar search and timing team, especially I. Stairs, J. Hessels, P. Freire, and S. Begin. F.A.R. thanks Ingrid Stairs for help with the organization of IAU JD06, particularly in Prague.

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