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THE DISCOVERY OF A SECOND LUMINOUS LOW-MASS X-RAY BINARY IN THE GLOBULAR CLUSTER M15

NICHOLAS E. WHITE AND LORELLA ANGELINI[1]
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771;
nwhite@lheapop.gsfc.nasa.gov, angelini@davide.gsfc.nasa.gov

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ABSTRACT

We report an observation by the *Chandra X-Ray Observatory* of 4U 2127+119, the X-ray source identified with the globular cluster M15. The *Chandra* observation reveals that 4U 2127+119 is in fact two bright sources, separated by 2″.7. One source is associated with AC 211, the previously identified optical counterpart to 4U 2127+119, a low-mass X-ray binary (LMXB). The second source, M15 X-2, is coincident with a 19th *U*-magnitude blue star that is 3″.3 from the cluster core. The *Chandra* count rate of M15 X-2 is 2.5 times higher than that of AC 211. Prior to the 0″.5 imaging capability of *Chandra*, the presence of two so closely separated bright sources would not have been resolved. The optical counterpart, X-ray luminosity, and spectrum of M15 X-2 are consistent with it also being an LMXB system. This is the first time that two LMXBs have been seen to be simultaneously active in a globular cluster. The discovery of a second active LMXB in M15 solves a long-standing puzzle where the properties of AC 211 appear consistent with it being dominated by an extended accretion disk corona, and yet 4U 2127+119 also shows luminous X-ray bursts requiring that the neutron star be directly visible. The resolution of 4U 2127+119 into two sources suggests that the X-ray bursts did not come from AC 211 but rather from M15 X-2. We discuss the implications of this discovery for understanding the origin and evolution of LMXBs in globular clusters as well as X-ray observations of globular clusters in nearby galaxies.

Subject headings: globular clusters: individual (M15) — stars: individual (AC 211) — X-rays: binaries — X-rays: individual (4U 2127+119)

On-line material: color figure

1. INTRODUCTION

The X-ray source 4U 2127+119 associated with the globular cluster (GC) M15 was the first to be identified with an individual star within a GC. The identification with the $V \sim 15$ star AC 211 was made by Aurière, Le Fèvre, & Terzan (1984) using the *Einstein* High Resolution Imager (HRI) position (Hertz & Grindlay 1983, hereafter HG83). The identification of AC 211 with 4U 2127+119 was further strengthened from a spectroscopic study by Charles, Jones, & Naylor (1986), which showed characteristic signatures of a low-mass X-ray binary (LMXB). AC 211 was found to have a modulation of 8.5 hr in the optical (Ilovaisky et al. 1987), which was then subsequently seen in the X-ray flux of 4U 2127+119 (Hertz 1987, hereafter H87). Further observations and a more detailed analysis by Ilovaisky et al. (1993, hereafter I93) revealed the true orbital period of AC 211 to be 17.1 hr, twice the originally proposed value.

AC 211 is optically one of the brightest known LMXBs and yet has a relatively low X-ray luminosity of $\sim 10^{36}$ ergs s^{-1}. The high optical–to–X-ray luminosity ratio suggests that a very luminous central X-ray source is hidden behind the accretion disk, with X-ray emission scattered into our line of sight via an accretion disk corona (ADC; Aurière et al. 1984; H87; Naylor et al. 1988). An ADC is also required to explain the X-ray orbital modulation (H87; I93). This neat picture was put into doubt when a luminous X-ray burst from 4U 2127+119 was recorded by the *Ginga* satellite in 1988 (Dotani et al. 1990). This burst was long-lived (>150 s), with a precursor event ~6 s before the longer event. The peak luminosity of the burst was above 10^{38} ergs s^{-1}, with an expansion of the neutron star photosphere (Dotani et al. 1990; van Paradijs et al. 1990), meaning that the neutron star surface had been directly observed. A dip in the continuum flux between the precursor and the main burst seemed to tie this event to the X-ray source in M15. A second X-ray burst from 4U 2127+119 in 2000 September, with similar properties to the first, has been reported by Smale (2001) using the *Rossi X-Ray Timing Explorer* (*RXTE*). The observation of X-ray bursts from 4U 2127+119 has been hard to reconcile with the idea that the central source is hidden behind an ADC. In this Letter, we report the results of a *Chandra* High-Energy Transmission Grating (HETG) observation that solves the puzzling behavior of 4U 2127+119.

