Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 31 July 2013 (MN LaTeX style file v2.2)

The X-ray source population of the globular cluster M15: Chandra high resolution imaging

D.C. Hannikainen,[1,2], P.A. Charles[1], L. van Zyl[3,4], A.K.H. Kong[5], L. Homer[6]
P. Hakala[2], T. Naylor[7], and M.B. Davies[8]

[1] *Department of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK*
[2] *Observatory, PO Box 14, FIN-00014 University of Helsinki, Finland*
[3] *Astrophysics Group, School of Physics, Keele University Staffordshire, ST5 5BG, UK*
[4] *Department of Astrophysics, Oxford University, Keble Road, Oxford OX1 3RH, UK*
[5] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*
[6] *Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580, USA*
[7] *School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK*
[8] *Lund Observatory, Box 43, SE-221 00 Lund, Sweden*

31 July 2013

ABSTRACT

The globular cluster M15 was observed on three occasions with the High Resolution Camera on board *Chandra* in 2001 in order to investigate the X-ray source population in the cluster centre. After subtraction of the two bright central sources, four faint sources were identified within 50 arcsec of the core. One of these sources is probably the planetary nebula, K648, making this the first positive detection of X-rays from a planetary nebula inside a globular cluster. Another two are identified with UV variables (one previously known), which we suggest are cataclysmic variables (CVs). The nature of the fourth source is more difficult to ascertain, and we discuss whether it is possibly a quiescent soft X-ray transient (qSXT) or also a CV.

Key words: globular clusters: individual: M15 – X-rays: binaries – planetary nebulae: individual: K648 – stars: dwarf novae

1 INTRODUCTION

M15 is renowned for containing the first globular cluster Low-Mass X-ray Binary (LMXB; X2127+119) to be optically identified (with AC211, see Aurière, Le Fevre & Terzan 1984 and Charles, Jones & Naylor 1986), a counterpart that is still one of the most optically luminous of all LMXBs. AC211 is also the first globular cluster X-ray source to have both an optical and X-ray demonstration of its 17.1 hour orbital period via extended, partial eclipses (see Ilovaisky et al. 1993 and Ioannou et al. 2002 and references therein). Subsequent studies of M15 show that it contains additional exotic, highly evolved binaries. For example, there are at least 8 millisecond pulsars (MSP), 6 of them within 8 arcsec of the cluster core (Kulkarni & Anderson 1996). Two of these MSPs have a negative $\dot{P}$ (i.e. an acceleration toward us as they move in the cluster potential) implying a mass concentration of ~ 4000 $M_{\odot}$ at the cluster centre (Phinney 1996). Phinney argues that this mass *cannot* consist of low-mass stars and is either a central black hole, or more likely a concentration of stellar remnants: neutron stars and white dwarfs.

M15 is one of the most metal-poor globular clusters known ([Fe/H] ~ -2.1) and has a low reddening factor ($E_{B-V} = 0.10 \pm 0.01$; Harris 1996). A recent study has refined the distance to M15 to 9.98±0.47 kpc (McNamara, Harrison & Baumgardt 2004) which places it 5% closer than the previously quoted value of 10.4±0.8 kpc (Durrell & Harris 1993). McNamara et al. (2004) also provide a new estimate for the age and the mass of the cluster which are 13.2±1.5 Gyr and $(4.5\pm0.5)\times10^5$ $M_{\odot}$ respectively. M15's main-sequence turn-off point lies at $V \simeq 19.4$, $B-V \simeq 0.47$.

M15 was for a long time believed to be a classic example of a central-surface-brightness-cusp globular cluster (Newell & O'Neill 1978; Djorgovski & King 1986; Peterson, Seitzer & Cudworth 1989), i.e. a cluster which has undergone core-collapse, with a small (~ 0.06 pc), densely-crowded core containing many non-luminous remnants, or even a single, massive black hole. However, more recent work shows that M15's core, while compact, is larger than previously thought (0.13 pc; Lauer et al. 1991), and the central velocity dispersion lower (~ 10 km s^{-1}; Gebhardt et al. 1992). As a result, it is no longer possible to tell whether M15 has, in fact, undergone core-collapse: a classical pre-collapse, thermal equilibrium cluster model fits the data just as well as post-collapse models with a re-expanding core (Grabhorn et al. 1992; De Marchi & Paresce 1994).

Recently, van der Marel et al. (2002) and Gerssen et al. (2002, 2003), using longslit spectra obtained with the Hubble Space Telescope (HST), have shown that radial velocity measurements are consistent with a central dark mass. Models of the data which include a central black hole of mass ~ 2000 $M_\odot$ fit the data slightly better than models without one. However, a central concentration of non-luminous, massive stellar remnants fits the data just as well, as shown in the dynamical simulations of Baumgardt et al. (2003). Furthermore, the *Chandra* X-ray images presented by White & Angelini (2001) show no evidence for any X-ray emission at the cluster centre, again indicating that it is unlikely to harbour a central black hole (see also Ho, Terashima & Okajima 2003).

One of the primary motivations for this project was to attempt to solve one of X2127+119/AC211's biggest mysteries: the X-ray and optical light curves, and its very low L_X/L_{opt}, show unambiguously that it is an accretion disc corona source (e.g. Ilovaisky et al. 1993; Ioannou et al. 2002), in which the compact object is obscured at all times by the accretion disc. But luminous type I X-ray bursts have been observed from the system (e.g. Dotani et al. 1990), requiring that a neutron star is visible (at least at certain times)! We inferred therefore that X2127+119 may actually consist of *two* luminous X-ray binaries in M15's core, too close together to be resolved by previous X-ray observations (Charles, Clarkson & van Zyl 2002). This suggested exploiting *Chandra's* superb ∼0.5-arcsec spatial resolution, and the result was the High Resolution Camera (HRC-I) images presented here, in order to search for additional sources close to AC211.

