USING XMM-NEWTON TO SEARCH OUT THE COMPACT BINARIES IN GLOBULAR CLUSTERS

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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 four of the eight 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 have identified neutron star low mass X-ray binaries and their descendants (millisecond pulsars), cataclysmic variables, active binaries as well as other exotic objects, such as subdwarf B stars and evidence for double degenerates. We discuss the characteristics of these systems, along with their formation and evolution in globular clusters and their use in tracing the dynamical history of these clusters.

Key words: globular clusters: individual:M 55 - NGC 3201 - M 22 - ω Centauri – X-rays: general – binaries: general – stars: variables: general.

1. INTRODUCTION

It is expected that globular clusters (GCs) should contain many binary systems, due to interactions occurring within the clusters (e.g. Di Stefano & Rappaport, 1994), and that these systems *could* play a critical role in the dynamical evolution of GCs, serving as an internal energy source which counters the tendency of GC cores to collapse (e.g. Hut et al., 1992, for a review). However, these binaries are extremely difficult to locate at long wavelengths, because of over-crowding. It is almost uniquely using X-ray observations that the binaries, which are also visible at such high energies, can be located. Indeed the small population of bright X-ray sources ($L_x > 10^{36}$ erg s^{-1}), known to be X-ray binaries (Hertz & Grindlay, 1983), were detected and identified primarily through their X-ray emission. However, there is a large population of faint ($L_x \lesssim 10^{34.5}$ erg s^{-1}) X-ray sources, whose nature is only now beginning to be revealed. A variety of objects have been identified, including many binary systems and their progeny, i.e.: X-ray binaries (e.g. Gendre et al., 2003b; Rutledge et al., 2002); cataclysmic variables (e.g. Carson et al., 2000; Webb et al., 2005); millisecond pulsars (e.g. Grindlay et al., 2001; Camilo et al., 2000); active binaries (e.g. Kaluzny et al., 1996; Carson et al., 2000); as well as fore- and background objects, e.g. stars (e.g. Gendre et al., 2003a) or clusters of galaxies (Webb et al., 2004). The populations of these binaries, with the exception of neutron star X-ray binaries which appear to scale with the cluster encounter rate (Gendre et al., 2003a; Pooley et al., 2003; Heinke et al., 2003), are still unknown. It is important to determine the different populations in order to understand the evolution of the clusters as well as for studying the individual classes of objects.

Many types of field cataclysmic variables (CVs) show outbursts, primarily in the optical domain, every few weeks to months. Observers have therefore tried to exploit the large variations in the optical lightcurves of outbursting cataclysmic variables as a means to detect them in GCs (e.g. Bond et al., 2005; Kaluzny et al., 2005). Only very few GC outbursts have been observed (e.g. Paresce & de Marchi, 1994; Shara et al., 1996, 1987). Even when Ciardullo et al. (1990) searched for outbursts in 54 of M31's GCs over two years, they found no evidence for an outburst. The lack of outbursts observed in GC CVs remains one of the most striking and unexplained differences between GC cataclysmic variables and field CVs. Several theories have been proposed to explain the paucity of GC CV outbursts. Firstly, X-ray observations have shown themselves to be much more efficient in detecting the expected populations of cataclysmic variables (Webb et al., 2005, 2004; Heinke et al., 2005), which have X-ray luminosities of $\sim 10^{30}$-$10^{32.7}$ ergs s^{-1} (extrapolating from Verbunt et al. (1997) into the *XMM-Newton* 0.2-12 keV band). Thus it has been suggested that the X-ray detected GC CVs may be mainly magnetic CVs (polars and intermediate polars) c.f. the 5 magnetic CVs in Grindlay (1999), which could explain the lack of cataclysmic variable outbursts detected in GCs. Magnetic CVs have high L_x/L_{opt} values due to magnetically channelled accretion onto the white dwarf, making them more easily detected in X-rays (Patterson, 1994) and polars do not show outbursts because their accretion discs are disrupted by their magnetic fields. Edmonds et al. (2003b) has tentatively suggested that GC CVs may have low accretion rates, as first suggested by Shara et al. (1996), implied by their faint optical luminosities, which could explain the scarcity of GC CV outbursts, where some low mass transfer rate systems, such as SU UMa systems, can have quite long recurrence times between outbursts. However, more recently, Dobrotka et al. (2005) proposed that the lack of outbursts 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 ($\lesssim 10^{30}$ G cm^3) which could stabilise the CV discs in GCs and thus prevent most of them from experiencing frequent outbursts.

