X-RAY BINARY SYSTEMS IN GLOBULAR CLUSTERS

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ABSTRACT

The extreme stellar densities in the cores of globular clusters are expected to result in a number of interesting dynamical effects because of the relatively high frequency of close encounters (and even mergers) between cluster members. It has been known for decades that globular clusters are a favored environment for X-ray binaries, with formation rates per unit mass exceeding those in the Galactic disk by orders of magnitude. These X-ray binaries, as well as other close binaries, play a pivotal role in a cluster's evolution. Even a modest population of binaries contains a potential reservoir of binding energy that easily exceeds the kinetic energy of all single stars in the cluster.

The interplay between stellar dynamics and stellar evolution, as external and internal factors modifying the binary properties, is highly complex, and many details of these processes are not well understood. However, in recent years, we have made much progress, due in large part to X-ray observations from *Chandra* and *XMM-Newton*, which are extremely efficient at finding large numbers of close binary systems. Identifying the nature of these systems allows us to assess the effects of the parent cluster's physical properties on its different binary subpopulations. I will discuss this ongoing effort and some of the highlights of this new era.

Key words: globular clusters; binaries; X-rays.

1. INTRODUCTION

An excellent recent review of the state of globular cluster X-ray research was given by Verbunt & Lewin (2005), and the reader is encouraged to peruse that article for a comprehensive overview. I highlight only a few areas in this talk.

The X-ray sources in globular clusters have historically been divided into two phenomenological classes: the high luminosity sources (with $L_\mathrm{X} \gtrsim 10^{35.5}$ erg s^{-1}) and the low luminosity sources (with $L_\mathrm{X} \lesssim 10^{34}$ erg s^{-1}). In each of these classes, I have selected a few topics to illustrate that unusual objects are found in large numbers in globular clusters, indicating that the dense stellar environment is responsible, at least in part, for their production.

2. HIGH LUMINOSITY X-RAY SOURCES

It has long been known that globular clusters are a favored environment for X-ray binaries, with formation rates per unit mass exceeding those in the Galactic disk by orders of magnitude (Clark, 1975; Katz, 1975). There are currently 13 high luminosity X-ray sources known in a total of 12 GCs (Deutsch et al., 2000; White & Angelini, 2001). Twelve of them are known to be neutron star low-mass X-ray binaries (NS-LMXBs) because they exhibit Type I X-ray bursts (Kuulkers et al., 2003), which are known to be thermonuclear runaways on the surface of a neutron star (see Lewin et al. 1993 for a review), and the thirteenth one is probably a NS-LMXB as well, based on the properties of its X-ray spectrum (in't Zand et al., 1999; White & Angelini, 2001).

One particularly interesting aspect of this population is that many of these NS-LMXBs show good evidence of having “ultrashort” binary periods of less than 80 min. Such a binary is so compact that the Roche-lobe filling donor star cannot be a lower main-sequency hydrogen burning star; it must be partially degenerate and partially depleted in hydrogen. Following Verbunt & Lewin (2005), I review the evidence for such ultracompact systems in globular clusters.

The source X1820$-$30 in NGC 6624 and the source X1850$-$087 in NGC 6712 have known orbital periods. Stella et al. (1987) first found the 11.47 min period of X1820$-$30 using *EXOSAT* data, and Anderson et al. (1997) found it in *HST* UV observations. Fig. 1 shows the X-ray and UV power spectra. Homer et al. (1996) discovered the 20.6 min period of X1850$-$087 with *HST*.