However, before the HRC-I observations were performed, White & Angelini (2001) serendipitously resolved X2127+119 into two bright LMXBs with the zero-order ACIS-S/HETG image. M15 X-2 was found to be associated with a $U \sim 19$ star located 2.7 arcsec from AC211 and 3.3 arcsec NW of the cluster core. While M15 X-2 is ∼4 mag fainter than AC211, it has an X-ray count rate ∼2.5 times greater. Nothing is known yet about the nature of M15 X-2, other than that – if we assume it to be responsible for the type I X-ray bursts (and thereby resolving the controversy of AC211's X-ray properties) – the compact object is a neutron star. This then leaves the nature of the object in AC211 unconstrained.

High resolution X-ray imaging is now revealing a wide range of low-luminosity sources in globular clusters (see e.g. Heinke et al. 2003a; Hakala et al. 1997). The advent of *Chandra* has made it possible to investigate these sources in earnest. Some of the first results, (e.g. Pooley et al. 2002a,b), show detections of CVs in the globular clusters NGC 6752 and NGC 6440. Dozens of low-luminosity X-ray sources have also been discovered in ω Cen and NGC 6397 (see Verbunt & Lewin 2004 for a recent review), and ∼300 in 47 Tuc (Heinke et al. 2004).

These studies are narrowing the gap between the predicted and observed CV population densities, but have been primarily restricted to the cases of those clusters that do *not* contain central luminous steady LMXBs. However, one should note that a number of studies has emerged recently using *Chandra* to look for faint sources in globular clusters which do contain bright LMXBs, e.g. Heinke, Edmonds & Grindlay (2001), Heinke et al. (2003b), Wijnands et al. (2002), Homer et al. (2002).

M15 is a good cluster to hunt for CVs and LMXBs because of its large mass and high compactness: its very dense core should be an ideal breeding ground for CVs and LMXBs (as indicated already by the MSP population). In addition, its very low reddening will not hinder the UV/optical identification of any new sources that are found.

What are the chances of optically detecting a dwarf nova (DN) in outburst in M15 during a single HST visit? Di Stefano & Rappaport (1994) predicted a population of $\sim$ 200 CVs in 47 Tuc, of which $\sim$ 50 are DNe. We would expect M15 to have a much higher population of CVs because of its greater core mass and central condensation than 47 Tuc. Nevertheless, assuming that M15 has say 50 DNe, with a mean outburst recurrence time of 50 days and outburst length of 10 days, then at any given time, one would expect to see ∼10 DNe in outburst.

Although DNe are brighter in the optical during outburst than in quiescence, their behaviour in the X-ray is harder to predict. A good summary of the current view of the origin of the X-rays is given by Verbunt, Wheatley & Mattei (1999). For our purposes the crucial point is that in outburst the 2.5–10 keV flux from the boundary layer largely disappears, and is replaced by a very soft extreme ultraviolet (EUV) component. The disappearance of the hard component should drive the X-ray flux down in outburst, but the EUV component is so luminous that if its hard energy tail reaches the soft X-ray range, it will dominate the flux there, and lead to a brightening in that range. Thus whether the DN brightens or fades depends crucially on the X-ray energy range in question, and to a lesser extent the reddening. Given that we know at least one DN (U Gem; Swank et al. 1978) whose flux increases even in the 2–10 keV range, some DNe will be brighter in outburst than quiescence in HRC-I, but it is not clear this is true for all of them.

From an observational point of view, we are particularly interested in the DNe subclass of CVs because of their frequent outbursts making them easier to detect and classify as definite CVs. Outburst recurrence intervals for DNe range typically from 14 – 120 days or longer, and last ∼10 days (see e.g. Warner 1995).

Hence, we use our *Chandra* data here to investigate these fainter sources, in an attempt to reveal M15's menagerie of CVs, quiescent low-mass X-ray binaries, (chromospherically) active binaries and other exotica for the first time. This work is still in progress: detecting the faint X-ray sources in the core, which is dominated by the flux from AC211 and M15 X-2, has been – and continues to be – a considerable challenge as we will discuss below.

In Section 2 we present our *Chandra* HRC-I observations, with particular emphasis on how to remove the two luminous sources so as to reveal the faint population within. In Section 3, we use archival HST imaging to search for optical counterparts to these faint X-ray sources and discuss the implications of these results for the nature of this faint source population.

Table 1. *Chandra* observation log

Observation number	Date	UT_{start}	UT_{stop}
1903	2001 Jul 13	07:07:43	10:04:42
2412	2001 Aug 3	16:24:35	19:23:48
2413	2001 Aug 22	04:57:07	08:23:19

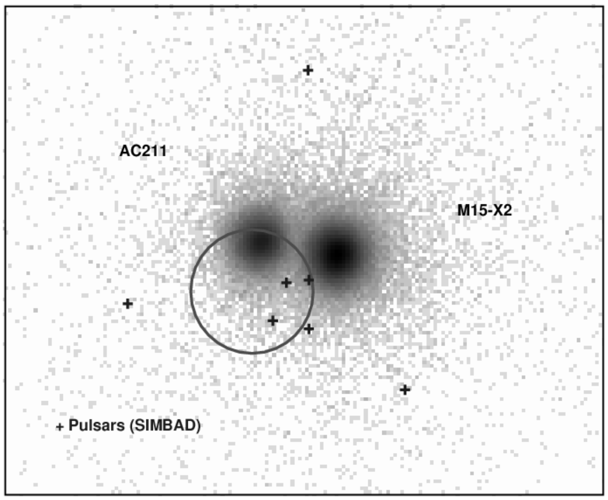

Figure 1. Our summed HRC-I image of the centre of M15, showing the two bright sources, AC211 and M15 X-2, and the positions of 7 of the 8 known millisecond pulsars (from SIMBAD). The circle represents the location and extent of the cluster core (which has a radius of 2.2 arcsecs, see Lauer et al. 1991).

