X-RAY BINARIES IN GLOBULAR CLUSTERS

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ABSTRACT: X-ray binaries in globular clusters provide a powerful tool for the exploration of the evolution of compact binaries and their host globular clusters. Recent x-ray and optical studies of these systems have yielded long-sought binary periods and fundamental properties for two sources (in NGC 6624 and M 15). It appears that tidal capture formation of compact binaries in globular clusters can proceed by several different routes and lead to exotic systems such as the white dwarf-neutron star binary with an 11-minute period recently discovered in NGC 6624. Combined with previously reported long-term periods for several globular cluster (and field) x-ray sources, this suggests again that many of these systems may in fact be hierarchical triple systems. The prospects for forming these in the dense cores of clusters undergoing core collapse is discussed, and searches for color gradients in the cores of globular clusters showing cusps in their central surface brightness distribution are presented. A program to test for the high central density of binaries (and triples) expected in cusp clusters by searching for diffuse line emission from their constituent cataclysmic variables is briefly described. Finally, the case for globular cluster disruption and the formation of galactic x-ray burst source is reviewed in light of recent developments.

1. INTRODUCTION

The study of compact x-ray sources in globular clusters continues to provide important constraints on both the nature and physics of short-period (and ultra-short period) binaries containing neutron stars, the physics of accretion onto these objects, and the evolution of globular clusters themselves. In this review, we shall summarize a number of developments which bear on each of these topics. We shall build on the material presented in our recent reviews of these problems (Grindlay 1985a,b, 1986, 1987) as well as the recent discoveries, both observational and theoretical, which have triggered new developments in the field.

We begin with an update on the process of tidal capture for the formation of binaries in globular clusters since several recent

J. E. Grindlay and A. G. Davis Philip (eds.),
The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, 347–366.

calculations have indicated this is more complex than previously recognized. The tidal capture of a triple companion by a compact binary is then briefly discussed. We then turn to the recent discoveries of the binary periods for the first two globular cluster x-ray sources: those in NGC 6624 and in M 15. These apparently disparate systems, with periods of 11.4 minutes and 8.5 hours (respectively), may in fact be linked in a common evolutionary scenario which we outline. In an attempt to identify more globular cluster x-ray binaries, both low and high luminosity, we are carrying out extensive optical imaging and spectroscopic studies. A status report on this work is briefly described. Similarly, a status report on our ongoing study of the central surface brightness of clusters is presented. We describe preliminary results on the colors of the cusps in NGC 6624 and M 15 which suggest they are not significantly bluer than their surrounding clusters, and we present plans for follow-up studies with narrow-band imaging to search for diffuse line emission from the cataclysmic variables (CVs) expected to have been formed. Finally, we return to our often-stated hypothesis that the galactic bulge x-ray sources may have been created in globular clusters since disrupted and consider this, vs. the alternative scenario of binary ejection, in light of the work discussed here and in progress. Our conclusions and directions for future work follow.

2. TIDAL CAPTURE FORMATION

The formation of compact binaries in globular clusters can proceed by at least two different mechanisms: three-body interactions or tidal capture (see Cohn 1987). Since the two-body tidal capture process must become important as the stellar density in a cluster core increases (e.g. during core collapse) before the three-body mechanism sets in, we shall focus on the tidal capture process. It can, or should, be operative for both the formation of binaries and "higher order binaries", or hierarchical triples (cf. Grindlay 1985a,b, 1986). We note, however, that three body interactions may be especially important for the formation of binaries containing degenerate components if the central densities (e.g. in cluster core collapse) are high and are dominated by relatively massive degenerate stars (Lee 1987).

2.1 Binaries

The approximate maximum closest approach distance for tidal capture was found to be ~ 3 stellar radii by dimensional arguments in the original discussion of Fabian et al. (1975) and in the detailed calculations of Press and Teukolsky (1977). Recently, these calculations have been extended, and a (small) numerical error corrected, by Lee and Ostriker (1986). New calculations by McMillan, McDermott, and Taam (1987) and by Antia et al. (1987) have also included a more realistic treatment of the effects on the structure of the interacting stars by the tidal dissipation of energy in their encounter. In spite of these improvements, the maximum tidal capture impact parameter is still found to be approximately 3.3 stellar radii (McMillan et al. 1987), so that the various inferences drawn for the number of neutron stars required in globular clusters to produce the numbers of sources observed (e.g. Lightman and Grindlay 1982, Grindlay 1987) are essentially unaffected by the new capture cross section results, though they are affected by other considerations (cf. sections 3.3, 5, and 7 below).

The new results for the effects of tidal heating during the tidal capture process (e.g McMillan et al. 1987) have shown that the captured star on which the tidal bulge is raised will expand and be heated significantly by the dissipative effects of the encounter. This means that for tidal capture between two normal (i.e. non-degenerate) stars, the expansion of each could lead to a common envelope binary and coalescence of the binary. (We note that tidal capture of main-sequence stars by cluster giants may thus be even more effective than main-sequence star - white dwarf collisions in creating the centrally-concentrated faint blue horizontal-branch star systems discussed by Bailyn et al. (1987)). Tidal capture binaries thus coalesced would therefore be unavailable to interact with other stars in the cluster, suggesting that such binaries formed from main-sequence (or perhaps also giant) stars in the cluster may not be (McMillan 1986) the effective sources of dynamical heating previously suspected (Ostriker 1985). In this case, cluster core collapse might proceed to still higher densities and be halted only by the formation then of three-body binaries. However, tidal capture binaries involving a white dwarf or a neutron star as one member of the pair are probably not so affected (Taam 1986), since the expansion of the radius of the captured star (main sequence or giant) is then not great enough to engulf the degenerate companion causing it to spiral in. Tidal capture would thus remain the most efficient source (at intermediate densities) of binary formation for compact x-ray sources involving either white dwarfs (Hertz and Grindlay 1983, Hertz and Wood 1985) or neutron stars (Lightman and Grindlay 1982).