2. RESULTS

4U 2127+119 was observed with the *Chandra* HETG grating in conjunction with the ACIS-S CCD array on 2000 August 24, for a total exposure of order 21,000 s. The event file was gain-corrected, using the calibration released on 2001 June 7 (Caldb 2.6), screened for bad pixels and good time intervals. Streaks caused by flaws in the serial readout of the CCDs were also removed. A CCD grade histogram shows a large fraction of grade seven events, indicating considerable pileup. The zero-order image from the cleaned event file using all grades is shown in Figure 1*a*—two bright sources separated by 2″.7 can be seen. To determine the best source positions, we used data from all grades and determined the peak of the distribution in a box of 3 × 3 pixels. The positions of the two sources are, for M15 X-1, R.A. (J2000) = $21^h29^m58^s.25$, decl. (J2000) = $+12°10'02''.9$, and for M15 X-2, R.A. (J2000) = $21^h29^m58^s.06$, decl. (J2000) = $+12°10'02''.6$.

[1] Also with the Universities Space Research Association.

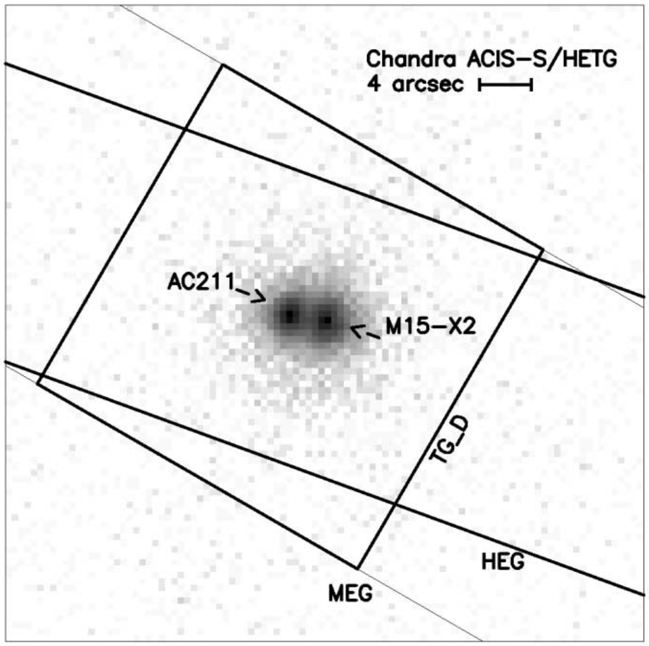

FIG. 1*a*

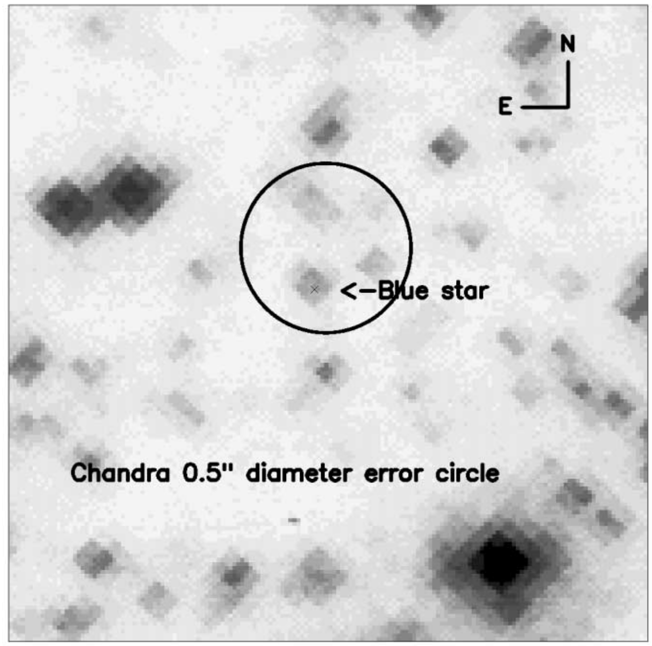

FIG. 1*b*

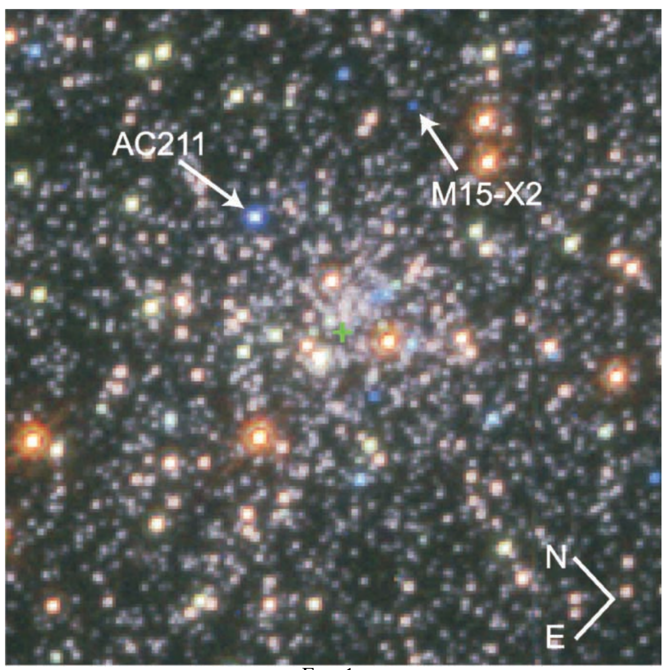

FIG. 1*c*

FIG. 1.—(*a*) ACIS-S/HETG *Chandra* zero-order image of M15 showing the two sources. The tick lines across the image mark the dispersion directions for the MEG and the HEG, which are separated by 10°. The dispersion direction for the MEG and HEG with respect to M15 X-2 is offset by ∼5 pixels in the *x*-direction and ∼1 pixel in the *y*-direction. The perpendicular line marked with TG_D (shown only for the MEG) indicates the cross-dispersion