2 *CHANDRA* HRC IMAGING

2.1 Observations

We obtained three separate observations of M15 with *Chandra's* HRC-I (Murray et al. 1997) of approximately 10 ksec each over a six week period in 2001 Jul–Aug. The HRC-I has a $30' \times 30'$ field of view. Table 1 summarizes the details of the observations. All data were reduced and analyzed using CIAO versions 2.0 to 2.3.

Figure 1 shows our summed HRC-I image of the central region of M15. The crosses show the positions of 7 of the 8 known MSP's, while the circle represents the $2''.2$ core radius centred on the position of the cluster centre ($\alpha = 21^h29^m58.^s335, \delta = 12°10'0.''89$, J2000; van der Marel et al. 2002). The *Chandra* and HST images (Sec. 3) were realigned on the basis of the AC211 positional match.

Figure 2 shows the light curves obtained for AC211 and M15 X-2 during the three observations. The phase of each observation, obtained using the ephemeris in Ioannou et al. (2002), is given in each plot. They show that the observations were undertaken just prior to the eclipse in AC211. It is clearly seen that M15 X-2 is a steady source with an average count rate of 6.8 ct/s, while AC211 enters a flaring state during the last observation on 2001 Aug 22.

Table 2 shows the average count rates and the fluxes derived for both sources using the spectral parameters from White & Angelini (2001). For M15 X-2 we fixed the hydrogen column density to the expected value of M15, i.e. $N_H = 6.7 \times 10^{20}$ cm^{-2}, and used a power law with an index of 1.89 to derive the 0.5–7.0 keV luminosity. In the case of AC211, we used the partial covering model with a power law photon index of 2.0, a covering fraction of 0.92 and an intrinsic absorption of 2.05×10^{22} cm^{-2}. Again, the interstellar absorption was set to that of M15. Assuming a distance of 9.98 kpc to M15, these convert to an average luminosity of $L_x = 1.4 \times 10^{36}$ erg s^{-1} for M15 X-2 (consistent with that found by White & Angelini, although note that they used the previous value for the distance to the cluster of 10.3 kpc) while AC211 varies between $L_x = 7.9 \times 10^{35}$ erg s^{-1} in the first observation to $L_x = 2.2 \times 10^{36}$ erg s^{-1} in the last observation.

The luminosity of M15 X-2 is consistent with that of White & Angelini (2001), as are the luminosities for AC211 in observations 1903 and 2412. However, the luminosity of AC211 in observation 2413 is significantly higher than in the other two observations, and indicates a brightening of the source at that time.

Table 2 also shows the count rate and X-ray luminosities for source D, most likely identified with the planetary nebula (PN) K648, as we discuss in more detail in Section 2.2.

2.2 Searching for faint sources

The main problem in detecting faint sources in M15 is that, unlike for instance the clusters studied by Pooley et al. (2002a,b) in which there are no X-ray bright sources, M15 houses not just one but *two* bright central sources. Any faint sources lurking near the centre of the cluster – which is where we would expect to find them – will be contaminated by the wings of the AC211 and M15 X-2 point spread functions (PSF). Thus to have any hope of detecting faint sources, the two bright central sources must first be subtracted. We did this by constructing a PSF for each of the two sources using the *Chandra* PSF libraries. To increase the signal-to-noise of any possible faint sources, we merged the three observations. We then used the faint source algorithm WAVDETECT on the PSF-subtracted merged image.

Figure 3 shows both the merged image (a) and the resulting PSF-subtracted image (b) of the merged observations. They both show the positions of potential sources (A and B) found after WAVDETECT was run on the PSF-subtracted image. As can be seen immediately from these images, the software and understanding of the *Chandra* PSF is not yet able to smoothly subtract bright sources from images without leaving large-scale (but smooth) artefacts such as the central "hole". Nevertheless, it does allow a more sensitive search for fainter sources to be undertaken on the subtracted image, and we can gauge the effectiveness of this analysis to search for potential counterparts by using archival Hubble Space Telescope images. In addition to the sources found close to AC211 and M15 X-2, WAVDETECT also found two sources (C and D) at larger radii, one being the planetary nebula K648, shown in Figure 4.

Table 3 shows the coordinates and U-magnitudes for the four sources found in and near the centre of M15. Table 4 shows the X-ray luminosities for these four sources estimated using typical spectral parameters, based on our candidate IDs. For sources A and C (DNe) we used a Bremsstrahlung temperature of 4 keV. The merged dataset was used to extract the parameters for source A. For source B (qSXT/DN?) we applied several models. We used the parameters for Aql X-1 in *quiescence* (taken from Rutledge et