2.2 Triples

A compact binary (however created) should be an effective target for the tidal capture of a third star, as suggested by Grindlay (1985a,b, 1986). This process has now been partially calculated by McMillan (1986) and is being studied in greater detail by Bailyn, Grindlay and McMillan (1987). Preliminary results suggest that at least 3 % of the collisions of a third star with a compact binary at a minimum separation of at least three times the binary semi-major axis result in a stable hierarchical triple system. Such systems must have a ratio of inner to outer semi-major axes of at least ~ 3 for dynamical stability. In this case, and in fact out to separation ratios of ~ 30, the outer binary is still "hard" in the frame of the globular cluster (i.e. its orbital velocity exceeds the central velocity dispersion of the cluster). In actual fact, separation ratios of ~ 10 are probably not exceeded since this is also limited by the tidal capture cross

https://doi.org/10.1017/S0074180900042595 Published online by Cambridge University Press

section, or radius, of the third star. Thus the intrinsically stable hierarchical triples created by tidal capture in a dense globular cluster core are not disrupted as "soft" cluster binaries.

3. STUDIES OF COMPACT BINARIES IN GLOBULAR CLUSTERS

The study of x-ray binaries in globular clusters has taken a great quantum leap forward with the recent discoveries of the first binary periods for members of this class of objects. An x-ray periodicity of 11.4 minutes was found (Stella, Priedhorsky and White 1986) for the archetype globular cluster source 4U1820-30 in NGC 6624 using the EXOSAT x-ray observatory. Within two months, an 8.5 hour period was announced from the optical photometry (Ilovaisky et al. 1986) and absorption line spectrum (Naylor et al. 1986) of the proposed (Aurière et al. 1984) optical counterpart, AC211, for the bright x-ray source 4U2127+12 in M 15. The period and the optical counterpart, the first for any globular cluster source, was confirmed by a detection of the periodicity in archived x-ray data for this source (Hertz 1986). We have incorporated these discoveries into a model (Bailyn and Grindlay 1987a; hereafter referred to as BG) for the formation and evolution of a class of tidal capture x-ray binaries in globular clusters which is summarized below (section 3.3).

3.1 The 11 Minute Binary in NGC 6624

The 11.4 minute period discovered for the bright x-ray source 4U1820-30 in NGC 6624 (Stella et al. 1986) was also found in archival data extending over the past 10 years and showing that the period remains constant to within ~ 0.1 msec per year (Morgan et al. 1986). This greatly strengthened the original claim of Stella et al. (1986) that the period must be orbital, not rotational (which, given the large mass transfer rate inferred from the x- ray luminosity of $\sim 5 \times 10^{37}$ erg/sec, would lead to a much larger rate of change of period as the neutron star spins up). The ultra-short binary period, which is shorter than any binary period known, requires the mass- losing star be a degenerate dwarf to fit in so small an orbit. A helium white dwarf of mass 0.06 $M_\odot$ orbiting a 1.4 $M_\odot$ neutron star could supply the necessary mass transfer by Roche lobe overflow at a rate of 1×10^{-8} $M_\odot$/yr (as required by the x-ray luminosity) by virtue of the angular momentum losses expected from the gravitational radiation from such a system (Stella et al. 1986, BG).

Such a relatively well constrained system begs for an explanation. Verbunt (1986) suggested that it is the result of a collision of a red giant (containing a white dwarf core) and a neutron star in the cluster, but BG show that this is relatively less likely than an alternative mechanism (described below). Red giant collisions may also be subject to a possible mass transfer instability which would cause the white dwarf and neutron star to coalesce. The system parameters imply that the x-ray lifetime for the system in its current (second) mass transfer phase (cf. section 3.3 below) has been relatively short (~ 10^7 years). This suggests that the total number of such systems in a dormant (i.e. not transferring mass) state must be large and that the corresponding number of capture binaries involving neutron stars is also large.

We note also that the previously discovered long-term period of 176 days for the source (Priedhorsky and Terrell 1984) may be due to a hierarchical triple companion (cf. Grindlay 1986). If the 176 day period is due to precession of the 11.4 minute orbit, an outer orbit with a period of ~ 15 hours is required (cf. Bailyn and Grindlay 1987b). However, as discussed in the evolutionary scenario of BG, the binary period for 4U1820-30 may have been originally ~ 9 hours in which case a ~ 15 hour triple period would not be stable; the resolution may be (Bailyn 1987) that the longer (i.e. ≥ 40 hour) periods required for stability of the hierarchical triple companion to a ~ 9 hour binary could still give rise to the 176 day precession period when the binary has shrunk to 11.4 minutes if the system is not co-planar (as was assumed in Bailyn and Grindlay 1987b). Indeed, non-coplanarity would be expected for a tidally captured triple companion.