direction. The MEG count histogram (shown in Fig. 2) is accumulated with respect to that dimension. (*b*) Enlargement of the $U+B+V$ *HST* image taken from Guhathakurta et al. (1996) centered on the *Chandra* position of M15 X-2. The "blue star" corresponds to star 590 in De Marchi & Paresce (1994). (*c*) True color ($U+B+V$) *HST* image of the central 9″ × 9″ region of M15 reproduced from Guhathakurta et al. (1996). The positions of AC 211 and the ∼19th *U*-magnitude blue star identified with M15 X-2 are indicated. The green cross shows the center of M15 (Guhathakurta et al. 1996). Note that the orientation is different from (*b*).

Accurate positions for AC 211 were reported by Kulkarni et al. (1990) based on radio measurements and by Geffert et al. (1994) based on meridian circle measurements and the Positions and Proper Motions (PPM) catalog. The separation between the radio-meridian and radio-PPM positions range between 0″.2 and 0″.27. M15 X-1 is within 0″.9 of the Kulkarni position of R.A. (J2000) = $21^h29^m58^s.31$, decl. (J2000) = +12°10′02″.9 for AC 211. This is within the uncertainty of the *Chandra* attitude solution. To obtain the best coordinates for the second source, we then corrected the image reference coordinates so as to give the Kulkarni position for AC 211. This corresponded to a shift of 0″.94 in right ascension and 0″.03 in declination and gives a revised position for M15 X-2 of R.A. (J2000) = $21^h29^m58^s.13$, decl. (J2000) = +12°10′02″.6. Since the M15 X-2 source shows pileup, which could effect the centroiding, we adopted a conservative positional uncertainty of 0″.5 diameter, based on the