Here we discuss four of the eight globular clusters (ω Centauri (NGC 5139), M 22 (NGC 6656), M 13 (NGC 6205), NGC 6366, M 55 (NGC 6809), NGC 3201, NGC 2808 and NGC 4372) that we have observed with *XMM-Newton* in which have identified the nature of some of the sources through X-ray observations and determine their membership to the clusters. We also present optical observations of sources detected in the direction of M 22, which have allowed us to confirm the nature of the X-ray identified sources and to identify other objects.

2. OBSERVATIONS AND DATA REDUCTION

2.1. X-ray data

We have between 20 and 40 ks of *XMM-Newton* EPIC (MOS and *pn*) data for each of the GCs. This paper will focus on the GCs ω Centauri, M 22, M 55 and NGC 3201. Observations were made between September 2000 and May 2003 in the full frame mode (Turner et al., 2001), with the medium filter. The data were reduced with different versions of the *XMM-Newton* SAS (Science Analysis Software), see Webb et al. (2005, 2004) and Gendre et al. (2003a) for further details.

The MOS data were reduced using the ‘emchain’ with ‘embadpixfind’ to detect the bad pixels. The event lists were filtered, so that 0-12 of the predefined patterns (single, double, triple, and quadruple pixel events) were retained and the periods of high background counts were then flagged in the event list. We used the energy range 0.2-10.0 keV. The *pn* data were reduced using the ‘epchain’ of the SAS. Again the event lists were filtered, so that 0-4 of the predefined patterns (single and double events) were retained, as these have the best energy calibration. Here we used the energy range 0.5-10.0 keV and again removed high background periods.

The source detection is described in Webb et al. (2005, 2004); Gendre et al. (2003a,b). Many of our detected sources are background sources. We have used the statistical Log N-Log S relationship of extragalactic sources derived from the Lockman Hole (Hasinger et al., 2001) to estimate the background population. We converted the source count rates to fluxes using a power law model (Γ=2), as Hasinger et al. (2001). We calculated the average limiting flux in the core, half mass radius and the whole field of view (radius=15’) with which we could estimate the number of sources expected.

2.2. Optical data

We have optical photometry and spectroscopy of the X-ray sources in M 22, see Webb et al. (2004; in prep.). Schott glass U-, B- and V-filter photometry was taken with the Wide Field Imager (WFI) mosaic at the 3.9m *Anglo Australian Telescope* (AAT) on September 15-16 2001. The camera has a field of view (FOV) of $33' \times 33'$, similar to the *XMM-Newton* FOV. Each image was bias-subtracted and then flat-fielded with twilight sky flats, using the *IRAF* software (Tody, 1986, 1993). The long U-band observations were also dark subtracted, as the dark-current was non-negligible in these longer exposures. The data were astrometrically calibrated using the *IRAF* package *MSCRED* (Valdes, 1998) and the package *Wide Field Padova REDuction* (WFPRED) developed at the Padova Astronomical Observatory (Held et al. in prep.) and the standard star fields. A refinement to the astrometry was then made using the UCAC (USNO CCD Astrograph Catalog) (Zacharias et al., 2000), so that the positions are good to less than $0.1''$. The data for each filter were then stacked to create a deep image and the photometry was carried out using DAOPHOT/ALLSTAR (Stetson, 1987). The instrumental magnitudes were corrected using the standard stars observed on 2001 September 13. We find 123 220 stars detected in the U-band and at least one of the other two bands, where the maximum matching distance was 3 pixels ($< 1.5''$). The magnitudes range from approximately 14.0-22.8 in each filter. The photometric errors range from 0.01-0.1 magnitudes.