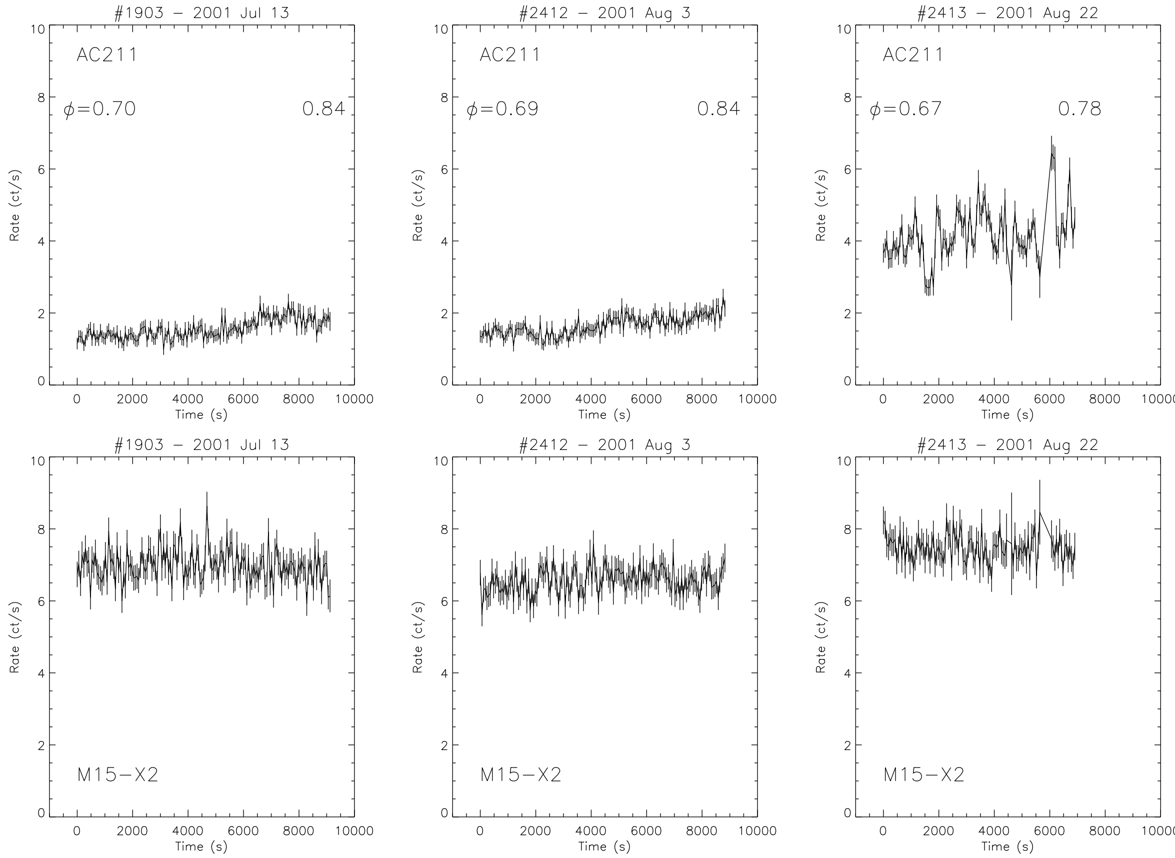

Figure 2. The light curves of AC211(top) and M15 X-2 (bottom) from the three observation dates. The binary phase of AC211 is given on the plots at the beginning and end times.

Table 2. Count rates and luminosities

Obs. no.	1903		2412		2413	
	Count rate (s^{-1})	L_X (0.5–7 keV) (erg s^{-1})	Count rate (s^{-1})	L_X (0.5–7 keV) (erg s^{-1})	Count rate (s^{-1})	L_X (0.5–7 keV) (erg s^{-1})
AC211	1.55±0.18	7.9×10^{35}	1.65±0.19	8.4×10^{35}	3.87±0.27	2.2×10^{36}
M15 X-2	6.97±0.36	1.4×10^{36}	6.57±0.35	1.3×10^{36}	6.95±0.36	1.5×10^{36}
K648	$0.26 \pm 0.18 \times 10^{-3}$	$2.6 - 6.1 \times 10^{31\star}$	$< 0.06 \times 10^{-3}$	$< 0.6 - 1.4 \times 10^{31\star}$	$1.03 \pm 0.42 \times 10^{-3}$	$1.0 - 2.4 \times 10^{32\star}$

* See Table 4 and Section 2.2.

al. 2001 using *Chandra* data). Two estimates were derived, one for a power law with photon index 4.1 and one for a blackbody temperature of 0.33 keV. In addition, we also used a Bremsstrahlung temperature of 4 keV. Finally, for source D (PN) we applied two models: we used parameters from Guerrero et al. (2001), i.e. a Raymond-Smith model with temperature 0.64 keV, and – in the case that the emission might arise from a compact region (as discussed in Section 3.3) – we applied a thermal Bremsstrahlung temperature of 4 keV. We discuss the nature of these sources and compare them to HST data in the next section.

To estimate whether any of the four faint sources may actually be background sources, we use the log N – log S relations of Giacconi et al. (2001). Using the count rate of our faintest source to set a flux detection limit (and assuming that it is in fact a typical background object with $\Gamma = 1.5$), we obtain $F_{lim} \simeq 2$ (0.5-2 keV) and 4.5 (2-10 keV) $\times 10^{-15}$erg s^{-1} cm^{-2}, and hence we expect $\simeq 0.5$ discrete background sources within the area enclosed by the half-mass radius (1.06′) of M15. This provides an upper limit since, even with our PSF subtraction, much of the central region of M15 is not probed to this depth. We conclude that at most one source could be a background object, but given our optical counterpart IDs (see next section) we would suggest that they are all in fact associated with M15.

Table 3. Optical counterparts of faint *Chandra* sources in M15

ID	Object	Location*	Coordinates (J2000) RA DEC	U-magnitude	Variable?
A	DN	0.3" NE	$21^h29^m58.37^s + 12°10'00.8''$	17.6†	Yes
B	qSXT/DN?	11." N	$21^h29^m58.32^s + 12°10'12.4''$	21.8	Possibly
C	DN	46." NE	$21^h29^m57.34^s + 12°10'43.7''$	20.2†	Yes
D	K648	31." NW	$21^h29^m59.38^s + 12°10'27.5''$	13.5‡	Yes (X-rays)

*With respect to the cluster centre.
†Magnitude in outburst (object not visible in quiescence).
‡from Alves, Bond & Livio (2000).

Table 4. X-ray luminosities of faint *Chandra* sources in M15 assuming a distance of 9.98 kpc

X-ray luminosities (erg s^{-1} in the 0.5–7 keV range)					
Source		Model	1903	Obs # 2412	2413
A	DN	kT_{Bremss}=4 keV		3.3×10^{32} †	
B	qSXT?	$\alpha = 4.1$	2.34×10^{31}	7.30×10^{31}	1.15×10^{32}
		kT_{BB}=0.33 keV	4.28×10^{31}	1.34×10^{32}	2.10×10^{32}
	DN?	kT_{Bremss}=4 keV	7.46×10^{31}	2.33×10^{32}	3.66×10^{32}
C	DN	kT_{Bremss}=4 keV	8.65×10^{31}	1.94×10^{32}	1.66×10^{32}
D	K648	kT_{RS}=0.64 keV	2.6×10^{31}	$< 0.6 \times 10^{31}$	1.0×10^{32}
		kT_{Bremss}=4 keV	6.1×10^{31}	$< 1.4 \times 10^{31}$	2.4×10^{32}

† The merged dataset was used to derive the luminosity of source A.