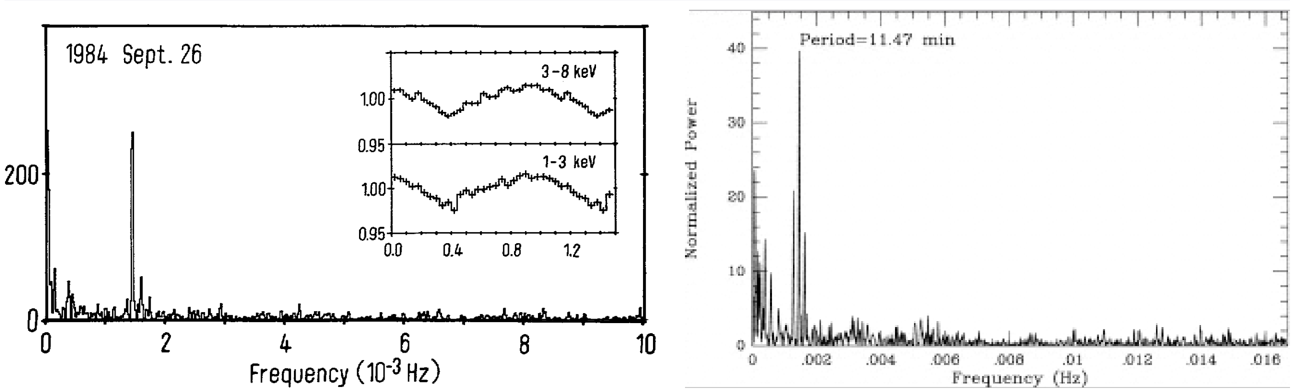

Figure 1. Left: The X-ray power spectrum of X1820−30 found by Stella et al. (1987). Right: The UV power spectrum of X1820−30 found by Anderson et al. (1997).

In addition to this direct evidence of an ultracompact nature, there are three lines of indirect evidence which indicate that a number of other globular cluster LMXBs are ultracompact. These come from considering the X-ray burst properties, the optical luminosities, and the broadband spectra of these sources.

Many of the globular cluster LMXBs have exhibited radius-expansion bursts, in which the maximum luminosity achieved in the burst is closely related to the Eddington limit. Kuulkers et al. (2003) have shown that in a number of these radius-expansion bursts the maximum luminosity is higher than is possible for hydrogen rich accretion, implying that the donor stars are at least partly depleted. This suggests that these sources — the high luminosity LMXBs in NGC 1851, NGC 6652, NGC 7078 (X-2), and Terzan 2 — are likely ultracompact systems.

Based on the relationship between the optical luminosity, X-ray luminosity, and orbital period of an X-ray binary found by van Paradijs & McClintock (1994), the LMXBs in NGC 6652 and NGC 1851 are likely to have ultrashort periods. Because the optical flux of a bright LMXB is dominated by light from the accretion disk, a small disk (or a low L_X) will give a low optical luminosity. Therefore, the X-ray to optical flux ratio can give some idea of the orbital period. Based on *HST* observations of NGC 1851 (Deutsch et al., 2000) and NGC 6652 (Heinke et al., 2001), the high luminosity LMXBs in these clusters likely have very short periods.

In a comprehensive analysis of the broadband X-ray spectra of all of the high-luminosity globular cluster LMXBs, Sidoli et al. (2001) found that the best-fit parameters of a multicolor disk blackbody plus comptonized spectrum separated the known ultracompact systems from the known normal period systems. Based on their similarity in best-fit spectral parameters to the known ultracompact systems, the LMXBs in NGC 1851, NGC 6652, and Terzan 5, are suggestive of also being ultracompact.

In summary, there are definitely two, probably four, and as many as seven ultracompact LMXBs in globular clusters. This is a remarkably high fraction (∼15–50%) of the high luminosity X-ray sources. The formation of ultracompacts is not well understood. See the Verbunt & Lewin review for an overview of the theories and their associated shortcomings, as well as recent work by Ivanova et al. (2005); Lombardi et al. (2005); van der Sluys et al. (2005a,b). One thing does seem clear, however, and it is that cluster dynamics has a large role in producing the observed population. The role of dynamics in producing unusual populations can be further explored by investigating the low luminosity sources.