Spectroscopic observations were made in service mode with the VIsible Multi-Object Spectrograph (VIMOS) on the 8.2 m Melipal telescope of the European Southern Observatory Very Large Telescope (VLT), with an aim to identify the X-ray sources in Webb et al. (2004). The observations were carried out on three nights, June 9 and 22 and July 9 2004. The blue grism has a range of 3700-6700Å and a resolution of 180 for a $1''$ slit, with a dispersion of 5.3 Å/pixel. The red grism has a range of 5500-9500Å, a resolution of 210 for a $1''$ slit and a dispersion of 7.1 Å/pixel. The seeing was typically below $0.8''$, except for the last night when it exceeded $1''$. Flat-field and He-Ar arc lamps and flux standard stars were also observed during the night to calibrate the spectra.

The data were reduced using the latest public version of the VIMOS pipeline recipes (V1.0). The data were bias subtracted, but the dark current was negligible, so no dark correction was carried out. Due to flexures of the instrument, the flat-field corrections also made no improvement to the data and were thus disregarded. The spectral extraction was carried out using the two step method in the pipeline, using either an optimal extraction method (Horne, 1986) or manually if the pipeline was unable to automatically distinguish between multiple sources, due to their close proximity. The wavelength correction was carried out in the standard manner using the pipeline. Using the flux standards we corrected for the instrument response and flux calibrated the spectra. We have both red and blue spectra for 8 of the 14 possible optical counterparts and blue spectra only for 3 further counterparts and a red spectrum for another. Some sources are without spectra due to a misalignment of the mask during the observations. We also have spectra of approximately 500 other stars in the line of sight of the cluster.

3. RESULTS AND DISCUSSION

The formation mechanism of neutron star low mass X-ray binaries in GCs has now been constrained, as described in Sect. 1. This result has also allowed Pooley et al. (2003) to predict the expected number of neutron star low mass X-ray binaries in Galactic GCs, thought to be approximately one hundred. However determining the CV formation mechanism is more difficult as we do not yet have a complete population of CVs. CVs are fainter than neutron star low mass X-ray binaries and with minimal X-ray data they can be confused with active binaries or even millisecond pulsars. Further, it is believed that there are two populations of GC 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 as primordial binary. This latter population should 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 GCs, 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 GCs 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 GCs e.g. AKO 9 in the GC 47 Tuc (Aurière et al., 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 GCs e.g. in ω Cen (e.g. Carson et al., 2000; Gendre et al., 2003a), M 22 (e.g. Webb et al., 2004), and in 47 Tuc (e.g. Edmonds et al., 2003a,b).

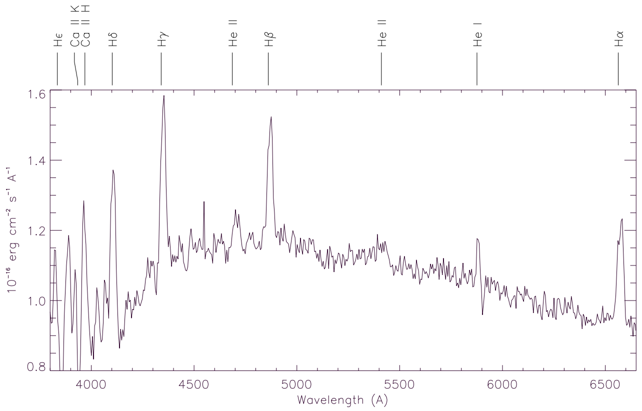

Figure 1. Spectrum of the optical counterpart to source 36. The Balmer lines are indicated as well as He I (5876Å) and He II (4686, 5411Å), which are all seen in emission. Also marked are the Ca H and K lines at 3968.49Å and 3933.68Å respectively.

