Abstract.

X-ray imaging and spectroscopy can be used to probe the binary content of globular clusters. Binaries are thought to play a key role in the dynamical evolution of the clusters by serving as an internal source of energy which counters the tendency of their cores to collapse. Various kinds of binaries are found in clusters in X-rays, including BY Dra or RS CVn systems, Cataclysmic Variables and low mass X-ray binaries as well as millisecond pulsars. In this review, we will present the most recent X-ray observations of globular clusters as performed with XMM-Newton and Chandra. We will illustrate the power of X-ray observations to separate the different X-ray source populations, and emphasize how the results are important in understanding the binary formation processes.

1. Introduction

It is thought that through dynamical evolution, globular cluster cores become increasingly more concentrated (Hénon 1961) and eventually collapse. This core collapse should occur within $\sim 10^8 - 10^{10}$ years unless additional energy is injected into the central regions of the cluster. This would indicate that many Galactic globular clusters should have already undergone core collapse. However, we observe that many have not yet done so, see e.g. Harris (1996).

Both primordial binary systems and those formed due to encounters should exist in globular clusters due to the dense environments. Binaries can subsequently encounter cluster stars and in doing so, if the binding energy of the binary is larger than the kinetic energy of the cluster star, harden (become tighter) (Heggie 1975). The third body leaves the encounter with more energy than before the interaction (see e.g. Hut et al. 1992; Elson et al. 1987, for reviews). It is therefore clear from this, that a population of binaries could be important in helping to delay globular cluster core collapse. Binaries and their descendants are thus valuable objects with which to complete the study of stellar and globular cluster evolution, stellar dynamics, binary formation and evolution, as well as the study of compact objects and the binaries themselves, see e.g. Verbunt & Lewin (2004), Hut et al. (1992) for extensive reviews of these topics.

X-ray sources were first detected in Galactic globular clusters in the early 1970’s using the Uhuru and OSO-7 observatories (Giacconi et al. 1972, 1974; Clark et al. 1975). Following the launch of the EINSTEIN observatory in 1978,
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Hertz & Grindlay (1983a) surveyed 71 Galactic globular clusters and showed that there were in fact two distinct populations of globular cluster X-ray sources. The bright sources, with $L_X > 10^{36}$ erg s$^{-1}$, were proposed to be accreting neutron star systems. The nature of the faint sources, with $L_X \lesssim 10^{34.5}$ erg s$^{-1}$, was unclear but it was thought that they could also be binary systems containing a compact object, but in this case a white dwarf. Verbunt et al. (1984) then suggested that the brighter of the faint sources, which they stated were too bright to be cataclysmic variables (CVs), by comparing their luminosities with Galactic plane CVs, could be quiescent soft X-ray transients. Margon & Bolte (1987) also supported a hypothesis made by Hertz & Grindlay (1983b), that some of the faint X-ray sources could be foreground and background superpositions of unrelated sources. The discovery of radio millisecond pulsars (MSPs), which are believed to be descendants of neutron star X-ray binaries, in globular clusters (Lyne et al. 1987) was followed by the identification of the X-ray counterparts (e.g. Danner et al. 1997), indicating that some of the faint X-ray sources could be MSPs. Bailyn, Grindlay, & Garcia (1990) also suggested that some of the faint sources could be active binaries, such as RS CVn binaries.

Observations with the Rosat observatory (e.g. Johnston & Verbunt 1994; Johnston et al. 1996b; Verbunt 2001) dramatically increased the number of known faint X-ray sources, although the number of identifications of these sources remained limited. The new generation of X-ray telescopes e.g. XMM-Newton and Chandra, whose sensitivity and angular resolution (respectively) far surpasses that of previous X-ray observatories, has not only allowed us to detect but also identify a large number of the faint X-ray source population.

