THE GLOBULAR CLUSTER POPULATION OF X-RAY BINARIES

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Abstract. We discuss formation mechanisms for low-mass X-ray binaries in globular clusters. We apply the most efficient mechanism, tidal capture in close two-body encounters between neutron and main-sequence stars, to the clusters of our galaxy. The observed number of X-ray sources in these can be explained if the birth velocities of neutron stars are higher than estimated from velocity measurements of radiopulsars, or if the initial mass function steepens at high masses. We perform a statistical test on the distribution of X-ray sources with respect to the number of close encounters in globular clusters, and find satisfactory agreement between the tidal capture theory and observation, apart from the presence of low-mass X-ray binaries in four clusters with a very low encounter rate: Ter 1, Ter 2, Gr 1 and NGC 6712.

EXOSAT observations indicate that some dim globular cluster sources may be less luminous than hitherto assumed, and support the view that the brighter dim sources may be soft X-ray transients in quiescence.

1. Introduction

Globular clusters are a favoured environment for low-mass X-ray binaries: of the ~ 50 bright low-mass X-ray binaries in the galaxy, ~ 10 are located in globular clusters. With $\sim 10^7 M_\odot$ in globular clusters and $\sim 10^{11} M_\odot$ in the galactic disk, the number of bright low-mass X-ray binaries per unit of mass is ~ 2000 times higher in globular clusters than in the galactic disk, or ~ 200 times if we consider Population II mass only (Katz 1975). It is thought that this high frequency is the result of the frequent occurrence in globular clusters of a close encounter between a neutron star and an ordinary star, resulting in the formation of a low-mass X-ray binary through tidal dissipation (Sutantyo 1975; Fabian, Pringle & Rees 1975). This mechanism does not operate in the galactic disk because of the low number densities there of stars.

The formation rate of low-mass X-ray binaries in globular clusters depends on the numbers of neutron stars and ordinary stars in the clusters. The observed

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number of low-mass X-ray binaries further depends on their lifetime. Thus by combining the observed numbers of low-mass X-ray binaries in globular clusters with our knowledge of their formation mechanisms and of their lifetime we can derive the number of neutron stars in globular clusters, and obtain clues on their origin.

In Section 2 we review the formation processes in globular clusters of low-mass X-ray binaries, in Section 3 the numbers of neutron stars and field stars are derived from the initial mass function, and in Section 4 the lifetime of a low-mass X-ray binary is estimated. Application to observations follows in Section 5. In Section 6 we discuss the nature of the low-luminosity X-ray sources in globular clusters.

2. Formation mechanisms of X-ray binaries in globular clusters

2.1 Close encounters between neutron stars and other stars.

If a neutron star with mass m passes at closest distance d of a main sequence or giant star with mass M and radius R, the tidal bulge on this star will have a maximum height

$$h \simeq \frac{m}{M}\frac{R^4}{d^3}$$

and contain an amount of mass of order

$$m_t \simeq k\frac{h}{R}M \simeq k(\frac{R}{d})^3 m$$

where k is the apsidal motion constant (e.g. Schwarzschild 1958). For a star with deep convection $k \simeq 0.14$ (Motz 1952). The potential energy in the tidal bulge is of order

$$E_t \simeq m_t\frac{GM}{R^2}h \simeq k\frac{Gm^2}{R}(\frac{R}{d})^6$$

This can be compared with the kinetic energy at infinity

$$E_{in} = \frac{1}{2}\frac{mM}{m+M}v_{in}^2$$

where v_{in} is the relative velocity between the stars at infinity. The energy in the bulge exceeds the relative kinetic energy if

$$d \leq 3.2R(\frac{k}{0.14}\frac{m}{M}\frac{m+M}{2M_\odot}\frac{R_\odot}{R}\frac{10km\ s^{-1}}{v_{in}})^{1/6} = yR \quad (1)$$

The small power in this expression, caused by the strong radial dependence of tidal interactions, justifies the rough approximations made before. A binary will be formed if 1) the energy in the tidal bulge exceeds the kinetic energy at infinity, i.e. if eq.(1) is satisfied, and 2) the energy in the tidal bulge is dissipated.

The cross section for passage within distance d of two stars is given by

$$\sigma = \pi d^2 (1 + \frac{2G(m+M)}{v_{in}^2 d}) \simeq \pi d \, \frac{2G(m+M)}{v_{in}^2} \qquad (2)$$

The second term within brackets gives the effect of gravitational focussing and dominates for the small relative velocities in globular clusters, justifying the approximation in the third member.