We have found several X-ray sources in the GCs 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 and may therefore be primordial. We find four such sources in the GC NGC 3201 (Webb et al., 2005). However, we also find possible millisecond pulsars (MSPs) in this region. Edmonds et al. (2003b) have shown that the distribution of millisecond pulsars and CVs is indistinguishable in the much more concentrated GC 47 Tuc, however all these sources fall within the half mass radius. As the possible CVs and MSPs in NGC 3201 appear to be similarly distributed outside of the half mass radius, we may be seeing evidence for disruption of NGC 3201. We have previously shown evidence for disruption of the GC ω Centauri. We found that many of the sources belonging to the cluster lie toward the exterior of the cluster. ω Cen is the most massive Galactic GC and an optical study by Pancino et al. (2000) showed that there are two stellar populations in this cluster, where we expect only one in a canonical GC. This could indicate that the cluster may have either been disrupted by the interaction with another body or that the cluster has accreted a stellar system during its past (see Gendre et al., 2003a, and references therein). NGC 3201 is also an unusual cluster as its orbit is retrograde with respect to the Galaxy and there is evidence for possible structure in the velocity field of the cluster stars (Côté et al., 1995). This could be due to several things including the stripping of stars of the cluster from prolonged interaction with the Galactic tidal field (see Webb et al., 2005, and references therein). This tidal interaction can disrupt the cluster, which could result in the perturbation of the mass segregation.

To confirm the nature of the sources found outside the half mass radius and to confirm their membership of the cluster, we require observations at longer wavelengths. We have thus managed to obtain time to take optical photometry of these clusters clusters. Although we don’t yet have these data, we do already have both optical photom-

Table 1. Equivalent widths and fluxes of CV1's principal spectral lines

Line	Eq. Width (Å)	Flux ($\times 10^{-16}$) (erg cm^{-2} s^{-1} Å^{-1})
Hα	-6.0	4.3
Hβ	-3.5	3.3
Hγ	-3.7	3.9
Hδ	-3.6	3.3
He I (5768Å)	-0.7	0.7
He II (4686Å)	-0.9	1.2
He II (5411Å)	-1.8	2.3

etry and spectroscopy of the X-ray sources in M 22. Our optical photometry has allowed us to identify the possible counterparts to eleven of the X-ray sources in M 22 (Webb et al., 2004). Using the good astrometry of these sources we were able to obtain the optical spectra described in Sect. 2.2 as well as a twelfth counterpart, identified by Anderson et al. (2003). The counterpart to this source was not detected in our AAT data as the core of the cluster was saturated. Anderson et al. (2003), using Hubble Space Telescope (HST) photometry, found a highly variable source, which showed H_α emission and was coincident with the *Einstein*/*Rosat* source X4/B, which led them to conclude that this source is a cataclysmic variable and one of a very small number of confirmed or probable dwarf nova eruptions seen in globular clusters as well as being the first to be found in such a low-concentration cluster. Anderson et al. (2003) named this source CV1. Bond et al. (2005) confirmed the variable nature of CV1 using a four year light curve of this source, based on an analysis of accumulated data from the Microlensing Observations in Astrophysics (MOA) survey. From the regularity of the outbursts and their magnitude, Bond et al. (2005) also propose that this source is a CV.

CV1 is coincident with our *XMM-Newton* source 36 in Webb et al. (2004), where the *Einstein*/*Rosat* source X4/B has been resolved into two sources using the *XMM-Newton* data. We have extracted the optical spectrum of CV1 as described in Section 2.2, using the manual extraction as the source falls very close to it's brighter neighbour. We estimate that the brighter neighbour in the optical data contributes approximately 5% to the spectrum of the optical counterpart of source 36. The neighbouring star's spectrum contains no emission lines and appears to be a mid K-type star. Our optical spectrum of CV1 (see Fig. 1) is typical of a cataclysmic variable, in support of the Anderson et al. (2003)/ Bond et al. (2005) identification. The spectrum shows Balmer line emission as well as some helium lines in emission, indicative of accretion. We give the equivalent widths and fluxes of the principal lines (Å) in Table 1. The Balmer lines show some evidence of a double peak that evolves with time, further support for an accretion disc. We have identified the Ca II H and K absorption lines at 3968.5 and 3933.7 Å which we assume are due to the late type secondary star.