Stellar encounters in globular clusters result in an equipartition of energy. Through virialization, the more massive stars, such as degenerate objects and binary systems, are concentrated towards the centre of the cluster. The angular resolution of the Chandra instruments can be as good as 0.4" (Charta et al. 2000), which makes it the ideal instrument to peer into the centres of globular clusters that are either nearing or have undergone core collapse. The large majority of X-ray sources can thus be resolved and unprecedented positional precision can obtained, essential for multi-wavelength follow-up observations, which are in turn crucial in determining the nature of the X-ray sources. The XMM-Newton observatory, thanks to its 58 grazing-incidence mirrors in each of its three telescopes, is an extremely sensitive instrument (Jansen et al. 2001), ideal for observing faint X-ray sources. Its angular resolution of 6" (Full Width Half-Maximum of its Point Spread Function), limits its usefulness to less concentrated globular clusters. However, the large collecting area means that for even faint sources ($\sim 1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) in less concentrated clusters, a useful X-ray spectrum can be obtained in a short observation i.e. 15 kiloseconds and thus the nature of certain sources derived from X-ray spectroscopy alone.

In this review we concentrate on XMM-Newton’s contribution in the last five years, to understanding faint X-ray sources (and thus binary systems) in Galactic globular clusters (see Table 1 for clusters observed). For articles oriented towards Chandra’s contribution to this subject, we recommend, amongst others, Verbunt & Lewin (2004); Heinke et al. (2003); Pooley et al. (2003, 2002a); Grindlay et al. (2001a). For discourses on black hole(s) (binaries) and neutron star retention in globular clusters, which are not discussed here,
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see Kalogera et al. (2004); Ivanova et al. (2004); Podsiadlowski et al. (2004); Pfahl et al. (2002).

| Name   | alias | core radius | half-mass radius | Sources in core (Expected) | Sources in half-mass (Expected) |
|--------|-------|-------------|------------------|----------------------------|-------------------------------|
| NGC 3201 |       | 87          | 161              | 2 (0.7±0.1)                | 4 (1.8±0.4)                   |
| NGC 5139 | ω Cen | 155         | 258              | 11 (4)                     | 27 (9)                        |
| NGC 6205 | M 13  | 55          | 98               | 2 (0)                      | 5 (1)                         |
| NGC 6366 |       | 110         | 154              | 1 (1)                      | 3 (2)                         |
| NGC 6656 | M 22  | 85          | 198              | 3 (1.0±0.1)                | 6 (3.3±0.8)                   |
| NGC 6809 | M 55  | 170         | 173              | 4 (3.5±1)                  | 5 (3.5±1)                     |

Table 1. Globular clusters observed by XMM-Newton. Physical characteristics (core and half mass-radii in arcseconds) and the number of sources detected, along with the expected number of sources if no cluster was present (i.e. fore- and background sources) for the core and half-mass radii.

2. Binary formation

Globular clusters are extremely dense environments, with as many as $10^5$ stars pc$^{-3}$ (Davies 2002), thus stellar encounters, which are extremely rare in lower density regions, can occur in globular clusters on time-scales comparable with or less than the age of the Universe. This would indicate that many Galactic globular cluster stars have undergone at least one encounter in its lifetime. Encounters between stars is one way in which binaries can be produced. The encounter rate ($\Gamma$) due to tidal capture (Fabian et al. 1975) is proportional to the encounter cross-section ($A$), the relative velocity of the stars ($v$) and the number density of stars in the cluster (core). For encounters between a compact object and an ordinary cluster star, we require $n_c$ compact objects and $n_s$ cluster stars per unit volume, see Hut & Verbunt (1983); Verbunt (2003) and Eq. 1.

$$\Gamma \propto \int n_c n_s A v dV \propto \int \frac{n_c n_s R}{v} dV \propto \frac{\rho^2 r_c^3}{v} R$$

where $\rho$ is the central mass density and $r_c$ the core radius.

An encounter between a binary and either a single star or a binary system would more readily occur as the cross sections are significantly larger, thus increasing the likelihood of an encounter. Wide (soft) binaries would be broken up in such an interaction, but tight (hard) binaries interacting with single stars could result in triple systems, a merged binary, a common envelope system or more likely a fly-by or an exchange binary. Such encounters were thought to explain the over-abundance of binaries, in particular neutron star binaries in globular clusters, compared to the number in the field (Clark 1973).