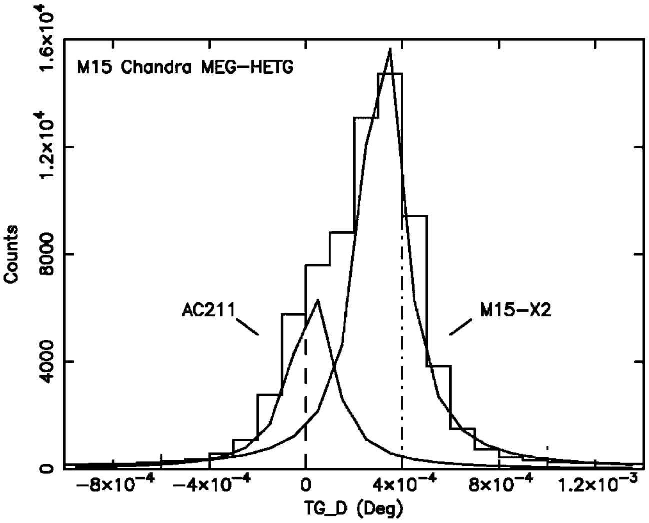

FIG. 2.—Histogram of the MEG cross-dispersion direction (TG_D) with respect to AC 211, shown with the best Lorenzian fits to model the two sources. The dashed and dash-dotted lines mark the regions selected to extract the spectra for AC 211 and M15 X-2. These are taken from the tail of the distribution to minimize contamination. The *x*-axis boundary of the M15 X-2 region are shifted relative to the AC 211 position to give an overall view from where the spectra were taken with respect to TG_D.

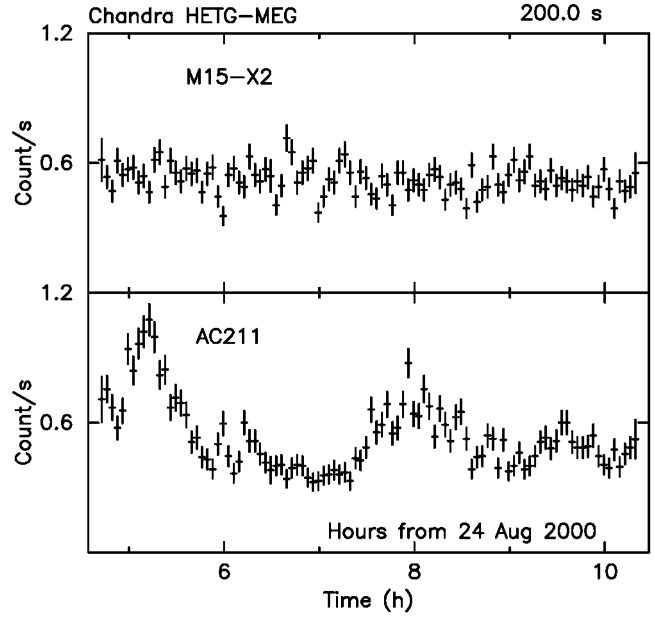

FIG. 3.—The 0.3–10 keV light curves of the two sources using the same extraction regions used for the spectra. These are not corrected for the extraction region used, and the count rates must be scaled up by ~2 and ~5.5 for AC 211 and M15 X-2, respectively. The *Chandra* observation covers from phase 0.6 to 0.9 of the AC 211 orbit, using the ephemeris given by I93.

size of 1 pixel in the *Chandra* CCD. We designate the new source *CXO J212958.1+121002* although continue to refer to it here by the more concise name M15 X-2.