3.2 The 8.5 Hour Binary in M 15: AC211

As mentioned above, the x-ray source 4U2127+12 in M 15 has been found to have an ~ 8.5 hour period in both its optical and x-ray flux. Although a best estimate period of 8.53 hours is given by Ilovaisky et al., the period is still not well determined due to aliasing with finite observing time windows. In any case, the ~ 8.5 hour period is almost certainly the orbital period as it is appropriate to a 0.8 $M_\odot$ terminal age main-sequence star in an orbit such that it overflows its Roche lobe onto a 1.2 $M_\odot$ neutron star (BG). These parameters are, in turn, those expected by our evolutionary model which can account for both the 8.5 hour and 11.4 minute binaries.

It is likely (e.g. Grindlay 1986) that 4U2127+12 is much more luminous than suggested by its relatively modest x-ray flux (~ 5-10 UFU), which itself would indicate a luminosity of ~ $10^{36.4}$ erg/sec. Rather, its luminosity is probably in excess of 10^{38} erg/sec and the source is surrounded by a so-called accretion disk corona (ADC) which prevents us from seeing the compact object directly. The x-ray flux observed is then scattered to us by the corona, which has only modest optical depth and intercepts only a fraction of the emitted flux. Such ADC sources are usually the highest luminosity objects, such as 4.8 hour binary Cyg X-3, but they can include somewhat lower luminosity systems such as the 5.6 hour binary 4U2127+49 from which an x-ray burst was recently discovered (Garcia and Grindlay 1987). The high luminosity is indicated for 4U2127+12 by the apparent lack of burst activity for this source (indicating it is probably more luminous than, say, 4U2127+49), by the anomalously low x-ray to optical flux ratio (only ~ 20 vs. ~ 10^3 for typical low mass x-ray binaries), and by the unusual variable low energy x-ray variability of the source which suggests variable absorption around the system. The latter variability was discovered for the M 15 source by Hertz and Grindlay (1983) (cf. Fig. 3 in their paper) but has been found to be generally present in a re-analysis of the bulk of the Einstein observations of M 15. In Fig 1 we show the general correlation evident between the low energy absorption (expressed as the equivalent neutral column density N_H) and the hard x-ray flux from the source which measures the overall x-ray luminosity: when the luminosity increases, the apparent low energy absorption decreases. This indicates that there may be substantial material surrounding the binary system which can be partially ionized, and made more transparent, when the x-ray flux increases. This material is expected if the system is in fact entering a common envelope stage.

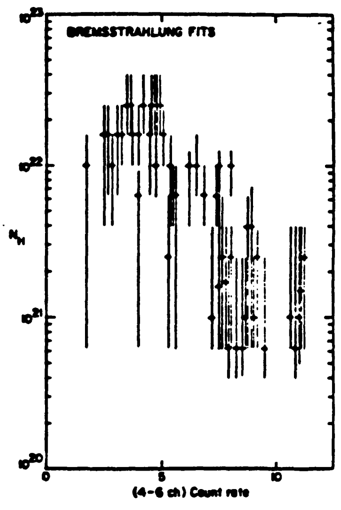

Fig. 1. Low energy absorption column vs. hard x-ray flux for M 15.

If the system is accreting at or near the Eddington limit to produce the inferred high luminosity, and is surrounded by the inferred circumsource material, then mass loss from the system in an outflowing wind is expected. This is the likely explanation for the systemic velocity of ~ − 150 km/sec in the λ 14471 He I absorption line reported by Naylor et al. (1986), rather than their suggestion of ejection of the binary from the cluster core since this would occur in only ~ 10^3 years. A marginal confirmation of the blueshifted helium line velocity was obtained by Grindlay and Huchra (1987) in an average of three short exposure MMT spectra obtained on three successive nights in September 1986. It is encouraging that the possible velocity of - 150 km/sec is close to what might be expected from around the Roche surface of the binary. The velocity variation of ~ 45 km/sec at the orbital period (Naylor et al. 1986) might then be due to the variable potential gradient, and thus velocity of the wind, around the Roche surface as it rotates at the binary period relative to our line of sight. A detailed treatment of the mass loss expected and its expected velocity variation is needed.

The MMT spectra (both recent and previous - cf. Grindlay 1985b, 1986) also showed that the Balmer line (absorption) spectrum from the (vicinity of) AC211 is blueshifted by only -30 ± 10 km/sec from the cluster mean velocity of -107 km/sec. The discrepancy with the He line velocity is probably because the Balmer lines, which are much narrower than those from M 15 horizontal-branch stars (e.g. the velocity standard HB star I-51), arise from the typical metal-poor cluster K-giants (R. Peterson, private communication) in the core (or cusp) of M 15 and not from the much hotter object AC211, which shows such a pronounced uv-excess relative to a HB star. This can be seen by comparing the MMT spectra of AC211 vs. I-51 in Fig. 2.