A great deal of work has been done on binary formation in globular clusters and we refer the reader to several papers and reviews not already referenced in this section for further details e.g. Davies (1997); Di Stefano & Rappaport (1994); Verbunt & Meylan (1988); Hills (1973). However, for the formation of most types of binary, it is only in recent years, with the launch of the new generation of X-ray observatories, that we are beginning to be able to observationally...
test the theory (and simulations) that have been developing over the last 30 years. These observations are discussed in Sections 3.1 and 4.1.

3. Neutron star low mass X-ray binaries

Bright X-ray sources in globular clusters were shown to be neutron star low mass X-ray binaries (NSLMXBs) following X-ray observations with the early X-ray satellites and studying their X-ray bursts (Canizares & Neighbours 1975; Hertz & Grindlay 1983). Verbunt & Hut (1987) showed that there was a correlation between the number of NSLMXBs and the globular cluster encounter rate. This indicated that most NSLMXBs were formed through encounters.

Amongst the ever growing population of faint X-ray sources in globular clusters, a subset were found to have very soft X-ray spectra that are well fitted by a neutron star hydrogen atmosphere model (e.g. Pavlov et al. 1992; Zavlin et al. 1996). The model fits indicate radii that are consistent with those expected from either a neutron star (approximately 10 km e.g. Lattimer & Prakash 2001) or a polar cap being heated by material accreted from a companion star and channelled towards the pole via a magnetic field (Heinke et al. 2003). These sources have X-ray luminosities between $\sim 10^{32}$ and a few $10^{33}$ erg s$^{-1}$, which are consistent with X-ray luminosities of quiescent NSLMXBs (qNSLMXBs) in the disc (Narayan et al. 2002). This supports the idea that these sources are also qNSLMXBs. Indeed Haggard et al. (2004) recently found the probable optical counterpart to the X-ray source of the proposed qNSLMXB in $\omega$ Centauri. The optical source, found with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope is a blue source with $H\alpha$ emission, implying that there is some accretion resulting in an accretion disc, although the faintness of the disc suggests a very low rate of accretion. They constrain the mass of the counterpart to be $M<0.14M_\odot$, if it is a main-sequence star. All of these points are consistent with the idea that this is the optical counterpart to a qNSLMXBs.

So far 28 X-ray sources with spectra indicative of qNSLMXBs have been found using either XMM-Newton or Chandra, see Heinke et al. (2003) for a list of the best fitting parameters to the X-ray spectra, luminosities etc. The X-ray spectra for the proposed qNSLMXBs detected with XMM-Newton in $\omega$ Centauri (Gendre, Barret, & Webb 2003a) and M 13 (Rosat data also included in plot, Gendre, Barret, & Webb 2003b) can be seen in Figure 1.

3.1. Neutron star X-ray binary formation in globular clusters

As the faintest detection limit of all the XMM-Newton and Chandra observations of globular clusters ($\sim 10^{29}$-$10^{31}$ erg s$^{-1}$) is considerably fainter than the minimum luminosities of qNSLMXBs ($\sim 10^{32}$ erg s$^{-1}$), we can consider that the populations of qNSLMXBs detected in each globular cluster are (almost) complete (although source confusion could mar the completeness Heinke et al. 2003, or some qNSLMXBs may show hard X-ray spectra and not be accounted for in this analysis, see Section 3.3).

Plotting the number of qNSLMXBs found with soft spectra against the globular cluster collision rate, Gendre et al. (2003b) found that a correlation existed for the 10 globular clusters (containing 10-11 qNSLMXBs) that had been observed by either XMM-Newton or Chandra by 2003, see Fig. 2 left hand
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3.2. The population of globular cluster neutron star X-ray binaries

Using results presented above, Pooley et al. (2003) estimate that there are approximately 100 LMXBs residing in Galactic globular clusters. Of these 100 LMXBs, there are 13 persistently or transiently bright LMXBs, many of which have been known for almost 20 years. With the increase in the number of detected qNSLMXBs over the last 5 years, thanks to XMM-Newton and Chandra, we have already recovered about 40% of the population. The entire population will be very useful for testing models of cluster evolution and LMXB formation.