3. LOW LUMINOSITY X-RAY SOURCES

An additional population of X-ray sources (those with low X-ray luminosity) was discovered in globular clusters with the *Einstein* satellite (Hertz & Grindlay, 1983a,b) and further explored with *ROSAT* (Verbunt, 2000). The nature of this population remained elusive for nearly two decades. Of the 57 low luminosity sources discovered by *ROSAT*, only two were securely classified: a cataclysmic variable (CV) in NGC 5904 (Hakala et al., 1997; Margon et al., 1981) and a millisecond pulsar (MSP) in NGC 6626 (Lyne et al., 1987; Saito et al., 1997).

The earliest *Chandra* observations of globular clusters — 47 Tuc (Grindlay et al., 2001a), NGC 6397 (Grindlay et al., 2001b), NGC 6440 (Pooley et al., 2002b), and NGC 6752 (Pooley et al., 2002a) — revealed not only a much larger population, but also allowed for the identification of optical and radio counterparts due to the subarcsecond angular resolution. This is clearly shown in Fig. 2 (from Verbunt 2004), which displays the *ROSAT* grayscale images of NGC 6752 and NGC 6440 with the *Chandra*-detected point sources overlaid as filled circles.

To date, *Chandra* has observed about two dozen globular clusters to a luminosity limit of a few $\times 10^{30}$ erg s^{-1} and a few even lower than this. Over 800 sources are detected within the halflight radii (Harris, 1996) of these clusters, with about 150 of them expected to be background sources based on the number-flux relation of Giacconi et al. (2001). One way to represent these sources

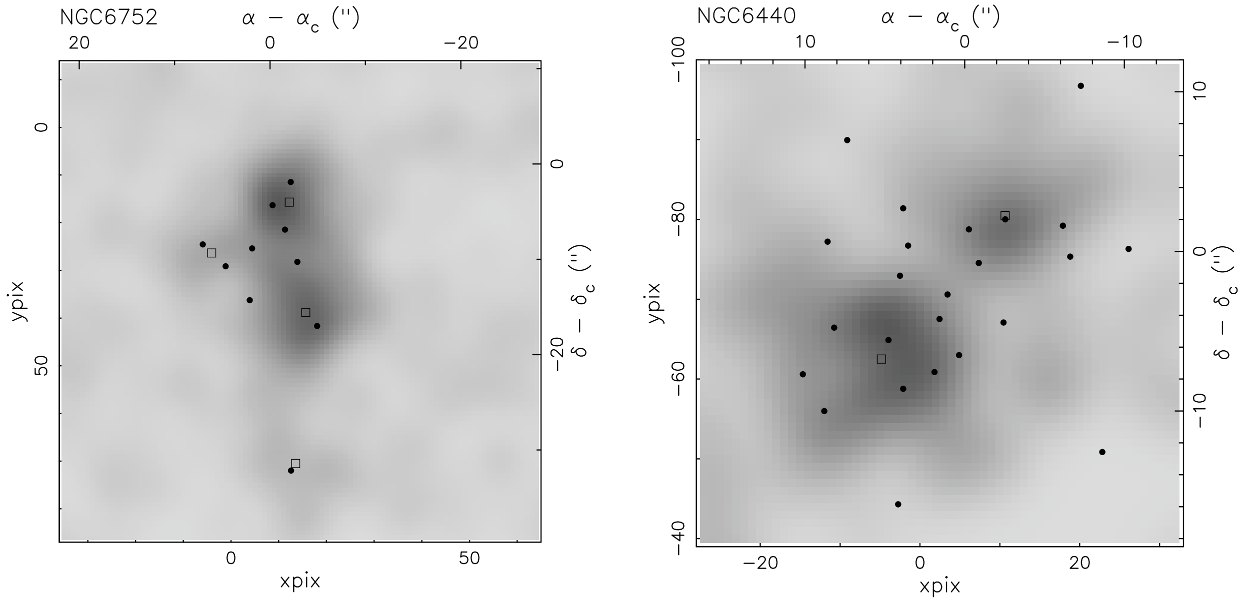

Figure 2. ROSAT grayscale images of NGC 6752 (top) and NGC 6440 (bottom) with Chandra sources overlaid as filled circles. The ROSAT identified point sources are indicated with open squares. From Verbunt (2004).

