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OBSERVATIONS OF THE FAINT X-RAY SOURCES IN GALACTIC GLOBULAR CLUSTERS USING XMM-NEWTON

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Abstract.
Globular clusters are thought to harbour a large number of compact binaries that could be responsible for delaying the inevitable core collapse of these dense clusters. Compact binaries and their progeny were previously elusive in the optical domain because of the high stellar densities. Observing these clusters in X-rays, where in such a domain the compact binaries are bright, diminishes the over-crowding problem. We present observations of seven Galactic globular clusters that we have made with XMM-Newton, along with follow-up optical photometry and spectroscopy made with the Very Large Telescope (VLT). We will discuss the populations of neutron star low mass X-ray binaries and their descendants (millisecond pulsars), cataclysmic variables, active binaries, as well as other objects that we have identified in these clusters. We also explore the formation mechanisms of these systems and their use in tracing the dynamical history of these clusters

1 Introduction

Globular clusters (GCs) are very dense groups of old stars which are unstable on thermal timescales, of the order 10^8-10^{10} years in the central regions and even less at the centre of the cluster (e.g. Hut al., 1992). As the ages of Galactic globular clusters are $\sim 10^{10}$ years (De Angeli et al. 2005), one would expect that the density of stars in the cores of the majority of these self gravitating systems would have become increasingly dense and have undergone collapse. This is not the case, in fact only 20% (Harris 1997) are collapsed, which implies the presence of an internal energy source to counter the collapse process.

It is believed that close binaries in globular clusters could provide the internal energy necessary to delay core collapse when they liberate binding energy during the interaction with another cluster star (see Hut et al 1992 for a review). It was predicted that globular clusters should contain a large number of binaries due to their dense nature (e.g. Di Stefano & Rappaport 1994). Binaries are extremely difficult to locate because of over-crowding in the optical domain. The close binaries that we are interested in have the advantage that they are also visible at high energies, where the majority of the globular cluster stars are invisible. We have observed eight Galactic globular clusters with the X-ray satellite *XMM-Newton* with an aim to locating these binaries (e.g. Webb, Wheatley & Barret 2006; Webb et al. 2004, Gendre, Barret & Webb 2003a,b; Webb et al. 2002). We have identified a variety of objects, including many binary systems and their progeny, i.e.: X-ray binaries (e.g. Gendre, Barret & Webb 2003b); cataclysmic variables (Webb et al. 2004); millisecond pulsars (Webb, Wheatley & Barret 2006); active binaries (Gendre, Barret & Webb 2003a); as well as fore- and background objects, e.g. stars (e.g. Gendre, Barret & Webb 2003a) or clusters of galaxies (e.g. Webb et al. 2004).

2 Discussion

2.1 Binary populations in globular clusters

Observations of Galactic globular cluster faint X-ray sources made with the two X-ray satellites *XMM-Newton* (Webb, Wheatley & Barret 2006; Webb et al. 2004; Gendre, Barret & Webb 2003a,b; Webb et al. 2002) and

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Chandra (e.g. Heinke et al. 2006; Pooley et al. 2003 etc) have revealed that 25 are neutron star X-ray binaries. *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. 2006), and taking advantage of the well constrained globular cluster distances and interstellar absorptions (Servillat et al. in prep and Gendre, Barret & Webb 2003a,b). The masses and radii are essential for determining the unknown equation of state of matter in these very compact stars.

We have also used the globular cluster observations of faint X-ray sources, coupled with the result that the bright X-ray sources ($L_x > 10^{36}$ erg s^{-1}, Hertz & Grindlay 1983) are also neutron star X-ray binaries to confirm, through observations, the theory that these objects are formed mainly through encounters. This implies a total population of approximately 100 neutron star X-ray binaries distributed throughout the 151 Galactic globular clusters (Pooley et al. 2003). This population is wholly insufficient to slow down the inevitable core collapse of these self gravitating clusters. It therefore must be other close binaries that are responsible.

Cataclysmic variables (CVs) exist in much greater numbers in globular clusters, indeed Di Stefano & Rappaport (1994) predict of the order one hundred CVs in a single Galactic globular cluster. 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. 2005) and approximately 60 candidate CVs have been identified in NGC 2808 using ultra-violet observations (Dieball et al. 2005). Thus although we do not yet have a complete sample of CVs in the globular clusters observed (unlike for the brighter, soft neutron star binaries) with which to determine their formation mechanisms and numbers, it is apparent that they exist in large numbers and thus it is likely that they are important to the cluster's fate.