3.3. The neutron star equation of state

This population is also useful for other observational tests. As stated above, qNSLMXBs have spectra that are, in general, well fitted by neutron star hy-
hydrogen atmosphere models. These models have only 5 parameters. Two of the parameters are fairly well constrained, as the binary is located in a globular cluster: the distance (known to a few percent thanks to Hipparcos) and the interstellar absorption. The three remaining parameters are the mass of the neutron star and its temperature and radius. Assuming a canonical mass for the neutron star, we can constrain the other two parameters. For the two qNSLMXBs detected by XMM-Newton we find $T_{\infty}^{\text{ref}} = 67 \pm 2$ eV and $R_{\infty} = 13.6 \pm 0.3$ km. The unabsorbed luminosity is $L = 3.2 \pm 0.2 \times 10^{32}$ erg s$^{-1}$ (0.1-5.0 keV), for the source in $\omega$ Cen. We find $T_{\infty} = 76 \pm 3$ eV and $R_{\infty} = 12.8 \pm 0.4$ km and an X-ray luminosity of $7.3 \pm 0.6 \times 10^{32}$ erg s$^{-1}$ (0.1-5.0 keV) for the source in M 13, assuming a mass of $1.4M_\odot$ in both cases. If the X-ray emission observed is indeed due uniquely to the neutron star cooling, then the measurements for the temperature and radius using XMM-Newton are very accurate.

By detecting the optical counterpart, which is now starting to be possible thanks to the small errors in the positions of the X-ray sources (in particular the Chandra sources) and good angular resolution obtained with optical telescopes such as the Hubble Space Telescope (HST) and the Very Large Telescope (VLT) we can eventually derive the mass function of the binary, using optical spectroscopy and Kepler’s laws. Using optical spectroscopy to determine the spectral type and thus the mass of the companion, we can deduce the mass of the compact object and thus ultimately constrain both the mass and radius of the neutron star. If the mass and radius can be determined for a substantial part of the proposed population of NSLMXBs in Galactic globular clusters, this will place very strict constraints on the neutron star equation of state, which is important to our understanding of the physics of matter at ultra-high densities as well as the astronomical implications, understanding: the core collapse of massive stars, the supernova phenomenon and the existence and properties of neutron stars \cite{vanKerkwijk2004, Lattimer2001}. 

Figure 2. Left: The number of qNSLMXBs versus collision rate ($\rho^{1.5}_0 r_c^2$), shown with a linear fit, $n_{\text{qNSLMXB}} \sim 0.04 \times \rho^{1.5}_0 r_c^2 + 0.2$. The collision rates have been normalized to 100 for NGC 6440 \cite{Gendre2003}. Right: The number of qNSLMXBs versus collision rate for all 18 globular clusters that have been observed with XMM-Newton or Chandra by mid 2004.
3.4. Understanding the nature of neutron star X-ray binaries

The well constrained temperatures obtained using these models can be used to estimate the cooling time. The exact cooling time depends on the thermal conductivity of the crust, the core cooling processes and the accretion history of the source (Wijnands et al. 2004a), but by assuming the mass transfer rate during outburst, the time between outbursts can be determined (e.g. Rutledge et al. 2002). Observing a system going into outburst, then fading into quiescence could help give us a handle on accretion processes.

Several NSLMXBs, including two field qNSLMXBs: Cen X-4 (Asai et al. 1996) and Aql X-1 (Campana et al. 1998a) show hard spectral components that dominate the spectrum above 2 keV. The nature of this hard power-law tail is not yet understood. It has been explained by accretion onto the neutron star surface, accretion down to the magnetospheric radius or non-thermal processes powered by the rotational energy loss of a rapidly spinning neutron star (Campana et al. 1998a, and references therein). Using the XMM-Newton qNSLMXBs spectra above 2-3 keV, we have been able to place a limit on the contribution from a hard power law tail. For the ω Cen source, assuming a power law with photon index of 2, an upper limit of 10% of the total flux (90% confidence limit) was derived (Gendre et al. 2003a). For the source in M 13, Gendre et al. (2003b) found no evidence for a hard power-law contribution. Heinke et al. (2003) list 21 probable globular cluster qNSLMXBs and find that only one (NGC 6440 CX1) requires a power law component in fitting the X-ray spectrum and is the only qNSLMXBs in their sample to have experienced a recorded outburst. They suggest that the strength of the power-law component may be a measure of continuing low-level accretion. Indeed the qNSLMXB in Terzan 5 (EXO 1745-248), which shows a hard power law spectrum with little evidence for a soft component (Wijnands et al. 2004b) had previously been in a high state, indicative of recent accretion. Further observations of these Galactic globular cluster qNSLMXBs should help in resolving the nature and origin of the hard power law tail.