To search for an optical counterpart we used the *Hubble Space Telescope* (*HST*) images published in Guhathakurta et al. (1996). In Figure 1*b*, we overlay the 0".5 diameter circle centered on the M15 X-2 position. Near the center of the error circle is a faint blue star. De Marchi & Paresce (1994) have cataloged the M15 stars seen in earlier *HST* images, and in their list the faint blue star is number 590, a star with an equivalent *U* magnitude of 18.6. Star 590 is 0".13 from the *Chandra* position centroid for M15 X-2. In Figure 1*c*, we indicate on the original color ($U+B+V$) image from Guhathakurta et al. (1996) the positions of AC 211 and the blue optical counterpart to M15 X-2. The new source M15 X-2 is 3".4 from the center of M15 (the green cross in Fig. 1*c*). A faint blue optical counterpart is the classic signature of an LMXB (e.g., van Paradijs & McClintock 1996), and it seems very likely that this is the counterpart to the X-ray source.

The High-Energy Grating (HEG) and Medium-Energy Grating (MEG) dispersion directions and the two source positions relative to the *Chandra* roll angle are such that the dispersed grating spectra of the two sources overlap (Fig. 1*a*). Because of the 10° difference in dispersion angle between the two gratings, the overlap is more severe in the HEG compared to the MEG. To extract the spectra of the two sources, histograms for the MEG and HEG along the cross-dispersion dimension were fitted with Lorenzian models. The Lorenzian width was fixed at the value obtained from a similar histogram of a point source. The width of the HEG histogram is consistent with a single source, while the MEG requires a double Lorenzian fit (see Fig. 2). We concentrated on the MEG spectrum because it is the best separated. The relative normalization between the two Lorenzian models for the MEG histogram is ~2.5, with M15 X-2 the brighter source. This is consistent with the fact that most of the zero-order grade seven events, caused by pileup, are coincident with M15 X-2. MEG spectra and light curves were accumulated by selecting regions across the cross-dispersed direction, where the contamination was a minimum (Fig. 2). The percentage of counts from each source included in the extracted spectra are ~50% for AC 211 and ~20% for M15 X-2.

The light curves of the two sources exhibit quite different variability, confirming that the cross-contamination is minimal (Fig. 3). The X-ray flux of AC 211 is highly variable across the observation, typical of that reported in the past (see, e.g., Ilovaisky et al. 1987). Using the ephemeris given in I93, the observation began at orbital phase 0.6 and ended at 0.9, just prior to the predicted time of the partial X-ray eclipse. In contrast, M15 X-2 shows little variability, with just a very slight decline of a few percent across the observation. A power spectrum analysis of each source for a frequency range from 4.8×10^{-5} to 0.196 Hz (twice the CCD readout) did not reveal any periodic signal with a peak-to-mean amplitude greater than 10%, neither from AC 211 nor from M15 X-2. There was some quasi-periodic activity on a timescale of ~2.7 hr from AC 211 (which can be seen in the light curve) and a 700 s modulation in both sources caused by a deliberate wobble in the spacecraft pointing to reduce pileup in the CCD.

The spectra of the two sources, separated by orders, were extracted using the TGEXTRACT routine included in CIAO v.2.1. For each source, the first-order positive and negative MEG spectra were added together and grouped with a minimum of 20 counts bin^{-1}. The MEG spectra of the two sources are shown in Figure 4. The X-ray spectrum of AC 211 is harder than that of M15 X-2. The new source, M15 X-2, can be fitted with a single power law with an energy index of 1.72 ± 0.06 and an absorption of less than 3.4×10^{20} H cm^{-2}. Fixing the overall absorption at the expected value to M15 equivalent to a hydrogen column density of 6.7×10^{20} H cm^{-2} still gives an acceptable fit (reduced χ^2 of 1.14), with a power-law index of 1.89 ± 0.05. In contrast, AC 211 is not well fitted by a single-component power-law or thermal bremsstrahlung model. A power-law model gives a relatively hard photon index of 1.2