is on an X-ray color-magnitude diagram (Fig. 3), with the X-ray color defined as the logarithm of the ratio of flux in the 0.5–2 keV band to that in the 2–6 keV band, and the magnitude defined as the logarithm of the 0.5–6 keV luminosity.

Based on half the current sample, Pooley et al. (2003) found evidence that the number of X-ray sources in a globular scales with the encounter frequency (Γ) of the cluster. The encounter frequency is a measure of the dynamical activity of the cluster (see Pooley et al. 2003 for specifics of the calculation). This result suggests that the majority of these systems were formed dynamically.

Using the current sample, I have performed a similar analysis. I now use “specific” units, i.e., the number of X-ray sources per mass and the encounter frequency per mass. This is plotted in Fig. 4; the mass unit is $10^6 M_\odot$, with values obtained from Gnedin & Ostriker (1997). Using specific units mitigates the complication that arises from the natural correlation between encounter frequency and mass: on average, more massive clusters have higher encounter frequencies. The previous finding is seen to hold, namely, that over many orders of magnitude the number of X-ray sources (per mass) associated with a globular cluster scales with the encounter frequency (per mass).

This relationship deals with a hodge podge of close binaries, and there is no $apriori$ reason to believe that the relationship should be same for each subpopulation (LMXBs, CVs, main-sequence binaries, and MSPs). It is therefore important to separate the subpopulations and deal with them on their own.

In general, classifying these low luminosity sources requires a radio or optical counterpart identification, but it is becoming clear that we can make a rough classification of source type at the upper end of this luminosity regime based soley on the X-ray data. Above a few times 10^{31} erg s^{-1}, the observed X-ray sources are largely LMXBs and CVs, and the LMXBs are much softer spectrally than the CVs. This is best illustrated by *XMM-Newton* observations of two sources in ω Cen (Fig. 5).

We can therefore construct a fairly complete picture of the LMXBs in these clusters, and it appears that the number of LMXBs follows almost a linear relationship with the encounter frequency, in agreement with the conclusion from the 1970s. This result has been found by a number of authors (Pooley et al., 2003; Heinke et al., 2003; Gendre et al., 2003b)

As for the CVs, if we assume that the upper end of the CV luminosity distribution can act as a tracer for the whole CV population, we can then begin to explore whether the CVs also exhibit evidence of dynamical formation. We also need to assume that the number of bright, hard sources in the X-ray color magnitude diagram is dominated by CVs, and the results on the few clusters that have been analyzed in detail appears to support this. Therefore, we can use this bright hard region of the X-ray color-magnitude diagram as some kind of measure of the CV population. Fig. 6 shows the relationship of these sources versus the encounter frequency. Although there is a large dispersion, it does appear that a general trend exists. This is therefore the first evidence that CV formation in globular clusters is also influenced by the internal dynamics. Note that for any population that is strictly primordial, the number of sources per mass should be constant, plotted against *any* parameter. This is clearly not the case for these bright hard sources, which show a factor of $\sim$40

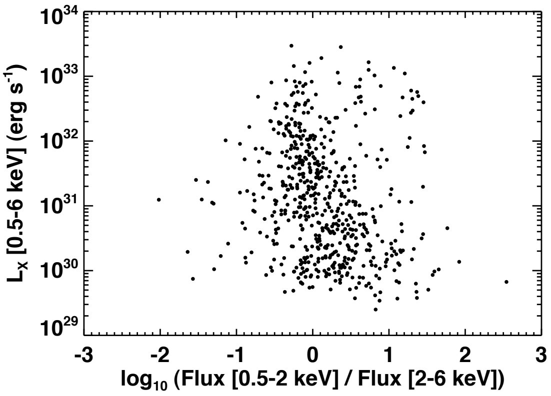

Figure 3. X-ray color-magnitude diagram of all Chandra detected low-luminosity globular cluster sources. An absorption correction (described in Pooley et al. 2002a) has been applied to all sources, based on the column density to the cluster, to bring all sources onto a common scale.

variation in the number per mass. Although perhaps not the entire story, dynamics is definitely playing a role.