4. Cataclysmic variables

A large number of cataclysmic variables are now being discovered in Galactic globular clusters. Of the 57 faint X-ray sources known in Galactic globular clusters following the Rosat period (Verbunt 2001), only a few had been identified as CVs (e.g. Grindlay et al. 1995; Cool et al. 1998; Carson et al. 2000). With the hundreds of new X-ray sources being detected in Galactic globular clusters with the new generation of X-ray observatories, many new CVs are being detected and identified. Part of this is due to the excellent sensitivity of XMM-Newton, as we can now obtain X-ray spectra and lightcurves of these faint sources which show CV characteristics, i.e. spectra well fitted by high temperature bremsstrahlung models and lightcurves showing variability on different timescales (seconds to days) (Richman 1996; Eracleous et al. 1991; Osborne 1987).

Two of the core sources in ω Centauri, first detected by Cool et al. (1995) were proposed to be CVs from the characteristics of their optical counterparts, observed with the HST Wide Field Planetary Camera 2. The counterparts were found to have with strong Hα emission and a blue excess. The
fits to the X-ray spectra observed with XMM-Newton support the CV hypothesis (Gendre et al. 2003a). The spectra can be seen in Fig. 3 and the fits are bremsstrahlung models with $K_T = 23.0^{+39.0}_{-10.1}$ keV, $\chi^2 = 0.72$ (31 degrees of freedom (dof)), $L_{0.5-10.0\,\text{keV}} = 6.7(\pm 0.3) \times 10^{32}$ erg s$^{-1}$ and $K_T = 18.7^{+65.2}_{-10.0}$ keV, $\chi^2 = 0.78$ (17 dof), $L_{0.5-10.0\,\text{keV}} = 2.7(\pm 0.2) \times 10^{32}$ erg s$^{-1}$. Analysing the X-ray colours, there is evidence for a small population of CVs in this cluster.

Spectral fitting of a source found in the core of the globular cluster M 22 using XMM-Newton data, coupled with optical colours, indicates that this source is a CV ($K_T = 19.98^{+13.35}_{-10.0}\,\text{keV}$, $\chi^2 = 1.57$ (25 dof) and $L_{0.2-10.0\,\text{keV}} = 6.0 \times 10^{31}$ erg s$^{-1}$ (Webb et al. 2004a). The source is also found to be variable on time scales of hours. The two possible optical counterparts have U-band magnitudes of 18.9 and 19.1 and U-V values of 0.4 and 0.3 respectively. If either of these is the counterpart, the $L_x/L_{opt}$ value of $\sim 0.6$ indicates a CV nature (e.g. Schwpe et al. 2002; Verbunt et al. 1997). There are a further 6-7 sources in this cluster that also have X-ray and optical colours consistent with a CV nature. Follow-up spectroscopy of these sources taken with the VLT UT3 (VIMOS) is currently being analysed and will help clarify the uncertain nature of these sources.

X-ray spectral and temporal observations with XMM-Newton of the globular clusters M 55 and NGC 3201, reveal one and three sources that appear to be CVs. X-ray and optical colours of a second source in M 55 support the idea that there is a second CV in this cluster (Webb et al. 2004b).

Many CVs have been detected using follow-up optical observations of globular clusters observed with Chandra. X-ray sources detected with this satellite have positional errors of the order of 1". With HST photometry of these sources, the optical counterparts can be located. Clusters which have revealed substantial populations of CVs using this method are: NGC 6397 in which 6-7 sources have been optically identified as CVs (Grindlay et al. 2001b), six CVs have been optically identified in NGC 6752 (Pooley et al. 2002b), and 12-15 CVs have been identified in 47 Tuc (Grindlay et al. 2001a; Edmonds et al. 2003a,b).
Bassa et al. (2004) also detect 2-3 CVs in the globular cluster M 4 in a similar manner.