Our observations were made with an aim to identify the X-ray sources through their optical counterparts. The observations made of the red and the blue end were split into four shorter observations (seven for the red end observations made on the 9th June) so as to not to saturate the brightest counterparts. We have taken advantage of the fact that the individual optical spectra of CV1 contain enough counts to carry out a radial velocity analysis. Initially we fitted a Gaussian line to the cleanest calcium line (the H-line), which we assume comes from the secondary star and measured the absolute velocity shifts. We also added all of the blue spectra together to create a template spectrum and cross-correlated the region between 3900 and 4000Å (containing the two calcium lines) with the same region in the four blue spectra, using the *IRAF* task *fxcor*. We find very similar results. As we have no means of measuring the radial velocity of the white dwarf, we cross correlated the Hα line, because it is apparent in both the red and the blue spectra (6500-6600Å) with the template, even though it is unlikely that the this line is emitted from the region closest to the white dwarf. The radial velocities obtained for the disc lines were plotted against time. This plot spans the 13 days between the red and the blue observations. We fitted the points assuming that CV1 is in a circular orbit and that it has the same velocity as the globular cluster M 22, -148±0.8 km s^{-1} (Peterson & Cudworth, 1994), where the escape velocity is 24.2 km s^{-1}. We found a period of 0.069866±0.000012 days (~1.7 hours). Folding the data on this period we obtain the radial velocity curve given in Figure 2. The ephemeris is thus ϕ^{orb} = MJD 53166.1650(8) + 0.069866(12)E, where ϕ^{orb} = 0 indicates inferior conjunction of the white dwarf and the figures in brackets indicate the errors on the last decimal places. These errors are the formal 3σ errors to the fit. However, the true errors may be larger as the absolute wavelength calibration of the spectra is poor, although the calibration of consecutively taken spectra is reliable (errors of the order ±1Å). We have checked both the abso-

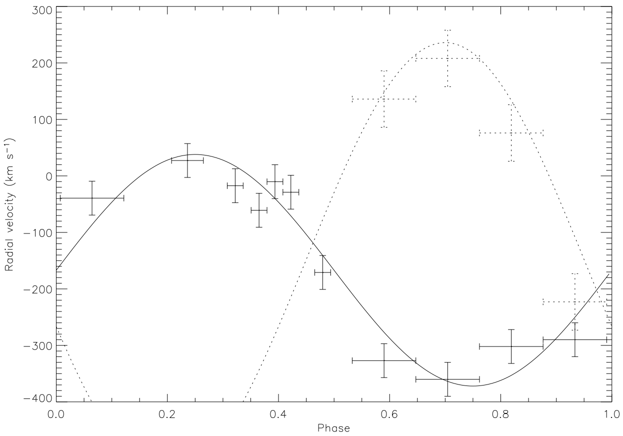

Figure 2. Radial velocities and errors of the disc Hα lines (indicated by the solid crosses) and the best fit to these date folded on the ephemeris derived above (also solid line) and the radial velocities and errors of the calcium lines (dotted lines) and the best fit to these points.

lute and relative calibration of the spectra using the spectra from other objects. We find shifts of 0±20km s^{-1} for consecutive spectra of stationary objects. However, it is for this reason we do not use the radial velocities to constrain the mass of the two stars. It is none the less encouraging that the radial velocities of the calcium lines, when folded on the above period are in almost anti-phase with the disc radial velocity, as one would expect if they are from the secondary.

Our X-ray spectrum of source 36 does not necessarily support the CV hypothesis. One would expect a high temperature bremsstrahlung model Richman (1996) or a single optically thin plasma model (i.e. the MEKAL model in XSPEC Baskill et al., 2005) to fit the X-ray spectrum. The X-ray spectrum to source 36 is best fitted using a power law plus a Gaussian absorption line, believed to be due to cyclotron resonance, as is found in several neutron star X-ray spectra (Webb et al., 2004). CV1, located at R.A.=$18^h36^m24^s74$ and dec.=23°54′35″8 does indeed fall within the X-ray positional error circle of 5″ (90% confidence). However, we have found a second serendipitous source in the slit placed on this proposed counterpart that shows H_α emission. This source may be the optical counterpart to the X-ray source as it also falls within the X-ray positional error circle but on the other side of the X-ray source to CV1, at R.A.=$18^h36^m24^s75$ and dec.=23°54′43″03. The two optical sources are separated by 7.2″. It is possible that the latter is the optical counterpart to the X-ray source and is thus a neutron star. Alternatively the X-ray source that we detect is not a single source but two (or more) unresolved sources. Planned follow-up X-ray observations with the X-ray satellite Chandra, which has an angular resolution of $<1''$ are necessary to determine whether the XMM-Newton X-ray source is indeed multiple X-ray sources or failing that, to improve the positional error, necessary to determine which of the two sources is the optical counterpart to the X-ray source.