The formation rate in globular clusters of low-mass X-ray binaries through tidal interactions follows with eqs.(1) and (2):

$$F = n_{ns} n v_{in} \sigma = 6 \times 10^{-11} \frac{n_{ns}}{10^2 pc^{-3}} \frac{n}{10^4 pc^{-3}} \frac{m+M}{M_\odot} \frac{yR}{R_\odot} \frac{10 km\ s^{-1}}{v_{in}}\ yr^{-1} pc^{-3} \qquad (3)$$

where n_{ns} and n are the number densities of neutron stars and other stars, respectively. The other stars can be main-sequence stars, or giants. The above formula corresponds to the results of Fabian, Pringle & Rees (1975). The different result of Sutantyo (1975) is due to his neglect of gravitational focussing. Press & Teukolsky (1977) estimate the dissipation rate for an n=3 polytrope star (cf. Burke 1967). Lee & Ostriker (1986) correct an error in the earlier estimate for the n=3 polytrope, and also present calculations for the n=1.5 polytrope. Because of the deep convective regions in low-mass stars, the result for the n=1.5 polytrope is more relevant, and it is similar to the result of the simple derivation above.

2.2 Exchange collisions

A close encounter of a binary with a single star often leads to the formation of a short-lived triple system, and generally ends with the expulsion of the least massive star of the three, leaving the other two stars in a binary. Thus a close encounter between a neutron star and a binary of two ordinary low-mass stars will usually lead to the replacement in the binary of an ordinary star with the neutron star (Hills 1976). The importance of this process in globular clusters depends on the number density in them of close binaries. Observational evidence on this is lacking at the moment. Even with an optimistic estimate of the number of close binaries in globular clusters the formation of low-mass X-ray binaries through exchange collisions barely competes with two-body encounters (Hut & Verbunt 1983). We will therefore neglect triple-body interactions.

2.3 Pushing a white dwarf over the Chandrasekhar limit.

Just as low-mass X-ray binaries are formed by close encounters between neutron stars and field stars, cataclysmic variables are formed by close encounters between white dwarfs and field stars (Hut & Verbunt 1983). Under special circumstances the white dwarf may accrete a sufficient amount of mass from its companion to transgress the Chandrasekhar limit and implode to a neutron star in a sufficiently quiet fashion to keep the binary intact. In the galactic disk the number of cataclysmic variables is $\sim 10^7$, the number of low-mass X-ray binaries ~ 50. Thus formation of a low-mass X-ray binary from a cataclysmic variable is an extremely rare event, and in globular clusters this mechanism does not compete with tidal capture in two-body encounters. We will therefore neglect white dwarf implosion.

3. The stellar population of globular clusters

3.1 The initial mass-function

To estimate the number densities of main-sequence stars, giants and neutron stars in globular clusters, Sutantyo (1975) and Van der Woerd & Van den Heuvel (1984) use the method of Tinsley (1974). It starts from the assumption that all stars in a globular cluster are born simultaneously, in numbers given by $dN = C_o m^{-1-x}\, dm$ with dN the number of stars with mass in the mass interval dm around mass m, and C_o a normalization constant. The number of stars originally in the interval between m_1 and m_2 is given by

$$N(m_1, m_2) = \int_{m_1}^{m_2} C_o m^{-1-x} dm = \frac{C_o}{x}(m_1^{-x} - m_2^{-x})$$

Gravitational interactions between the stars in a globular cluster enhance equipartition in kinetic energy between stars, leading to low velocities of massive stars and high velocities of less massive stars. Thus very light stars will escape from the cluster. The mass of the least massive stars still present in the cluster is called the cutoff mass, m_{co}. The time that a star takes to evolve away from the main sequence is smaller for more massive stars. The mass of the most massive stars in a cluster still on the main sequence is called the turnoff mass, m_{to}. Thus the number of main sequence stars is given by $N(m_{co}, m_{to})$.

The turnoff mass as a function of the age τ of the cluster can be written (Rood 1972)

$$log \frac{m_{to}}{M_\odot} = -0.28\, log \frac{\tau}{10^9 yr} + 0.013\, log Z - 0.75\, log Y + 0.453$$

Z and Y are the metal and helium contents of the cluster. The evolution of a giant star is fast with respect to the age of a globular cluster, and all giants will have a mass close to the turnoff mass. If the time that a giant spends at a given locus i of the giant branch is Δt_i, the number of giants at that locus is

$$N_{G,i} = 0.28\, C_o \frac{\Delta t_i}{\tau} m_{to}^{-x}$$

The total number of giants is found by summing the numbers at different evolutionary stages along the giant branch. All stars more massive than the turnoff mass will have completed their evolution. If all stars with original mass below m_a evolve into white dwarfs, and all stars with original mass between m_a and m_b into neutron stars, the number of white dwarfs in the cluster is given by $N(m_{to}, m_a)$, and the number of neutron stars by $fN(m_a, m_b)$. Here f is the fraction of neutron stars born with a velocity lower than the cluster escape velocity (see Section 3.2).