4.1. The formation of cataclysmic variables in globular clusters

The formation mechanisms of CVs in globular clusters is currently unclear. In the field, collisions are rare and therefore CVs evolve chiefly from their primordial binaries, where the more massive of the two stars evolves more quickly. It can then fill its Roche lobe and unstable mass transfer can occur which can lead to a common envelope system in which the stellar remnant and its companion lose their angular momentum and can form a contact binary (Paczynski 1976). However, in a globular cluster, such a primordial binary may have a very wide separation and during an interaction with another cluster star and/or binary, the binary can be broken up, especially if it is located in a dense region, such as the core of the cluster. Alternatively the initial binary may be harder, but eventually harden to such an extent, through successive encounters, that the ultimate fate of the system may be changed. Instead the binary could undergo an exchange encounter (Davies 1997). Alternatively, a single white dwarf remaining after a star dying in a planetary nebula can encounter a cluster star. This encounter can raise tides on the cluster star and transfer energy and angular momentum into the envelope. If sufficient energy is transferred, the two objects can either merge or form a binary system, a potential CV (Fabian et al. 1975).

Mass segregation concentrates binaries to the centre of cluster, although the less massive binaries will not necessarily be located in the core of the cluster (Davies 1997). Indeed the distribution of the binaries depends essentially on the central density of the cluster. A higher core density will yield a larger number of encounters, increasing the number of CVs formed through encounters and at the same time decreasing the primordial CV population. Primordial CVs should therefore be found preferentially outside the core and encounter CVs within it.

Unlike the qNSLMXBs that have limiting luminosities of $\sim 10^{32}$ ergs s$^{-1}$, CVs can have luminosities of $\sim 10^{29}$ ergs s$^{-1}$ (0.5-2.5 keV) or even fainter (Verbunt et al. 1997). Therefore, unlike the population of qNSLMXBs where we have (almost) a complete population for each globular cluster that has been observed, we do not have a complete population for the CVs. Indeed Di Stefano & Rappaport (1994) find from cluster simulations of 47 Tuc and $\omega$ Centauri, that there should be more than a hundred CVs in each of these two clusters alone. Without X-ray spectra and in many cases follow-up optical photometry and spectroscopy, we can not differentiate the CVs from other faint X-ray sources in the globular clusters, such as active binaries. Heinke et al. (2003) noted that the majority of fairly hard sources with luminosities greater than $10^{31}$ ergs s$^{-1}$, found in the centres of globular clusters by Chandra have been revealed through optical photometry and spectroscopy to be CVs. They then undertook a similar analysis on this hard population (after removing sources that were already known not to be CVs) as to that undertaken for the qNSLMXBs. They found that for this population, the results were not in agreement with the theoretically predicted formation rate from close encounters and that there was a weaker dependence on the central density than in the formation of qNSLMXBs. They propose that high-density environments preferentially destroy CVs. However, they note exceptions to this assertion. NGC 6397, the densest globular cluster studied in
this analysis, has an apparent excess of X-ray sources (Pooley et al. 2003), which suggests the opposite conclusion. However, Heinke et al. (2003) state that NGC 6397 may be an unusual cluster, being possibly disrupted. They also state that the formation of some CVs in globular clusters from primordial, undisturbed binaries may partially explain the weaker dependence on density. However, there are many different ways that a globular cluster can be disturbed, which can change the formation/evolution of the cluster members (see e.g. Webb et al. 2004b; Gnedin & Ostriker 1997).