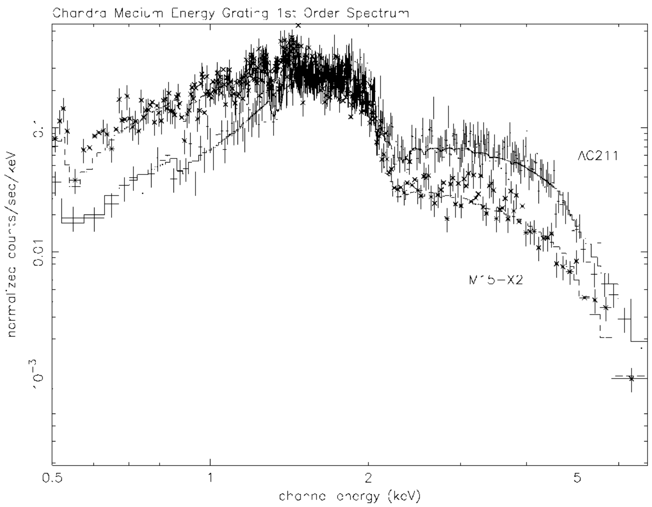

FIG. 4.—MEG spectra for M15 X-2 (*dashed line*) and AC 211 (*solid line*), with the best-fit models shown as histograms. The overall normalization is not corrected for the extraction region used. The correction factors for AC 211 and M15 X-2 are ∼2 and ∼5.5, respectively. [*See the electronic edition of the Journal for a color version of this figure*.]

with an absorption of 6×10^{21} H cm^{-2} but with a reduced χ^2 of 1.75. A partial covering model, one of several components used by Sidoli, Parmar, & Oosterbroek (2000, hereafter SPO) to fit the broader band *BeppoSAX* integrated spectrum of both sources, does provide an acceptable fit. This gives a power-law index of 2.1, a covering fraction of 0.87 with an absorption of 2×10^{22} H cm^{-2}, and an interstellar absorption of 1.6×10^{21} H cm^{-2}. Fixing the absorption at the expected interstellar value for M15 gives a power-law index of 2.0 ± 0.1, a covering fraction of 0.92 ± 0.01, and an intrinsic absorption of $(2.05 \pm 0.15) \times 10^{22}$ H cm^{-2}. This is higher than the covering fraction of 0.64 reported by SPO for the combined spectrum of both sources.

Using the expected point-spread function for a single source, we corrected for the partial extraction of the two sources. The 0.5–7.0 keV flux from AC 211 is 7×10^{-11} ergs cm^{-2} s^{-1}, corresponding to 9×10^{35} ergs s^{-1} using a distance of 10.3 kpc to M15 (Harris 1996). For the new source, M15 X-2, the 0.5–7.0 keV flux is 1.1×10^{-10} ergs cm^{-2} s^{-1}, corresponding to 1.4×10^{36} ergs s^{-1}.

The second burst from 4U 2127+119 reported by Smale (2001) occurred 1 month after the *Chandra* observation—indicating that the burst source was still active. The *RXTE* all-sky monitor (ASM) light curve of M15 does not show any transient outburst or unusual behavior around the time of the *Chandra* and *RXTE* observations. The 5 yr long ASM light curve is relatively steady, suggesting that the source is long-lived and not highly variable. There are short outbursts in the ASM every ∼365 days, but they occur when the source passes close to the Sun and are probably caused by Sun glint on the detector collimator upsetting the solutions. It is interesting to note that the original $\pm 1''$ position from the *Einstein* HRI (HG83) lies closer to that of M15 X-2 than AC 211 and that the search for the optical counterpart by Aurière et al. (1984) used a circle of 3''.3, the standard HRI 90% confidence error circle. The *ROSAT* HRI archival images from the mid-1990s appear somewhat elongated in the east-west direction, suggesting that the M15 X-2 source may have been present.