4. SUMMARY

We know from observations that globular clusters are very efficient catalysts in forming unusual binary systems, such as LMXBs (and the even more unusual ultra-compact LMXBs), CVs, and MSPs, with formation rates per unit mass exceeding those in the Galactic disk by orders of magnitude. The high stellar densities in globular clusters trigger various dynamical interactions: exchange encounters, direct collisions, destruction of binaries, and tidal capture. This binary population is, in turn, critical to the stabilization of a cluster against gravitational collapse (Goodman & Hut, 1989); the long-term stability of a globular cluster is thought to depend on tapping into the gravitational binding energy of such close binaries (Hut et al., 1992). The various interactions that tap this energy (exchanges in encounters with binaries, direct collisions, destruction of binaries, and tidal capture) can change the state of the core dramatically and can kick stars and binaries out of the core or even out of the cluster altogether.

The details of these processes are not well understood, primarily because of the complex feedback between stellar evolution and cluster dynamics and the strong dependence on the globular cluster's physical properties. For example, the relative importance of tidal capture and exchange encounters for the formation of binaries with neutron stars or white dwarfs is still uncertain and cannot, due to the complexity of the physics involved, be answered by theory alone. These dynamical issues can best be addressed by studying the empirically confirmed close binary populations of globular clusters, which is efficiently accomplished with *Chandra* and *XMM-Newton* observations.

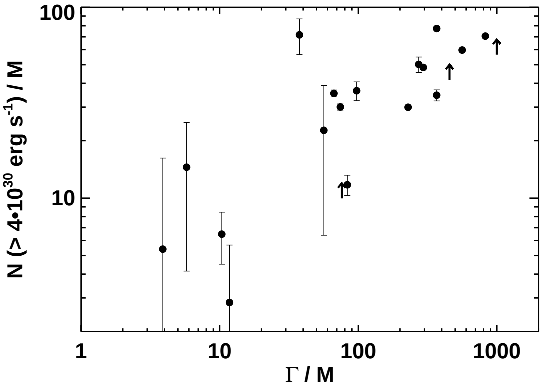

Figure 4. The number of X-ray sources above 4×10^{30} erg s^{-1} (per $10^6 M_\odot$) within the halflight radius of a cluster (minus the expected number of background sources) versus the encounter frequency Γ (per $10^6 M_\odot$) of the cluster. An arrow indicates a cluster that was not observed long enough to reach 4×10^{30} erg s^{-1}.

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REFERENCES

Anderson, S.F., Margon, B., Deutsch, E.W., Downes, R.A., & Allen, R.G. 1997, ApJ, 482, L69

Clark, G. W. 1975, ApJ, 199, L143

Deutsch, E.W., Margon, B., & Anderson, S.F. 2000, ApJ, 530, L21

Gendre, B., Barret, D., & Webb, N.A. 2003a, A&A, 400, 521

Gendre, B., Barret, D., & Webb, N.A. 2003b, A&A, 403, L11

Giacconi, R. et al. 2001, ApJ, 551, 624

Gnedin, O.Y., & Ostriker, J.P. 1997, ApJ, 474, 223

Goodman, J. & Hut, P. 1989, Nature, 399, 40

Grindlay, J.E., Heinke, C., Edmonds, P.D., & Murray, S.S. 2001a, Science, 292, 2290

Grindlay, J.E., Heinke, C.O., Edmonds, P.D., Murray, S.S., & Cool, A.M. 2001b, ApJ, 563, L53

Hakala, P.J., Charles, P.A., Johnston, H.M., & Verbunt, F. 1997, MNRAS, 285, 693.