4.2. Where are the cataclysmic variable outbursts?

One of the most striking differences between globular cluster CVs and field CVs is the lack of outbursts observed in globular cluster CVs. Many types of field CVs (U Gem, SU UMa, Z Cam etc) show outbursts every few weeks to months. However, the evidence for globular cluster CV outbursts is poor. Two eruptions of the CV V2 in the globular cluster 47 Tuc have been reported (Paresce & de Marchi 1994; Shara et al. 1996). Through imaging of the globular cluster M 5, Shara et al. (1987) observed what they proposed was an outburst and decline to quiescence of a CV identified as V101 (Margon et al. 1981). Naylor et al. (1989) confirmed the CV posit through optical observations in outburst and quiescence. Further, searches for evidence of the existence of CVs in globular clusters have often had little success. Ciardullo et al. (1990) searched for nova outbursts, as indicators for the presence of CVs in 54 of M 31’s globular clusters. Over an effective survey time of about 2.0 years, no cluster exhibited evidence for a nova explosion. Moreover, indications for CV outbursts have often been repudiated.

It is unclear why there should be so few CV outbursts observed, as there is no reason to suggest that CV activity should be suppressed in globular clusters. Shara et al. (1996) suggests that tidal capture may lead to runaway mass transfer in almost all cases, which would explain the lack of CVs observed. Alternatively low accretion rates may result and the time between outburst could be long. Following the detection of two CVs in an open cluster, where one was in outburst, Kaluzny et al. (1997) noted that it would be difficult to identify a CV undergoing a similar type of outburst in a globular cluster using the two methods most often applied to look for CVs in globular cluster centres (searching for photometric variability or selecting objects with strong Balmer emission). This may explain why few CVs in outburst have been detected using optical observations.

It has been suggested that the CVs detected by X-ray observatories in globular clusters may be primarily magnetic CVs c.f. the 5 magnetic CVs discussed in Grindlay (1999) that were detected initially by Rosat. Magnetic CVs have high L_x/L_{opt} values, do not show outbursts because their accretion discs are disrupted by the magnetic fields and show X-ray spectra which are particularly hard due to magnetically channeled accretion, which makes them more easily detected in X-rays (Patterson 1994). Indeed, the CVs observed by XMM-Newton for which we have X-ray spectra all have best fits that are consistent with very high temperature bremsstrahlung models, expected of magnetic CVs. This could explain why the CVs detected in X-rays have not been seen to outburst.
5. Millisecond pulsars

It is thought that millisecond pulsars (MSPs) are the descendants of NSLMXBs. During the accretion phase, it is believed that there is a transfer of angular momentum onto the neutron star, spinning it up to high velocities. Particles close to the surface of the neutron star are accelerated out along the open field lines, so we observe a beam of radiation as the neutron star rotates, most readily observable in the radio domain, but also observable at other wavelengths such as in X-rays \cite{Pringle&Rees:1972}. Many millisecond pulsars found in globular clusters prior to 1999 when the observatories XMM-Newton and Chandra were launched, were detected by radio telescopes \cite[c.f.][]{Camiloetal:2000, DAmicoetal:2001}. However, both X-ray observatories and notably Chandra have been efficient in detecting a large population of globular cluster MSPs.

Millisecond pulsars can also have soft X-ray spectra like the qNSLMXBs. These spectra are well fitted by low temperature blackbodies or hydrogen atmosphere models, where the temperature and radius of the emission are those of the heated polar cap ($10^6$-$10^7$ K and $\sim$1 km e.g. Zhang & Cheng \citeyear{Zhang&Cheng:2003}; Zavlin & Pavlov \citeyear{Zavlin&Pavlov:1998}, and references therein). MSPs can also have spectra that are well fitted by hard power laws, where the emission is due to particles accelerated in the magnetosphere or spectra composed of the two different types of emission \cite[c.f.][]{Webbetal:2004c,d}. These objects have lower luminosities than qNSLMXBs, unless there is accretion still taking place in the system.

MSP populations in globular clusters have been shown to be extremely diverse. Grindlay et al. \citeyear{Grindlayetal:2002} state that the implied population of MSPs in 47 Tuc, using Chandra observations, is between 35 and 90. However they note that NGC 6397 is relatively deficient in MSPs, with only one MSP detected using radio and/or X-ray observations. They also discuss the fact that this MSP lies at a radius of 11 core radii from the centre, which indicates that it may have been ejected from the core, perhaps in a second exchange encounter. Many of the MSPs observed with Chandra have been detected with only a few counts, not enough to extract a spectrum. An X-ray colour analysis has indicated that the (majority of the) sources have very soft X-ray spectra, exploited to identify their MSP nature. Again, an advantage of the XMM-Newton data is that we can obtain spectra of the MSPs, which can help to distinguish MSPs showing hard spectral emission from other sources showing hard spectra e.g. CVs (two MSPs in the globular cluster M 55 \cite{Webbetal:2004b}).