Returning to the nature of CV1, it appears clear that it is indeed a CV. The presence of fairly strong (compared with the other emission lines) He II lines in emission, in particular the He II 4686Å line, see Table 1, could indicate that this CV is magnetic in nature, where the presence of strong He II emission lines usually indicates either a magnetic white dwarf or a nova-like system with a high level of mass transfer (Szkody et al., 2005). If the period determined is confirmed, this would rule out the nova-like possibility, as these objects have periods $\gtrsim$ 3 hours. If CV1 is magnetic and as it has already been shown to undergo outbursts, it would seem likely that it is an intermediate polar (IP). IPs (which are thought to have lower magnetic fields than the polars) can undergo outbursts as an accretion disc can be present in the system. The magnetic field is powerful enough in these systems to influence the flow of the gas and disrupt the inner disc. If our derived period is confirmed, this would make it a very short period IP, in fact one of the shortest known, see Ritter & Kolb (2005). Further, many other CVs with periods $\lesssim$ 2 hours have low mass transfer rates (Ritter & Kolb, 2005). This could support the mechanism proposed by Dobrotka et al. (2005) to explain why GC CVs show so few outbursts is because they are *both* magnetic and have low mass transfer rates.

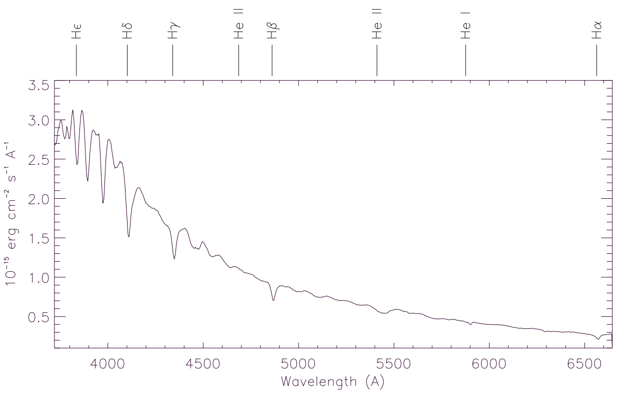

Figure 3. Spectrum of the optical counterpart to the X-ray source 20 (Webb et al., 2004).

We have also started to identify other X-ray sources in M 22 through their optical counterparts. Fig. 3 shows the spectrum of the proposed optical counterpart to the X-ray source 20 (Webb et al., 2004). The photometric observations showed that this source falls in the blue-straggler region of the colour magnitude diagram and the spectroscopic observations support this (e.g. Shetrone & Sandquist, 2000). Blue stragglers appear brighter and bluer than the main-sequence turnoff and they are thought to be formed through stellar collisions or binary mass transfer and mergers. However, blue stragglers do not usually emit in the X-ray domain, although they are often binary systems (e.g. Kaluzny et al., 2004), where the other star in the binary could be the source of X-ray emission. We have searched for radial velocity variations in the same way as for CV1 and we find no evidence for binarity in these observations. This makes it unclear whether this is indeed the optical counterpart to our X-ray source 20.

Several of the other spectra may indicate that some of our X-ray sources are double degenerates. However, due to the faintness of these systems and the overcrowding in the optical, the spectra are contaminated by neighbouring star spectra. We are currently deconvolving these spectra and the results will be presented in Webb et al. (in prep.) along with the results of other spectral identifications of the M 22 X-ray sources and a number of serendipitously detected subdwarf stars.

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