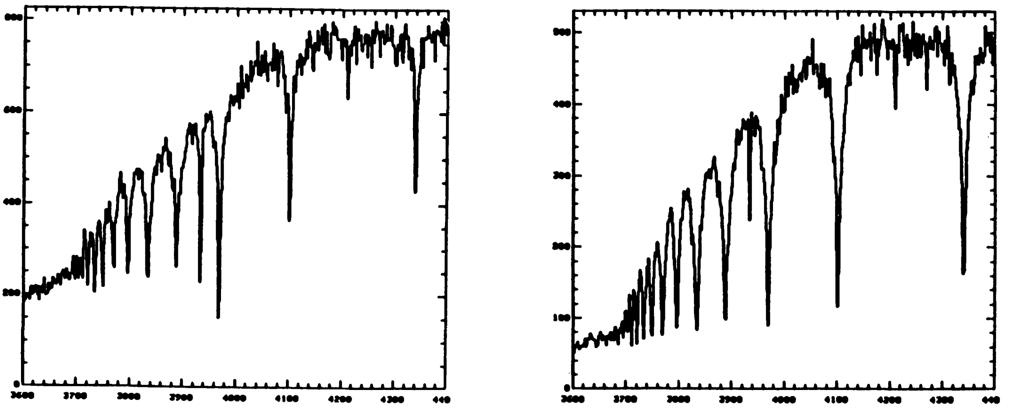

Fig. 2. MMT spectra of (a) AC211 and (b) the HB star I-51 in M 15.

We note that although we have never detected the Balmer emission features (e.g. Hα), reported as variable by Charles et al. (1986), we are confident we are observing AC211 since i) the object coordinates we have used (obtained originally from Aurière 1984 and updated by Aurière, private communication) to position the 1 arcsec MMT spectrograph aperture to ~ 0.3 arcsec setting accuracy (relative to nearby SAO stars) have been confirmed (to within ~ 0.5 arcsec) by our own astrometry of AC211 as detected on our CCD study of the core of M 15 (Bailyn et al. 1987), ii) the object observed clearly has a uv excess relative to a HB star, and iii) the Balmer absorption lines (sharp component) observed by Charles et al. are also not as significantly blueshifted as the He absorption spectrum (Charles, private communication).

3.3 Evolutionary Model

The tidal capture formation of compact binaries in globular clusters does not necessarily mean production at the outset of a mass transfer binary. Instead, if the binary is formed by an encounter with closest approach less than the maximum (~ $3.3R_*$) for capture but greater than the maximum for Roche lobe overflow of the secondary (with radius R_*), then a "dormant" x-ray binary will be formed. Mass transfer and x-ray emission will only begin when the captured star evolves off the main sequence and expands to fill its Roche lobe. This is the key idea in the evolutionary scenario of BG for the 11.4 minute binary system and possibly also the source in M 15. In this case, a 0.8 $M_\odot$ main-sequence star is captured into an orbit which circularizes at a separation $\geq 3R_{TAMS}$ (i.e. it encountered the neutron star with a separation of half this value), where R_{TAMS} is the radius of the star when it (later) has evolved to the terminal age main sequence and is perhaps ~ 1.5-2 times the radius R_* of the star on the main sequence. Hence the required range of closest approach distances is ~ 2.3-3.3 R_*, so that "dormant" tidal capture might occur for ~ 0.3-0.5 of all tidal capture encounters (since the cross section scales linearly with closest approach distance due to gravitational focusing).

When mass transfer finally begins, it will be unstable if the mass ratio $q = m_2/m_1 \geq 0.67$, where the subscripts 1 and 2 denote the primary and secondary masses, and if the accretion proceeds via an accretion disk (BG). This critical mass ratio would be exceeded for stars more massive than the present 0.8 $M_\odot$ turnoff mass which are captured by 1.2 $M_\odot$ neutron stars, where such a neutron star mass is expected if the neutron stars in globular clusters are predominantly the result of the accretion induced collapse of (massive) white dwarfs (Taam and Van den Heuval 1986, Grindlay 1987). The unstable mass transfer will result in accretion onto the neutron star at approximately the Eddington limit as well as accumulation of the excess mass (which cannot accrete) in the disk and in a surrounding circumstellar shell. This will lead to the formation of a common envelope and an evolution of the binary which is very difficult to predict in detail or in timescale. It is likely, however, that ultimately the circumstellar envelope will cause enough frictional drag on the secondary that it will spiral into the primary (probably finally on a rapid timescale) to a separation where the orbital energy of the binary exceeds the binding energy of the common envelope and atmosphere of the secondary exterior to the remaining core of the secondary. Since the secondary star is assumed to have (just) evolved off the main sequence, it will have developed a small (~ 0.1 $M_\odot$) white dwarf core. Thus the common envelope phase is expected to end with a detached white dwarf-neutron star binary in a ~ 31 minute orbit (BG). Gravitational radiation will then spiral the detached low mass white dwarf towards the neutron star primary on a timescale of 10^7 years

https://doi.org/10.1017/S0074180900042595 Published online by Cambridge University Press

after which it will begin a second stage of mass transfer onto the primary and a luminous (~ 10^{38} erg/sec) x-ray source will again be present. This is the stage at which the 11.4 minute binary is now found; the 8.5 hour binary in M 15 may well be the first phase (i.e. post main-sequence star secondary, entering a common envelope stage) of this generic tidal capture evolution.

4. OPTICAL SEARCHES FOR X-RAY BINARIES IN GLOBULAR CLUSTERS

We now turn to a brief update on our ongoing optical studies of the cores of globular clusters. We are carrying out both CCD photometry and spectroscopic investigations in an effort to both identify x-ray binaries and study the effects of binaries on globular cluster evolution.