2.2 The nature of globular cluster cataclysmic variables

Although we are identifying more and more cataclysmic variables in Galactic globular clusters, one striking and unexplained difference remains between globular cluster cataclysmic variables and field CVs. Globular cluster CVs show a distinct lack of outbursts (characterised 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 cataclysmic variable, material is accreted from the companion star and stored in the accretion disc 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 ionises and the viscosity increases sufficiently for the material to fall onto the white dwarf (Osaki 1974, Meyer & Meyer-Hofmeister 1981, Bath & Pringle 1981, etc). Many types of field CVs show such outbursts every few weeks to months. However, only very few globular cluster outbursts have been observed (e.g. Paresce & de Marchi 1994, Shara et al. 1996, 1987) and it is unclear why this should be.

It was orginally suggested that globular cluster CVs may be mainly magnetic c.f. the 5 CVs in Grindlay (1999). Magnetic CVs have accretion discs that are either partially or totally disrupted by the strong white dwarf magnetic fields, known as intermediate polars and polars respectively. Material is channelled along the field lines onto the white dwarf, although in the case of intermediate polars, a truncated disc can exist and these systems can undergo a limited number of outbursts (e.g. Norton & Watson 1989). However, 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 ($\lesssim 10^{14-15}$ g s^{-1}) and moderately strong white dwarf magnetic moments ($\gtrsim 10^{30}$ G cm^3) which could stabilise the CV discs in globular clusters and thus prevent most of them from experiencing *frequent outbursts*. This indicates that the globular cluster CVs that are brightest in X-rays should be intermediate polars. Ivanova et al. (2006) has also suggested that the lack of outbursts are due to higher white dwarf masses (which also indicates higher magnetic fields) in globular cluster CVs compared to those in the field. This is likely to be due to the difference in the formation mechanisms of globular cluster and field CVs, where 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 orbital modulation on the spin period (typically $\sim 10^2$-10^3 secs) of the accreting white dwarf which can be detected through fourier analysis of their X-ray lightcurves e.g. Parker, Norton & Mukai showed that 70% of the intermediate polars observed with *ASCA* and *RXTE* showed this modulation. Thanks to the sensitivity of the *XMM-Newton* satellite, our *XMM-Newton* observations of the globular cluster NGC 2808 reveal that the lightcurve of the brightest CV in this cluster, has evidence for modulation with a 430 s period (Servillat, Webb & Barret, this proceedings). This is likely to be the orbital modulation on the spin period, supporting an intermediate polar identification. We also have low resolution spectra of the brightest CV (candidate) in the globular cluster M 22 (Fig. 1, left), Webb et al. 2004 and Webb et al. in prep.) which shows some evidence for the He 4686Å 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, Cool & King 2003; Bond et al. 2005; Pietrukowicz et al. 2006), it would indicate that this CV is also an intermediate polar, again supporting the idea that globular cluster CVs have moderate magnetic fields, in part responsible for their lack of outbursts.