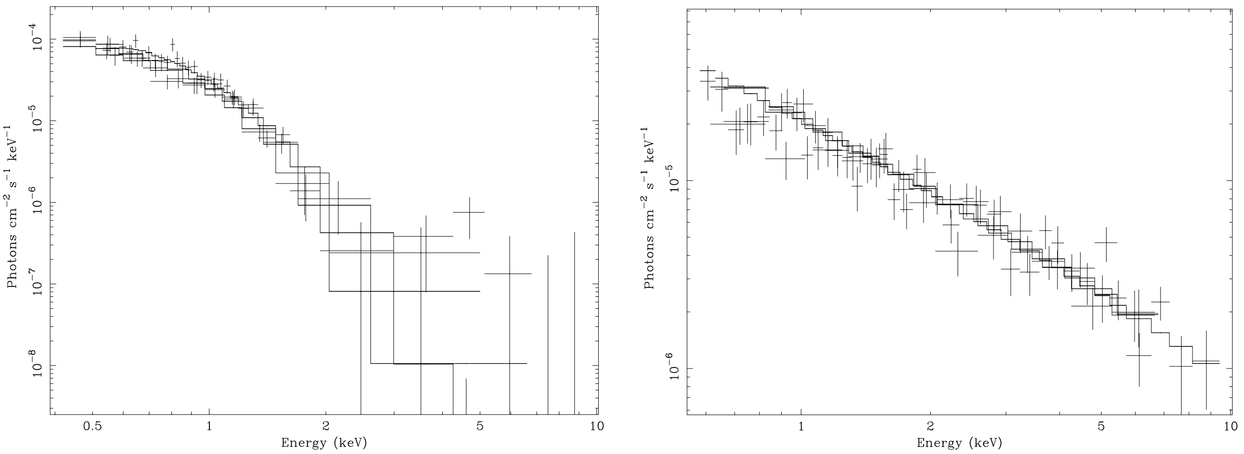

Figure 5. XMM-Newton spectra of two sources in ω Cen (from Webb & Barret 2005, originally in Gendre et al. 2003a). The quiescent LMXB (left) is much softer than the CV (right).

Harris, W. E. 1996, AJ, 112, 1487

Heinke, C.O., Edmonds, P.D., & Grindlay, J.E. 2001, ApJ, 562, 363

Heinke, C.O., Grindlay, J.E., Lugger, P.M., Cohn, H.N., Edmonds, P.D., Lloyd, D.A., & Cool, A.M. 2003, ApJ, 598, 501

Hertz, P. & Grindlay, J., 1983a, ApJ, 267, L83.

Hertz, P. & Grindlay, J., 1983b, ApJ, 275, L105.

Homer, L., Charles, P.A., Naylor, T., van Paradijs, J., Auriere, M., & Koch-Miramond, L. 1996, MNRAS, 282, L37

Hut, P. et al. 1992, PASP, 104, 981

in 't Zand, J.J.M., Verbunt, F., Strohmayer, T.E., Bazzano, A., Cocchi, M., Heise, J., van Kerkwijk, M.H., Muller, J.M., Natalucci, L., Smith, M.J.S., & Ubertini, P. 1999, A&A, 345, 100

Ivanova, N., Rasio, F.A., Lombardi, J.C., Jr., Dooley, K.L., & Proulx, Z.F. 2005, ApJ, 621, L109

Katz, J. I. 1975, Nature, 253, 698

Kuulkers, E., den Hartog, P.R., in't Zand, J.J.M., Verbunt, F.W.M., Harris, W.E., & Cocchi, M. 2003, A&A, 399, 663

Lewin, W.H.G., van Paradijs, J., & Taam, R.E. 1993, Space Sci. Rev., 340, 367

Lombardi, J.C., Jr., Proulx, Z.F., Dooley, K.L., Theriault, E.M., Ivanova, N., & Rasio, F.A. 2005, ApJ, submitted, astro-ph/0509511

Lyne, A.G., Brinklow, A., Middleditch, J., Kulkarni, S.R., & Backer, D.C. 1987, Nature, 328, 399.