4.1 The CCD Surveys

A massive program of UBV(RI) surface photometry of globular cluster cores has been carried out from CTIO, KPNO and the CFHT. While the primary goals have been to study the cusps in the central surface brightness profiles recently found in the cores of a number of clusters (Djorgovski and King 1984, 1986; Hertz and Grindlay 1985; Lugger et al. 1985, 1987a and 1987b); this work has also allowed a search for optical counterparts of both low and high luminosity x-ray binaries in clusters. Optical counterparts are sought as uv-excess (i.e. $(U-B) \lesssim -0.5$) objects with absolute magnitudes of ~ 2-6 and ~ 1-3 for the low and high luminosity objects, which are expected to be predominantly CVs and low mass x-ray binaries, respectively (Hertz and Grindlay 1983).

Identification of optical counterparts for the low luminosity sources, which are generally located only to ~ 30 arcsec by the Einstein IPC, is only possible (if at all) for sources well removed from the densest central regions of the cluster. Of the two globular clusters (ω Cen and M 22) with (several) non-central low luminosity point sources detected in the Einstein IPC survey (Hertz and Grindlay 1983), UBV frames have been obtained for the first (M 22 being too reddened). (Although 47 Tuc has at least two sources well removed from its central source, they did not meet the angular displacement criteria of the IPC survey and they have thus far not been included in our CCD survey). One additional cluster, NGC 5824, with a low luminosity source well resolved from the central core and also located to only ~ 10 arcsec uncertainty by the Einstein HRI detector, has also been observed in UBV.

A particularly promising 21st magnitude candidate has been found (Grindlay 1986) in the small error circle for the source in NGC 5824; spectroscopic confirmation of its suspected identity as a CV was clouded out in our 1986 CTIO run but will be attempted again in 1987. Several uv objects were found in the error circles of the ω Cen sources, and spectra for the brighter ($m_v \simeq 17-18$) of these were obtained under marginal conditions in May 1986. They were found to be members of the class of faint blue horizontal-branch (FBHB) stars which we have found to themselves be of special interest by virtue of their apparent central concentration in ω Cen (Bailyn et al. 1987). Although this latter study has indicated these objects may therefore be the result of binary mergers (of white dwarfs and main-sequence stars), there is no reason to suppose that they are in fact counterparts for the low luminosity x-ray sources. Although each IPC error circle (~ 30 arcsec radius) contains at least one of these objects, others of comparable brightness and uv excess are found outside the x-ray source positions, and their lack of emission lines would suggest the sources were (if CVs) in a perpetual outburst state. Additional spectra, which include both greater spectral coverage (e.g. Hα) and higher resolution are planned.

For the high luminosity sources, our major efforts have been to identify additional candidates beyond the AC211 counterpart for the M 15 source. For each source, now located to within ~ 3 arcsec by the Einstein HRI (Grindlay et al. 1984), we have searched for uv excess objects and can rule out objects as bright and blue as AC211 in each of the clusters NGC 1851, 6441, 6624 and 6712 (the remaining high luminosity clusters are heavily reddened and were thus not observed in U). Individual magnitude vs. color limits as well as color maps for the cores of each of these clusters (as well as M 15), are presented by Bailyn et al. 1987. Although analysis is still in progress, thus far the only other high luminosity source cluster with a possible optical candidate is NGC 6712.

4.2 Studies of NGC 6712

Within the HRI error circle of the high luminosity (~ $10^{36.4}$ erg/sec) source in NGC 6712 we have found a possible uv-excess object (Bailyn et al. 1987). Both the magnitude (≥ 20) and color (U-B) ≤ -0.5) of this object are very uncertain because of the severe crowding effects (only ~ 0.2 core radii from the cluster center). However, in the divided (U/B) image, the pixels containing the candidate stand out as among the bluest in the core. Spectra will be attempted at CTIO in May 1987.

The search for uv candidates and the color analysis of cluster cores in and around x-ray positions has required that the data be sky subtracted first to remove the bias otherwise present in the study of radial color gradients in cusps (see section 5.1). Sky subtraction is also important for determining the true surface brightness profile and the possible departures from a King model for the relatively diffuse cluster NGC 6712. All previous measurements of the structural properties (e.g. core radius) of this important x-ray cluster have used photographic data (cf. Hertz and Grindlay 1985). An improved surface brightness profile is particularly important for NGC 6712 because of the conjecture (Grindlay 1985a) that this cluster may be in an advanced state of post core collapse in which it has expanded to its present apparently diffuse form. The tidal capture binary systems (e.g. the high luminosity source) in NGC 6712 would then have formed during an earlier epoch of higher densities. To carry out such a sky-subtracted surface brightness profile and dynamical study of this cluster, we have recently obtained B and V frames of the adjacent surrounding fields out to ~ 10 arcmin radii. Analysis of these is in progress, and will also be used to extend (using DAOPHOT) the stellar photometry of the cluster to derive a color magnitude diagram at larger radii (than the central frames) for use in cluster membership studies.

The latter is necessary to extend our study (Grindlay et al. 1987) of the velocity dispersion (and its radial variation) of the cluster to larger radii. The present totals of some 50 stars out to ~ 3 core radii will each be at least doubled. This will enable a search for departures from isothermality of the measured central velocity dispersion value of 4.2 km/sec and the implied low M/L ~ 0.6 (Grindlay et al. 1987).