3. DISCUSSION

This is the first time that two LMXBs have been seen to be simultaneously active in a GC associated with our Galaxy. The separation of ∼2''.7 is less than the resolution of previous X-ray telescopes. It is only with the superb 0''.5 quality imaging of the *Chandra X-Ray Observatory* that 4U 2127+119 can be resolved into two sources. The new X-ray source M15 X-2 is 2.5 times brighter than AC 211 and associated with a faint 19th *U*-magnitude blue star, characteristic of an LMXB. It is 3''.4 from the center of M15 (Fig. 1*c*). The discovery of a second active LMXB in M15 provides a simple explanation for the apparently schizophrenic properties of 4U 2127+117—M15 X-2 is the source of the X-ray bursts, not the ADC-dominated AC 211. The presence of a second source also resolves why the spectrum of 4U 2127+119 is unusually complex (SPO). The X-ray continuum spectrum of M15 X-2 is a power law with a photon index of ∼1.9 and a luminosity of $\sim 10^{36}$ ergs s^{-1}, both typical of LMXBs that show X-ray bursts. *RXTE* and archival data suggests that the second source may have been present over the entire past 20 yr. This confirms earlier suspicions that two sources could explain the conflicting properties of 4U 2127+117 (Grindlay 1992, 1993; Charles, Clarkson, & van Zyl 2001). The ADC model to explain the X-ray and optical properties of AC 211 is now self-consistent. The X-ray spectrum of AC 211 alone is harder and resembles that of the classic ADC source 4U 1822−371 (White et al. 1981; White, Kallman, & Angelini 1997). The average X-ray luminosity of AC 211 is really one-third lower than previously thought. This both increases the amplitude of the orbital modulation and reduces the luminosity, strengthening the analogy with 4U 1822−371 (White & Holt 1982).

The ratio of LMXBs to stellar mass is more than 2 orders of magnitude higher for GCs than it is for the rest of the Galaxy (Clark 1975). This overabundance of LMXBs led Fabian, Pringle, & Rees (1975) to propose that the LMXBs in GCs are formed via tidal capture of neutron stars in close encounters with main-sequence or giant stars, a mechanism that operates efficiently in the high stellar density found in GCs. Hut, Murphy, & Verbunt (1991, hereafter HMV) discuss the probability of finding one or more LMXBs in any particular GC. This depends strongly on how many neutron stars stay in the cluster after they are born and the lifetime of the LMXBs. In general, these calculations suggest that more than one LMXB should be found in a GC. The fact that so few LMXBs in GCs are observed has required either short lifetimes (HMV) or larger fractions of neutron stars ejected from the GC (Verbunt & Hut 1987). The large number of millisecond radio pulsars found in GCs, thought to be the remains of LMXB systems, also points to many LMXBs having been active in the past (see HMV). *Chandra* observations of other GCs have revealed faint sources, some of which may be transient LMXBs in quiescence, suggesting that there are more LMXBs in a single GC (e.g., Grindlay et al. 2001). This discovery of two active LMXBs in M15 moves the observations in the right direction with respect to the theory and number of radio pulsars, especially given the small number of GC systems in our Galaxy with active LMXBs.

Chandra X-ray observations of nearby galaxies have identified many point X-ray sources with GCs (Sarazin, Irwin, & Bregman 2001; Angelini, Loewenstein, & Mushotzky 2001). Many of these GC sources have a luminosity above the Eddington limit for accretion onto a neutron star. Angelini et al. (2001) have suggested that some of these high-luminosity systems may be due to multiple LMXBs being active in some GC systems. The discovery of two LMXBs active at the same time in M15 adds weight to that argument.

We recognize the critical contribution of Cynthia Hess, the original principle investigator for this observation. We thank Ian George and Roy Kilgard for help with the grating analysis, Brian Yanny for providing an *HST* image of M15, Phil Charles for discussions on the optical counterpart, Robin Corbet for advice on the *RXTE* ASM, and Josh Grindlay, Peter Edmonds, and Sergio Ilovaisky for comments on the manuscript. This research made used of data extracted from the HEASARC, MAST, and CDS.

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