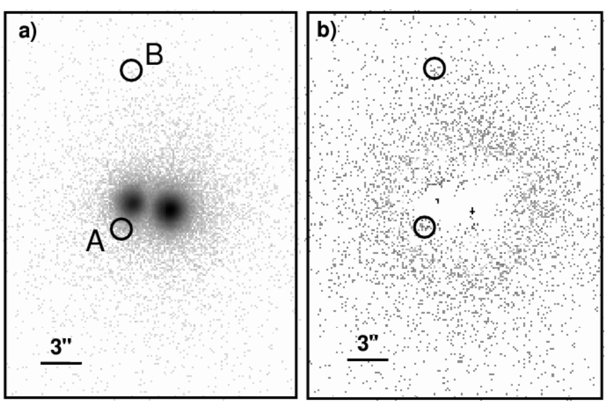

Figure 3. **(a)** The merged image of all three observations of the centre of M15, showing the two bright LMXBs. **(b)** The image after PSF-subtraction of these sources; the two faint sources detected by the source detection algorithm WAVDETECT in this image are overlaid in both panels.

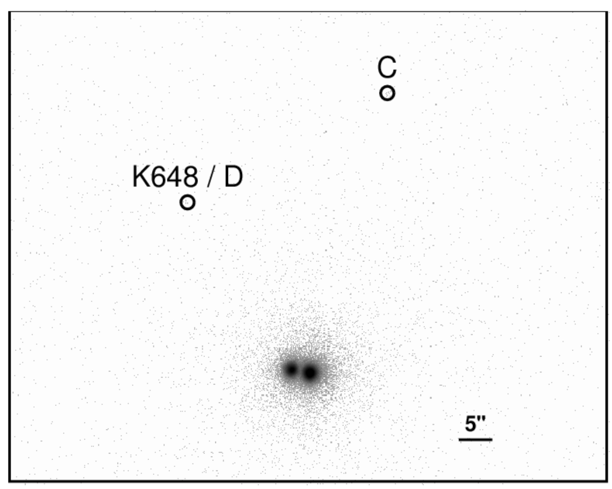

Figure 4. *Chandra* HRC-I image showing the locations of a possible dwarf nova (source C) and the planetary nebula, K648 (source D), detected using WAVDETECT, both well within the half-mass radius. The image is approximately 90″ (width) by 70″ (height). The bar shows 5″.

3 HST IMAGING AND THE NATURE OF THE LOW L_X SOURCES

M15 has been a regular target for HST. Studies of M15's stellar population have been carried out, for example, by Ferraro & Paresce (1993), De Marchi & Paresce (1994; 1996) Guhathakurta et al. (1996) and Sosin & King (1997), and an intensive photometric study of M15's PN, K648, was undertaken by Bianchi et al. (1995; 2001) and Alves, Bond & Livio (2000). The HST archives therefore contain many images of M15 obtained at different epochs.

At the distance to M15, DNe would be expected to have quiescent apparent magnitudes of 21 to 24, with outburst magnitudes ranging from 14 to 21. Magnetic CVs would have magnitudes similar to quiescent DNe (see Warner 1995), while the high mass transfer rate CVs (the nova-likes and nova remnants) would be 2–3 magnitudes brighter. X-ray transients would be expected to have quiescent apparent magnitudes similar to those of DNe, and outburst magnitudes ranging from 13 to 18. The deepest HST archival images of M15 go down to 22–23 mag. Therefore, most quies-

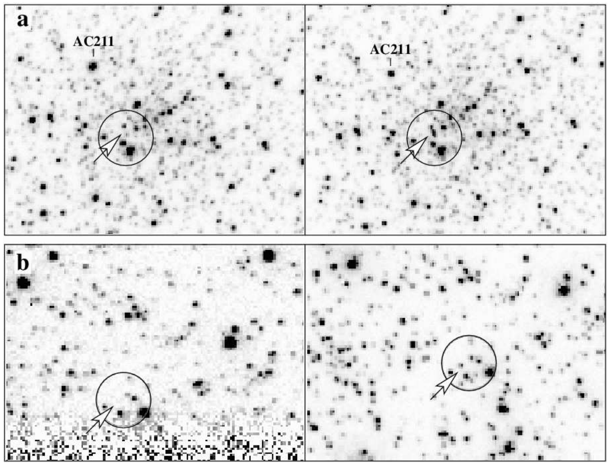

Figure 5. (a) Probable dwarf nova (source A) in the core of M15, found using image-subtraction, reported in Charles, Clarkson & van Zyl (2002), found here to be associated with a *Chandra* X-ray source. (b) Probable dwarf nova (source C) associated with a *Chandra* X-ray source, located 46″ NE of the cluster core. The error circles are the *Chandra* 0.25 arcsec error circle.

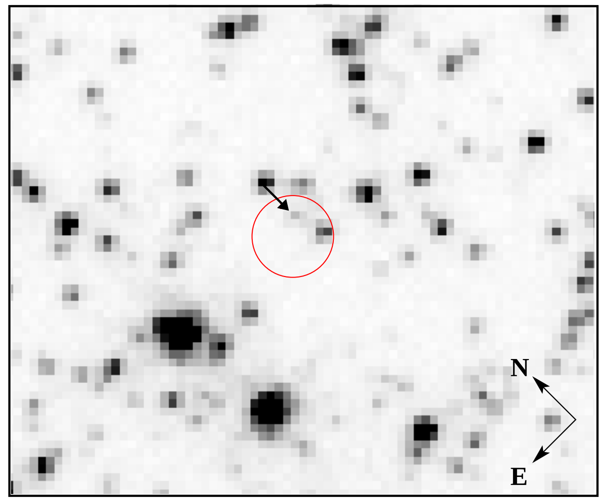

Figure 6. Possible qSXT? The faint blue star indicated appears to be variable. The error circle is the *Chandra* 0.25 arcsec error circle.

cent CVs and X-ray transients would be too faint to detect in such images.