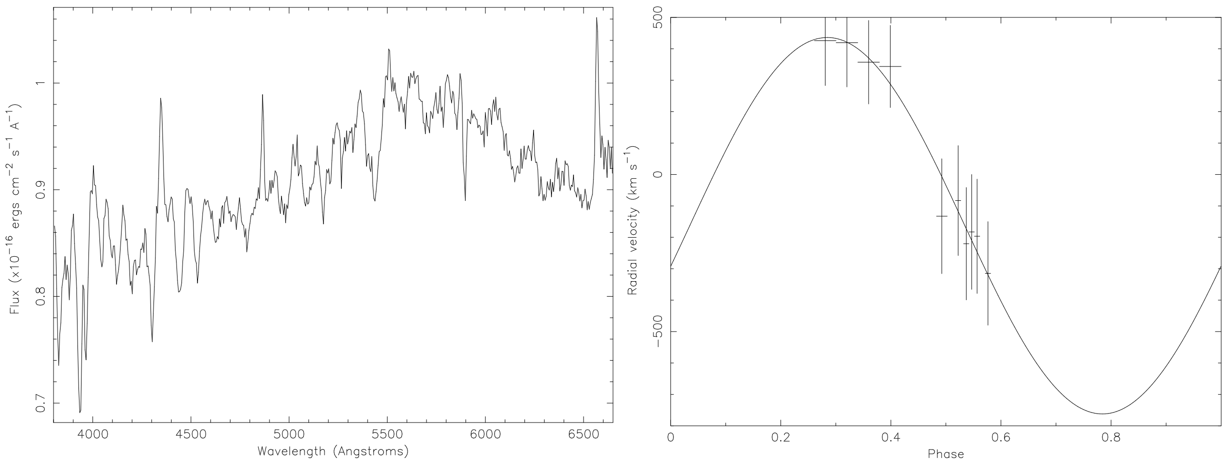

Fig. 1. *Left:* Combined blue spectrum of CV1 in M 22 taken with the VIMOS/VLT (resolution, 5.3Å/pixel). The Ca H&K lines due to the secondary are visible, as well as the Balmer lines in emission, emanating from the accretion disc. These are superposed on wide Balmer lines in absorption, presumably from the white dwarf. There is also some evidence for the He 4686Å line in emission, possibly due to the white dwarf magnetic field. *Right:* Radial velocity curve derived from the H_α line in the low resolution (blue, 5.3Å/pixel and red, 7.1Å/pixel) VIMOS VLT spectra folded on the ∼0.2d period derived from fourier analysis of the X-ray lightcurve.

2.3 Formation mechanisms for globular cluster cataclysmic variables

It is believed that there are two populations of globular cluster CVs, those formed dynamically (as the neutron star low mass X-ray binaries), thought to be located in the dense cluster cores and those that have evolved without undergoing an encounter, formed from the primordial binary. This latter population may reside outside the cluster core (Davies 1997), where the stellar density is much lower than in the core. Davies (1997) states that the more concentrated globular clusters, which have higher core densities, have higher encounter rates, thus increasing the number of CVs formed through encounters. In addition, the time-scales of encounters between primordial binaries and single stars are shortened, thus decreasing the number of primordial CVs. The globular clusters that we have observed with *XMM-Newton* are particularly well adapted to searching for a primordial binary population, as we have chosen low core density clusters, to ensure that we can resolve all the X-ray sources, given that the angular resolution of the EPIC cameras is approximately 6" Full Width at Half Maximum of the Point Spread Function. In addition, *XMM-Newton*'s large collecting area ensures that we have 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 globular clusters e.g. AKO 9 in the globular cluster 47 Tuc (Aurière, Koch-Miramond, Ortolani 1989) which Knigge et al. 2003 state was almost certainly formed dynamically, either via tidal capture or in a three-body encounter. Other such dynamically formed CVs exist in other globular clusters e.g. in ω Cen (e.g. Carson et al. 2000, Gendre, Barret & Webb 2003a) and M 22 (Webb et al. 2004).

We have found several X-ray sources in the globular clusters studied with *XMM-Newton* that lie outside of the half-mass radius and have X-ray luminosities, spectra/colours and lightcurves that infer that they may be CVs. Recently, Pietruckowicz et al. (2005) confirmed using optical photometry that one of our X-ray sources (Webb et al. 2004) lying at 3.9 core radii from the centre of the globular cluster M 22 is indeed a CV. It is possible that this CV was formed from it's primordial binary, because of its location in the cluster. Ivanova et al. (2006) predict that as many as 37% of the CVs in a cluster as concentrated as 47 Tuc should be formed from their primordial binaries, thus one would expect an even greater percentage for a low concentration cluster such as M 22, supporting the primordial formation mechanism, one of the first identified in Galactic globular clusters.

3 Concluding remarks

We have shown through our *XMM-Newton* observations of eight Galactic globular clusters that many of the faint X-ray sources are different kinds of binaries. The number of neutron star X-ray binaries is insufficient in the majority of Galactic globular clusters to inject the necessary energy required to slow down the inevitable core collapse. Cataclysmic variables may well be in part responsible as they are present in much greater numbers.

We have shown that the sensitivity of *XMM-Newton* allows us to make observations of neutron star X-ray binaries that help to constrain the unknown neutron star equation of state. Further, this quality has allowed us to detect the orbital modulation on the spin period of the white dwarf in a CV, supporting the idea globular cluster CVs have moderate magnetic field strengths, in part responsible for their lack of outbursts. Further observations should be made with this instrument to test other CVs in other globular clusters. However, follow-up optical spectroscopy can help in identifying the nature of the object, as well as confirming the orbital period (see Fig. 1), the possible magnetic nature, the mass transfer rate and for putting a limit on the white dwarf mass essential for revealing why CVs show fewer outbursts in globular clusters than in the field.

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