5. CUSPS (OF BINARIES ?) IN GLOBULAR CLUSTERS

It is interesting that the two x-ray binaries which may be representative of the dormant tidal capture model and consequent (relatively) short x-ray emission lifetime (cf. section 3) are in the two most conspicuous globular clusters with central cusps in their surface brightness profiles: M 15 and NGC 6624. These are the two "original" cusp clusters, as the measurements and references to earlier work in Hertz and Grindlay (1985) make clear. Our recent detailed CCD study of each of these clusters (Lugger et al. 1987b), together with the "control" cluster NGC 6388, shows that the cusps are well described by power laws with indices of approximately 0.7 for both clusters. This is flatter than the profile slope found for post-core collapse cluster models and indicates the cusps may be dominated by heavy remnants (Cohn 1987). Thus the fact that both cusp clusters contain luminous and relatively short-lived x-ray binaries suggests that the number of binaries containing neutron stars in cusps may be significantly enhanced, as expected.

5.1 Blue Colors ?

In general, globular cluster binaries should be blue. This seemingly glib statement reflects the fact that binaries are expected to be predominantly tidal capture products, especially in the dense cores of cusp clusters, and that these will undergo (either initially or eventually) mass transfer. If the binary components are both main-sequence stars, as in most cases, the products may resemble the cluster blue stragglers (cf. Nemec 1987). If the binary components are (initially) a white dwarf and main-sequence star, then either FBHB stars may form (Bailyn et al. 1987a) or CVs and low luminosity x-ray sources are the expected result (Hertz and Grindlay 1983). Finally, if the components are a neutron star and a main-sequence star, the products are either the "normal" globular cluster x-ray sources (Lightman and Grindlay 1982) or the "dormant" cluster sources (BG). In either of the last two cases, the optical counterparts are expected to be blue by virtue of x-ray heating and/or the energy released directly in a high temperature accretion disk.

If the cusp clusters are indeed rich in binaries, as suspected above and as predicted if they are indeed post core collapse signatures with binary fractions approaching 50 % (Statler et al. 1986), then they should be bluer than their surrounding clusters. We have searched for this by analyzing the U vs. B images of the central regions of both NGC 6624 and M 15 in a novel way (Bailyn et al. 1987b). The usual method would be to compare the surface brightness profiles in each band, or the profile of the divided U/B image, which would be sensitive to the fluctuations in brightness due to individual bright giants in or out of a given annulus in a radial distribution. Instead, we have measured the distribution of the number of pixels at each value in the divided (U/B) image, or equivalently the relative number of pixels at each (U-B) color index. This is relatively less sensitive to the presence of individual bright stars although they enter by crowding effects and are also still relatively more important at small annuli where the available number of pixels from which the distribution is drawn is small. To simulate the color effects of crowding, we co-add enough cluster pixels at large radii to match the measured intensity (counts/pixel) at the small radii of interest in the cusp. To remove the slight color gradients which could arise from increasing sky contribution at large radii from the cluster centers, all frames are sky subtracted first using the technique of Djorgovski (1987). In practice, we have used 90 x 90 pixel (0.6 arcsec/pixel) to derive the cluster "background" color and to simulate crowding effects and have compared these color distributions with those obtained for 30 x 30 and 10 x 10 pixel regions about the cluster center.

Our preliminary results on NGC 6624 and M 15 using this technique indicate that the two central regions are not significantly bluer than the outer comparison region of the clusters. This is shown in Fig. 3 for M 15. This result is surprising, since the central core of M 15 appears to be relatively blue on short exposure images. This is probably due to the effects of crowding of relatively blue horizontal-branch stars and does not seem to require the underlying cusp be significantly bluer than the surrounding cluster. However, the limited spatial resolution and relatively large pixel size severely limit the significance of this result; higher resolution data have been obtained on the CFHT and will be analyzed for this effect.

5.2 Diffuse Line Emission from CVs ?

Although we have not yet apparently detected the additional blue continuum from an underlying population of a binary population in the cusp of M 15 or NGC 6624, it is possible that the diffuse line emission (e.g. Hα) from the component of the binary population which are CVs has been detected. Possible detections of diffuse Hα for the core of NGC 6624 were reported by Grindlay and Liller (1977) and for the core of