3.1 Probable Dwarf Novae

We looked for variables in M15's core by aligning and subtracting images from different epochs, a technique which highlights stars which vary between the images. In addition to detecting two previously-identified RR Lyrae stars (Ferraro & Paresce 1993), we made a first detection of a probable DN in outburst (Fig. 5a), located just 0.3 arcsec from the cluster core (the optical discovery was reported in Charles, Clarkson & van Zyl 2002). The object appears in WFPC2 U-band images taken in October 1994 with U=17.60, but is undetectable in images obtained at other epochs. Therefore its variability range is >5 magnitudes (the deepest available images have a limiting $U\sim$22.5). This object is revealed here to coincide with one of our faint *Chandra* X-ray sources (source A); its luminosity of 3.3×10^{32} erg s^{-1} is consistent with the brighter CVs identified in other globular clusters. Outbursting DNe often start off hard, but this quickly disappears to be replaced by a much softer component (see e.g. the light curves of SS Cyg in outburst in Kuulkers et al. 2003). However, we have no way of knowing at what stage in its activity cycle it has been observed.

If this object is indeed a DN or an X-ray transient, it is statistically much more likely to be the former than the latter. DNe outburst recurrence times are weeks to months, while X-ray transients usually recur on much longer timescales, typically tens of years. The chances of catching an X-ray transient in outburst on the few occasions on which the HST has observed M15 over the last decade are therefore extremely small. The likelihood that we have a DN rather than an X-ray transient depends also on the relative numbers of these two kinds of object in the core of M15: we expect CVs to be more numerous than X-ray binaries. However, we do note that the (neutron star) transients in globular clusters appear to have shorter recurrence times between outbursts than those in the field (e.g. NGC 6440, Pooley et al. 2002b). With all of those in clusters having been identified as neutron star systems (due to the presence of type I X-ray bursts), they represent a different population from the soft X-ray transients overall, of which only ∼25% contain neutron stars, the rest being black-hole candidates (see e.g. Charles 2001). And since the well-known neutron star SXT Aql X-1 outbursts once or twice per year (e.g. Simon 2002), it is still possible that our source A might not turn out to be a DN.

The second probable DN was found in the error circle of a faint *Chandra* X-ray source 46 arcsec NE of the cluster core (source C in Figure 4, well within the cluster half-mass radius). It appears in outburst with U=20.24 in images obtained in October 1994 (Fig. 5b), but is completely absent in images at other epochs. Again, as we have no constraint on the light curve there is no way of telling whether we caught it at the peak of its outburst, but this magnitude is consistent with the DN outburst range (14 to 21) expected for M15. Of course, it is also possible that this object is an X-ray transient, but using the same arguments as above, we believe it is more likely to be a DN.

Tuairisg et al. (2003) conducted a ground-based search in 1997 for outbursting DNe in M15 but failed to find any. If these sources (A and C) do turn out to be outbursting DNe, then these are amongst the few identified thus far in globular clusters – only a handful of erupting dwarf novae in globular clusters have been confirmed (or suggested as possible outbursting DNe) to date (e.g. M22, Anderson, Cool & King 2003; M5, Kaluzny et al. 1999; 47 Tuc, Edmonds et al. 2003).

3.2 Possible qSXT or DN?

The two sources discussed above are designated 'probable' DNe, because they were obviously variable in the HST images and showed possible outbursts. The object discussed in this section is harder to classify, but is the only blue star near the corresponding *Chandra* X-ray source (Fig. 6). The source in question is source B in Fig. 3 and the possible counterpart is listed in Table 3. As explained in Section 2.2, we calculated its X-ray luminosity based on several models – two for a possible qSXT scenario and one for a possible DN scenario (see Table 4).

In all three cases, the X-ray source has a luminosity of a few $\times 10^{31}$ – 10^{32} erg s^{-1}. The candidate optical counterpart has U=21.8, V=22.54, and appears to show some variability ($\Delta V \sim 0.04$), although this is uncertain – the object is extremely faint and the apparent variability may simply be noise (van Zyl 2002). Its X-ray luminosity is more consistent with that of a CV, although it is also comparable to the faint end of the distribution of qSXTs in GCs (Heinke et al. 2003a). With $U - V = -0.74$, its optical colours are again consistent with those of the DNe SS Cyg and VW Hyi in quiescence (Bailey 1980), similar to that of the NS SXT Cen X-4 in quiescence (McClintock & Remillard 2000), but much bluer than the optically identified qSXT (X5) in 47 Tuc (Edmonds et al. 2002). We therefore suggest that source B is more likely another CV rather than a qSXT.

3.3 The Planetary Nebula K648

The fourth faint X-ray source we detected has a position consistent (within the *Chandra* uncertainties) with one of the rare globular cluster PNe, K648 (Alves, Bond & Livio 2000; hereafter ABL). The source was seen to vary by a factor greater than three during the *Chandra* observations, being observed at $L_X = 0.26$ and 1.0×10^{32}erg s^{-1} in two (#1903, #2413) but undetected in the third (#2412). We can reject that the source is constant at the >98% level. However, its luminosities are within the range 3×10^{29} to 3×10^{32} erg s^{-1} in the 0.4–1.7 keV band found for 13 X-ray-active PNe in the galactic plane using the ROSAT archive by Guerrero, Chu & Gruendl (2000), and for the well-resolved, extended X-ray emission detected with *Chandra* from the PNe BD+30°3639 (Kastner et al. 2000) and NGC 7027 (Kastner, Vrtilek & Soker 2001). Presuming, therefore, that K648 is the source of the X-rays, it would be both the first globular cluster and the most distant X-ray detected PN.