Margon, B., Downes, R.A., & Gunn, J.E. 1981, ApJ, 247, L89.

Pooley, David; Lewin, Walter H. G.; Homer, Lee; Verbunt, Frank; Anderson, Scott F.; Gaensler, Bryan M.; Margon, Bruce; Miller, Jon M.; Fox, Derek W.; Kaspi, Victoria M.; van der Klis, Michiel 2002a, ApJ, 569, 405

Pooley, David; Lewin, Walter H. G.; Verbunt, Frank; Homer, Lee; Margon, Bruce; Gaensler, Bryan M.; Kaspi, Victoria M.; Miller, Jon M.; Fox, Derek W.; van der Klis, Michiel 2002b, ApJ, 573, 184

Pooley, D., Lewin, W.H.G., Anderson, S.F., Baumgardt, H., Filippenko, A.V., Gaensler, B.M., Homer, L., Hut, P., Kaspi, V.M., Makino, J., Margon, B., McMillan, S., Portegies Zwart, S., van der Klis, M., & Verbunt, F. 2003, ApJ, 591, L131

Saito, Y., Kawai, N., Kamae, T., Shibata, S., Dotani, T., & Kulkarni, S.R. 1997, ApJ, 477, L37.

Sidoli, L., Parmar, A.N., Oosterbroek, T., Stella, L., Verbunt, F., Masetti, N., & Dal Fiume, D. 2001, A&A, 368, 451

Stella, L., Priedhorsky, W., & White, N.E. 1987, ApJ, 312, L17

van der Sluys, M.V., Verbunt, F., & Pols, O.R. 2005a, A&A, 431, 647

van der Sluys, M.V., Verbunt, F., & Pols, O.R. 2005b, A&A, 440, 973

van Paradijs, J., & McClintock, J.E. 1994, A&A, 290, 133

Verbunt, F. 2000, A&A, 368, 137

Verbunt, F. 2004, to appear in *Interacting Binaries*, eds. Antonelli et al., American Institute of Physics, astro-ph/0412524

Verbunt, F., & Lewin, W.H.G. 2005, to appear as Chapter 8 in *Compact Stellar X-ray Sources*, eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, astro-ph/0404136

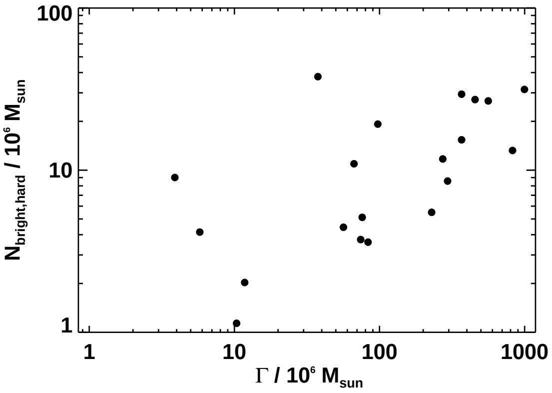

Figure 6. *The number (per $10^6 M_\odot$) of hard X-ray sources at the bright end of the low luminosity regime versus the encounter frequency Γ (per $10^6 M_\odot$) of the cluster. This number is expected to be a tracer of the entire CV population.*

Webb, N.A., & Barret, D. 2005, in *The Astrophysics of Cataclysmic Variables and Related Objects*, eds. J.-M. Hameury and J.-P. Lasota., Astronomical Society of the Pacific, astro-ph/0411506

White, N. E. & Angelini, L. 2001, ApJ, 561, L101