M 15 by Peterson (1976). Whereas the first result was obtained with

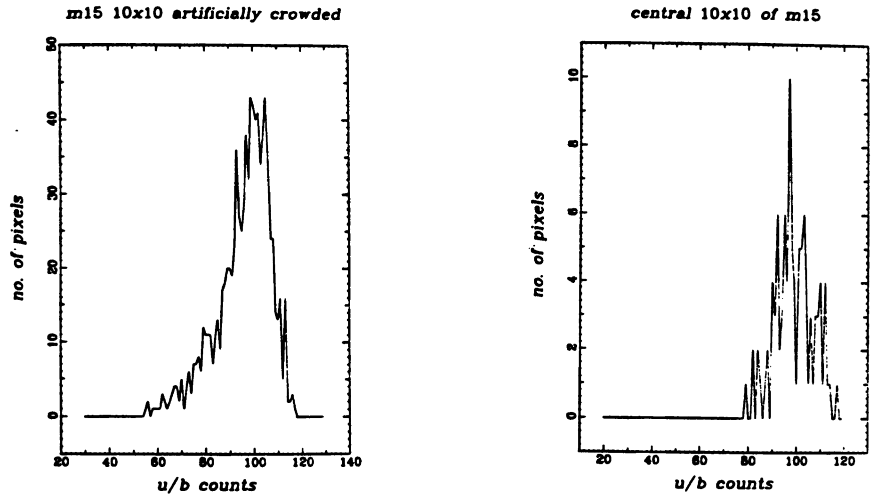

Fig. 3. Comparison of U/B pixel distributions for M 15 regions

concentric aperture photometry, and therefore is subject to the uncertainties of centering and the effects of individual red giants in the aperture (which, by undergoing mass loss, might be Hα emitters, as noted by Grindlay and Liller), the second result was photographic and obtained with a pre-filtered (10 Å) slitless spectrograph. The Hα image was noted as being smaller than the (central region) of the cluster and thus could be the central portion of the cusp instead of a new planetary nebula (much fainter than the known planetary in M 15) as suggested by the author. Once again, we have obtained (August 1986), but not yet been able to analyze, several test interference band (Hα) frames at the CFHT; we intend to extend this search to much deeper limits with future observations. For a cusp with only a ~ 15% fraction of CVs, which might be expected from the post-core collapse binary fractions of Statler et al. (1987), it should be possible to detect a 10% excess in a 10 Å wide band centered on Hα relative to the neighboring continuum. This estimate assumes a "typical" CV with Hα emission equivalent width of ~ 10 Å vs. cluster giants (which dominate the light) with Hα absorption equivalent widths of ~ 1 Å.

6. THE CASE FOR CLUSTER DISRUPTION

The possibility that many of the x-ray burst sources in the galactic bulge were formed by tidal capture in globular clusters, which have since been disrupted (Grindlay 1984, 1985a,b, 1986), is made somewhat more plausible by several recent developments. First, the "dormant" tidal capture model (BG) would help to solve the otherwise questionable lifetime problem: bursters or compact low mass x-ray binaries with emission lifetimes of ~ 10^9 years would imply cluster disruption on a similar (or shorter) timescale (Grindlay 1986). However, if a significant fraction of the tidal captures are initially dormant until the secondary has evolved, cluster disruption can occur over a more plausible ~ 10^{10} years. The 50-minute binary 4U1916-05, which we have pointed to as a prime candidate for origin in a cluster, is also a prime contender for a product of dormant tidal capture since its short period implies an evolved secondary (cf. Swank et al. 1984).

Secondly, the recent work on tidal disruption of globular clusters (Chernoff et al. 1986, Chernoff and Shapiro 1987) by the galactic field and encounters with individual giant molecular clouds, which we had suggested could disrupt globular clusters, has shown that indeed clusters within ~ 4 kpc of the galactic center can be disrupted. This work also bears out our hypothesis that only globular clusters on a rather narrow loss cone of orbital inclinations (with respect to the galactic plane) will be disrupted by GMCs and it reinforces the association (Grindlay 1984) of galactic bulge x- ray sources (with their flattened distribution) with a subset of bulge globular clusters (those with orbital inclinations initially near the galactic plane).

Finally, Cowley et al. (1986) have reported preliminary evidence that the velocity dispersion and distribution of the bulge x-ray sources (primarily bursters in their sample) is similar to that of the bulge x-ray globular clusters. They interpret this as kinematic evidence for the Pop II nature of the bulge x-ray sources, but it is also consistent with the globular cluster disruption picture for these objects. This is a promising area for further study, and many more velocities (than in their limited sample) are needed.

7. CONCLUSIONS

The study of x-ray binaries in both the x-ray and optical regimes has yielded important new results for the origin and evolution of compact binaries in globular clusters. The recent discoveries of the first binary periods for these objects has allowed fundamental constraints to be derived for the nature of the secondary stars supplying the accretion onto the neutron star primaries. It is surprising, but perhaps not coincidental, that these first binary identifications were made for the two prototype "cusp clusters": NGC 6624 and M 15. This is consistent with their having produced a significant enhancement in their populations of compact binaries if the cusps are indeed signatures of post-core collapse. This interpretation is also supported by the model described here and in BG whereby both the NGC 6624 and M 15 binaries are the two stages expected for a common channel of binary formation and evolution: the "dormant" tidal capture model. The relatively short x-ray lifetimes expected in this model, particularly for the second phase of x-ray emission due to accretion of a low mass white dwarf onto the neutron star primary (as in NGC 6624), may imply a total number of binaries in the cluster core ~ 10 times greater than previously suspected (e.g. by Lightman and Grindlay 1982).

Optical identification of the x-ray binaries in other globular clusters will allow the relative frequency of "dormant" tidal capture systems vs. the "normal" tidal capture binaries, with immediate production of lower luminosity but longer lasting x-ray emission. A possible optical candidate has been found for the source in the peculiar (diffuse) x-ray globular cluster NGC 6712. It may be possible to derive magnitudes and colors for this object from high resolution images (e.g. from the CFHT) but this may require HST. Our current estimates would allow either type of tidal capture binary, with absolute magnitudes expected to be ~ 1-2 (normal type) vs. ~ 4-6 (second stage dormant type), although a (first stage dormant type) system such as the M 15 source can already be eliminated. Our optical studies (Bailyn et al. 1987) also rule out M 15-type optical counterparts for any of the other four bright x-ray globular clusters (NGC 1851, 6441, 6624 and 6712) for which we have U-band CCD images, although higher spatial resolution is once again needed to make these limits more restrictive than, typically, ~ 2-3 magnitudes fainter than the AC211 optical counterpart in M 15.