Only four globular cluster PNe are known (see ABL and references therein), but their very existence implies an unusual evolutionary path. The lower the mass of a post-asymptotic giant branch (AGB) remnant, the longer it takes to heat up to temperatures sufficiently hot to ionize the ejected envelope and produce a visible PN, by which time the ejecta may have dissipated. Recent HST studies of white dwarfs in globular clusters indicate that AGB remnant masses are very low (0.50 ± 0.02 M$_\odot$; Renzini et al. 1996; Cool, Piotto & King 1996; Richer et al. 1997). AGB remnants with these masses have evolutionary timescales that are much longer than PNe dissipation timescales (Schönberner 1983; Vassiliadis & Wood 1994). Therefore, we should not expect to observe *any* PNe within globular clusters! Jacoby et al. (1997) have suggested that the globular cluster PNe were therefore formed through close binary interactions.

This certainly applies to the case of K648 since the most massive main sequence stars in M15 should have masses $M \leqslant 0.8$ M$_\odot$, with AGB remnant masses too low to produce PNe. Moreover, ABL measured an anomalously high mass of 0.60 ± 0.02 M$_\odot$ for the central star of K648. They suggest the most likely origin for this higher mass white dwarf is from mass augmentation of its progenitor star (i.e. formation of a blue straggler) due to either mass transfer in or merger of a close binary. They also note that the morphology of K648 is typical of elliptical PNe. This could be accounted for by either nebular ejection during a common envelope phase, or by enhanced rotation of the AGB progenitor (spun up in a binary system or during a stellar merger). In any event, a close binary evolutionary stage is indicated. Unfortunately, ABL were unable to find further evidence that the central star is currently a close binary, as no variability was seen over their 7-day HST/WFPC2 observing campaign.

In principle the X-ray emission from K648 might arise from either diffuse thermal emission from a large cavity inside the nebula, or point-like emission from the PN nucleus (PNN; see Soker & Kastner 2002 for a recent review). However, given its short-term variability (within 19 days), emission from the compact PNN is much more likely. Soker & Kastner (2002) predict that 20–30% of elliptical PNe probably have magnetically active late-type companions in binary systems with $a \lesssim 65$R$_\odot$ and X-ray luminosities of $L \gtrsim 10^{29}$ erg s^{-1}. Indeed, the most likely scenario, in view of K648's X-ray variability, is some sort of binary system, where accretion either directly or indirectly is reponsible (J. Kastner, priv. comm.).

4 CONCLUSIONS

We have identified four faint X-ray sources in the globular cluster M15 using *Chandra*. Three of these are probable DNe (although the possibility that source B is a qSXT cannot be ruled out) and the fourth is associated with the planetary nebula K648. One of the DNe (source A) was initially discovered by applying image subtraction to WFPC2 images of the core of M15 (Charles et al. 2001). In this study we reported on the detection of its X-ray emission. The qSXT/DN (source B) and the other DN (source C) were first detected using WAVDETECT in the *Chandra* images and then associated with optical counterparts in HST images, which allowed us to speculate on their nature. We have also discovered that the PN K648 in M15 (source D) is a variable X-ray source, perhaps indicating a binary nature for the planetary nebula nucleus. If K648 is indeed the source of the X-rays, it is both the first globular cluster and the most distant X-ray detected planetary nebula.

Sources A, B and C (both DNe and the qSXT/DN) had X-ray luminosities ranging from $2.34 \times 10^{31} - 3.66 \times 10^{32}$ erg s^{-1} in the 0.5–7 keV range during these *Chandra* observations. Converting the luminosities to the 0.5–2.5 keV range, one gets a minimum luminosity of 3.11×10^{31} erg s^{-1} and a maximum of 2.27×10^{32} erg s^{-1} – these luminosities place these sources at the bright end of the galactic systems studied by Verbunt et al. (1997). This implies that the majority of DNe in M15 remain to be discovered by more sensitive observations. In order to identify optical counterparts of more *Chandra* sources, we need deeper imaging of M15 (to identify very faint sources like qSXTs or magnetic CVs), as well as observations at different epochs (to catch quiescent DNe and X-ray transients in outburst).

ACKNOWLEDGMENTS

DCH is grateful to the Academy of Finland and to PPARC for financial support. MBD gratefully acknowledges the support of a Swedish Royal Academy of Sciences (KVA) Research Fellowship. The authors thank Craig Heinke, Bruce Balick and Joel Kastner for valuable comments. The authors also wish to thank Jonathan C. McDowell for useful suggestions, Miriam Krauss at the *Chandra* HelpDesk, and the anonymous referee for useful comments. DCH is grateful to Panu Muhli for useful comments. This research has made use of NASA's Astrophysics Data System, SAOImage DS9, developed by Smithsonian Astrophysical Observatory, and of the SIMBAD database operated at CDS, Strasbourg, France. Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the Data Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