Grindlay et al. \citeyear{Grindlayetal:2002} showed that one of the key results in their study was that MSPs in the globular clusters 47 Tuc and NGC 6397 may have a less efficient conversion of rotational spin-down energy into soft X-rays than most field MSPs \cite[see][]{Becker&Trumper:1997}. Why this should be is unclear. Grindlay et al. \citeyear{Grindlayetal:2002} suggest that these pulsars may have an altered surface magnetic field (and thus an altered light cone radius) or possibly larger masses (or compactness). They propose that MSPs in dense cluster cores, unlike those in the field, have the possibility to be driven back into contact and thus into an accretion phase, as a recycled NSLMXB. Renewed accretion could continue to bury the magnetic field, a process thought to be responsible for field decay observed from neutron stars at birth to the values typical of MSPs \cite{Romani:1990}. This could lead, in turn, to an altered magnetic field configuration, particularly for a secondary re-exchanged into an MSP (with random spin-orbital
encounter angular momentum). This method would also systematically increase the neutron star mass beyond that for field MSPs. There is, however, some opposition to the field burial hypothesis e.g. Ruderman (1991) who proposes that during spin up, the surface magnetic field evolution mirrors the changes in the core magnetic field configuration. The surface magnetic field can migrate to the pole of the hemisphere it started in, which can account for both the change in the magnetic field configuration and its strength. Further, Cheng & Taam (2003) suggest that a small-scale, strong, surface magnetic field may play a role in determining the X-ray emission properties of MSPs, where the existence of such a magnetic field may depend on the formation history, possibly providing an explanation for the differences between the MSPs in the field and in globular clusters. It is unclear which hypothesis is correct, but the study of globular cluster MSPs should help resolve the physical nature of their magnetic fields.

Another pertinent question pertains to the populations of MSPs in globular clusters. If MSPs are born from NSLMXBs, whose numbers appear to be correlated with the encounter rate of the cluster, where are all the MSPs in clusters with high encounter rates, such as NGC 6440 (Pooley et al. 2002a) which has shown evidence for very few MSPs? Grindlay et al. (2002) propose that some of the main-sequence or BY Dra binaries may harbour MSPs, such as in the case of the MSP 6397A in NGC 6397. Alternatively, this could be related to the problem of the retention of neutron stars in globular clusters, see e.g. Pfahl et al. (2002) or simply that the observations are insufficient to detect all the MSPs.

6. Outlook for the future

Both XMM-Newton and Chandra are expected to remain in service for several years to come. As outlined here, they have already revolutionised our understanding of faint X-ray sources in globular clusters. Not only have we confirmed the nature of these sources, we have identified populations of binaries and their descendants, that have already and will continue to assist us in understanding their formation and evolution. Future observations with these observatories, coupled with multi-wavelength follow-up observations, should not only increase the population sizes, but also enhance our understanding of these populations.

As outlined in Section 3, we expect to eventually place strict constraints on the neutron star equation of state through studying the NSLMXBs in globular clusters, as well as understand accretion processes in the quiescent systems. We also expect to be able to understand the nature and origin of the hard power law component observed in the X-ray spectra of some of the qNSLMXBs. Studying the optical counterparts to these systems, which are now beginning to be discovered, will also enhance our understanding of their origin.

Further observations should eventually provide observational support for the formation mechanisms of CVs in globular clusters, as well as understand the possible differences between globular cluster and field CVs.

With regards to MSPs, further observations should resolve the diversity puzzles: Why do globular cluster MSPs have soft X-ray spectra indicative of heated polar caps, but many field MSPs show hard X-ray spectra, indicative of particles accelerated in the magnetosphere? Why do globular cluster MSPs have...
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a less efficient conversion of spin-down energy into X-rays than most field MSPs? And what can explain the varying globular cluster populations of MSPs?

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