Higher spatial resolution is also needed to properly study the expected blue color gradients in cusps if they are indeed dominated by binaries. Our preliminary results do not show significant differences in the (U-B) colors in and out of cusps, but we are limited by pixel size and crowding effects to regions outside the central ~ 6 arcsec. Searches for diffuse line emission (e.g. Hα) expected from a central population of CVs in cusps may be more productive, and once again it is tantalizing that the two prototype cusp clusters both have reported Hα emission "cores". Higher resolution narrow-band visible (from CFHT) and uv (with HST) observations are needed, and are planned, to properly carry out these studies.

I thank my various collaborators in this work, particularly Charles Bailyn. This work was supported in part by NSF grant AST-84-17846 and by NASA grants NAGW-624 and NAS8-30751.

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DISCUSSION

GNEDIN: Is there any evidence for extended X-ray sources? I am referring to your paper with Hartwick and Cowley. What is the present situation?

GRINDLAY: There are no further data available from the Einstein Observatory beyond what we published. Further interpretation of these data is contained, however, in my paper in the I.A.U. 113 Proceedings. Upper limits for diffuse X-ray emission in ω Cen are reported by Koch-Miramond and Aurière at this meeting which do not contradict the Einstein results.

MCMILLAN: I have two remarks concerning tidal binaries. First, both the formation process and subsequent interactions with third stars are very likely to lead to stellar merges, significantly reducing the fraction of simple binary systems. Second, in my simulations of tidal binary interactions, I do indeed find a substantial number of hierarchial triples being formed.

DJORGOVSKI: I wonder how wise it is to present PCC clusters as a sum of a broad-core King model, and a cusp. They are single, unified dynamical systems, with a structure profoundly different from the King models. And another remark: Shri Kulkarni and I looked for a possible optical counterpart of the tentative pulsar in M 28, using our UBVRI CCD data; we did not find anything striking.

GRINDLAY: I agree PCC clusters are not composite dynamical systems. However, our fitting procedure is motivated by current models which indicate power law profiles (cusps) merging at larger radii with an apparently undistorted King model.

OSTRIKER: The close encounters which produce tidal binaries will also destroy them through their ejection or physical collisions. In the Princeton work we found a typical lifetime less than 10^9 years for tidal binaries at the relevant stage of cluster evolution. This increases the required rate of production.

GRINDLAY: I agree. This means either the neutron star fraction or the total density must be larger than the values assumed by Lightman and me (1982) for a "typical" cluster (i.e., not a post-core collapse cluster, since present indications are that these account for at most ~ 25% of the clusters).

KING: I have not yet done enough modeling to speak with certainty but it is my impression that if the neutron-star mass is as much as 10^{-3} of the total, it should have a strong effect on the central distribution of light. (White dwarfs have almost no effect, because they have a mass so similar to that of the bright visible stars.)

GRINDLAY: A neutron star mass fraction of 10^{-3} (total) or perhaps 1-10% (in the core alone), may indeed have a pronounced effect on the light distribution and probably contributes to the flatter slopes (than -1) for the PCC cluster cusps. The much larger mass fraction in white dwarfs (e.g. 35% in 47 Tuc claimed by Da Costa and Freeman) may also significantly affect the light profile, however, since many of these WDs are probably relatively massive (~1 $M_\odot$) remnants from the more massive stars in the cluster IMF than the stars producing ~0.6 $M_\odot$ white dwarfs currently.

OZERNOY: Have you considered the formation of binaries in the very central stellar core of the Galactic nucleus? What could you tell us about X-ray sources in the vicinity of the Galactic center?

GRINDLAY: That's a very interesting question which I have not considered. A dense stellar cluster at the Galactic nucleus should indeed be capable of producing (by tidal capture) a compact X-ray binary, and it is interesting then that the X-ray luminosity (~ 2-10 kev) of our own galactic center is ~ 10^{36} erg/sec, or about the same as a globular cluster source.

REES: If neutron star binaries form via tidal capture, there should be a comparable number of events when the neutron star undergoes a physical merging ending up inside an ordinary star. The resultant "Thorne-Zytkow Object" would be conspicuous, like a supergiant, with a lifetime that would (when mass loss was rapid) be at least several times 10^7 yrs. Have any optical observers found objects answering this description? And, if not, is it a constraint on anything?

GRINDLAY: Another interesting question. I question, however, whether a "Thorne-Zytkow Object" would really form (in a direct collision) without losing most, if not all, of the stellar envelope. In this case, it is not obvious how optically luminous such an object should be. Partial loss of the envelope would presumably cause the object to appear very blue (and luminous), so it is interesting to speculate whether the uv-luminous stars found by Zinn could be such objects and not Post-AGB stars as usually assumed. Bailyn and I (this conference) have also suggested a possible analogue object class for white dwarfs - star collisions; the faint blue horizontal branch stars.

PRYOR: Our velocity dispersion data for NGC 6712 shows a low central M/L. This central M/L suggests that there are not very many heavy remnants in the center of this cluster.

GRINDLAY: Our results for NGC 6712 (this conference) also suggest a low M/L ~ 0.6. We have commented this may be related to the possible expansion of this cluster.

COHN: I would like to say a few words in defense of our profile fitting procedure that has been commented on by Djorgovski and King. Our primary motivation is to determine the central slope of the cusp; thus we fit seeing-convolved power laws to the inner part of the profile. Our fitting King models to the outer part of the profile is motivated by the result from numerical simulations that while power law structure develops in the central region, the outer regions continue to resemble King models. Thus our empirical model fits both the simulated and real cluster profiles.