REFERENCES

Alves D.R., Bond H.E., Livio M., 2000, AJ, 120, 2044 (ABL)
Anderson J., Cool A.M., King I.R., 2003, ApJ, 597, L137
Aurière M., Le Fevre O., Terzan A., 1984, A&A, 138, 415
Bailey J., 1980, MNRAS, 190, 119
Baumgardt H., Hut P., Makino J., McMillan S., Portegies Zwart S., 2003, ApJ, 582, L21
Bianchi L., Ford H., Bohlin R., de Marchi G., Paresce F., 1995, A&A, 301, 537
Bianchi L., Bohlin R., Catanzaro G., Ford H., Manchado A., 2001, AJ, 122, 1538
Charles P.A., 2001, in Kaper L., van den Heuvel E.P.J, Woudt P.A., eds, Black Holes in Binaries and Galactic Nuclei. Springer, p. 27
Charles P.A., Clarkson W.I., van Zyl L., 2002, NewA, 7, 21
Charles P.A., Jones D.C., Naylor T., 1986, Nature, 323, 417
Cool A.M., Piotto G., King I.R., 1996, ApJ, 468, 655
de Marchi G., Paresce F., 1994, ApJ, 422, 597
de Marchi G., Paresce F., 1996, ApJ, 467, 658
Di Stefano R., Rappaport S., 1994, ApJ, 423, 274
Djorgovski S., King I.R., 1986, ApJ, 305, L61
Dotani T. et al., 1990, Nature, 347, 534
Durrell P.R., Harris W.E., 1993, AJ, 105, 1420
Edmonds P.D., Heinke C.O., Grindlay J.E., Gilliland R.L., 2002, ApJ, 564, L17
Edmonds P.D., Gilliland R.L., Heinke C.O., Grindlay J.E., 2003, ApJ, 596, 1997
Ferraro F.R., Paresce F., 1993, AJ, 106, 154
Gebhardt K., Pryor C., Williams T.B., Hesser J.E., 1992, BAAS, 24, 1188
Gerssen J., van der Marel R.P., Gebhardt K., Guhathakurta P., Peterson R.C., Pryor C., 2002, AJ, 124, 3270
Gerssen J., van der Marel R.P., Gebhardt K., Guhathakurta P., Peterson R.C., Pryor C., 2003, AJ, 125, 376
Giacconi R., et al., 2001, ApJ, 551, 624
Grabhorn R.P., Cohn H.N., Lugger P.M., Murphy B.W., 1992, ApJ, 392, 86 Guerrero M.A., Chu Y.-H., Gruendl R.A., 2000, ApJS, 129, 295
Guerrero M.A., Chu Y.-H., Gruendl R.A., Williams R.M., Kaler J.B., 2001, ApJ, 553, L55
Guhathakurta P., Yanny B., Schneider D.P., Bahcall J.N., 1996, AJ, 111, 267
Hakala, P.J., Charles, P.A., Johnston, H.M., Verbunt, F., 1997, MNRAS, 285, 693
Harris W.E,. 1996, AJ, 112, 1487
Heinke C.O., Edmonds P.D., Grindlay J.E., 2001, ApJ, 562, 363
Heinke C.O., Edmonds P.D., Grindlay J.E., Lloyd D.A., Cohn H.N. & Lugger P.M., 2003b, ApJ, 590, 809
Heinke C.O., Grindlay J.E., Lugger P.M., Cohn H.N., Edmonds P.D., Lloyd D.A. & Cool A.M., 2003a, ApJ, 598, 501
Heinke C.O., et al., 2004, submitted to ApJ
Ho L.C., Terashima Y., Okajima T., 2003, ApJ, 587, L35
Homer L., Anderson S.F., Margon B., Downes R.A., Deutsch E.W., 2002, AJ, 123, 3255
Ilovaisky S.A., Aurière M., Koch-Miramond L., Chevalier C., Cordoni J.-P., Crowe R.A., 1993, A&A, 270, 139
Ioannou Z., Naylor T., Smale A.P., Charles P.A., Mukai K., 2002, A&A, 382, 130
Jacoby G.H., et al., 1997, AJ, 114, 2611
Kaluzny J., Thompson I., Krzeminski W., Pych W., 1999, A&A, 350, 469
Kastner J.H., Soker N., Vrtilek S.D., Dgani R., 2000, ApJL, 545, 57
Kastner J.H., Vrtilek S.D., Soker N., 2001, ApJL, 550, 189
Kulkarni S.R., Anderson S.B., 1996, IAUS, 174, 181
Kuulkers E., Norton A., Schwope A., Warner B., 2003, astrop-ph/0302351
Lauer T.R., et al. 1991, ApJ, 369, L45
McClintock J.E., Remillard R.A., 2000, ApJ, 531, 956
McNamara B.J., Harrison T.E., Baumgardt H., 2004, ApJ, 602, 264
Murray S.S. et al., 1997, Proc SPIE, 3114, 11
Newell B., O'Neill E.J., 1978, ApJS, 37, 27
Peterson R.C., Seitzer P., Cudworth K.M., 1989, ApJ, 347, 251
Phinney F.S. 1996, in Milone E.F., Mermilliod J.-C., eds, ASP Conf. Ser. Vol. 90, The Origins, Evolution, and Destinies of Binary Stars in Clusters. Astron. Soc. Pac., San Francisco, p.163
Pooley D., et al. 2002a, ApJ, 569, 405
Pooley D., et al. 2002b, ApJ, 573, 184
Renzini A., et al., 1996, ApJ, 465, L23
Richer H.B., et al., 1997, ApJ, 484, 741
Rutledge R.E., Bildsten L., Brown E.F., Pavlov G.G., Zavlin V.E., 2001, ApJ, 559, 1054
Schönberner D., 1983, ApJ, 272, 708
Simon V., 2002, A&A, 381, 151
Soker N., Kastner J.H., 2002, ApJ, 570, 245
Sosin C., King I.R., 1997, AJ, 113, 1328
Swank J.H., Boldt E.A., Holt S.S., Rothschild R.E., Serlemitsos P.J., 1978, ApJ, 226, L133
Tuairisg S.Ó., Butler R.F., Shearer A., Redfern R.M., Butler D. & Penny A., 2003, MNRAS, 345, 960
van der Marel R.P., Gerssen J., Guhathakurta P., Peterson R.C., Gebhardt K., 2002, AJ, 124, 3255
van Zyl L., 2002, PhD thesis, Univ. Oxford
Vassiliadis E., Wood P.R., 1994, ApJS, 92, 125
Verbunt F., Bunk W.H., Ritter H., Pfeffermann E., 1997, A&A, 327, 602
Verbunt F., Lewin W.H.G., 2004, to appear in Lewin

W.H.G., van der Klis M., eds, Compact Stellar X-ray Sources. Cambridge University Press. astro-ph/0404136
Verbunt F., Wheatley P.J., Mattei J.A., 1999, A&A, 346, 146
Warner B., 1995, Cataclysmic Variable Stars, Cambridge Univ. Press, Cambridge
White N.E., Angelini L., 2001, ApJ, 561, L101
Wijnands R., Heinke C.O., Grindlay J.E., 2002, ApJ, 572, 1002