In the above we assumed that all stars leave either a white dwarf or a neutron star. It is possible that stars in a given mass interval do not leave remnants. Also, stars in close binaries may exchange mass with their companion, and leave a different remnant than single stars with the same initial mass. Inclusion of such effects is straightforward, but for the sake of clarity we will ignore them.

The constant C_o can be determined in a number of ways, for example:

a. count the number of main sequence stars in a given luminosity interval, and use the mass-luminosity relation to translate this into a mass interval.

b. count the number of red giants.

c. determine the total luminosity of the cluster, and equate this to the sum of the main-sequence and giant luminosities, found with the appropriate mas-luminosity relations.

3.2 Birth velocities of neutron stars

The average velocity of radio pulsars is $\sim 200\ km\ s^{-1}$, much higher than the escape velocity of a globular cluster. Katz (1975) argued that the presence of X-ray sources in globular clusters indicates that some compact objects are born with high velocity, and others with low velocity. Hut and Verbunt (1983) interpret this as indicating that single neutron stars are born with low velocity, whereas neutron stars born in a binary retain the high velocity of the orbital motion. The velocity measurements of 26 radio pulsars (Lyne, Anderson & Salter 1982) are compatible with such an interpretation. Consider a globular cluster with escape velocity 25 $km\ s^{-1}$. If the velocity distribution of the newly born neutron stars is identical to that of the 26 radio pulsars, some 16 % of the neutron stars would remain in the cluster ($f \simeq 0.16$). If there are no binaries in globular clusters the fraction remaining could be as high as 40 % ($f \simeq 0.4$).

4. Lifetimes of X-ray binaries

Our understanding of the evolution of low-mass X-ray binaries is too limited for exact estimates of the lifetime of these systems. For a system with a main-sequence companion an estimate for the lifetime is found by dividing the available mass by the mass transfer rate: a companion of 0.44 $M_\odot$ transferring at $10^{-9} M_\odot\ yr^{-1}$ is exhausted after $T_i = 0.44 \times 10^9 yr$. There is evidence that systems with mass transfer lower than $\sim 10^{-10} M_\odot yr^{-1}$ become transient, i.e. they transfer most of the mass in bursts lasting some months but are quiescent in the years between bursts (White, Kaluzienski & Swank 1984). The observed gap between bright and dim sources in globular clusters offers further evidence for a switch-off of systems at low mass- transfer rates (see Section 6). The theory of the evolution of low-mass X-ray binaries suggests that the mass transfer is drastically reduced when the mass of the main-sequence star is $\sim 0.3\ M_\odot$ (Rappaport, Verbunt & Joss 1983). The lifetime of bright X-ray binaries could then be as short as $T_i \simeq 0.1 \times 10^9 yr$ in globular clusters.

The lifetime of X-ray binaries with a giant is set by the evolution timescale of the giant: once the system passes the top of the giant branch, the system becomes detached and mass transfer stops.

5. Expected number of X-ray binaries in globular clusters

5.1 One cluster

As an example we consider the globular cluster NGC 6440. For this cluster we use the following parameters: $x = 2$, $m_{co} = 0.3M_\odot$, $m_{to} = 0.8M_\odot$, $\tau = 14\ 10^9 yr$ (cf. the values of Gunn & Griffin (1979) for M 3), $m_a = 8M_\odot$ (cf. Blaauw 1985), $m_b = 80M_\odot$, $m_{wd} = 0.6M_\odot$. The ratio of the numbers of main sequence stars, white dwarfs and neutron stars then is: $N_{ms} : N_{wd} : N_{ns} = 1 : 0.16 : 0.0016 f$. The average mass of the main sequence stars is $m_{ms} = M_{ms}/N_{ms} = 0.44M_\odot$. For the central density ρ_o we take $5 \times 10^5 M_\odot pc^{-3}$ (cf. Webbink 1985). If we neglect mass separation, it follows that the central number densities are $n_{ms} = 95 \times 10^4 pc^{-3}$, $n_{wd} = 15 \times 10^4 pc^{-3}$, $n_{ns} = 15f \times 10^2 pc^{-3}$. With the radius approximately proportional to the mass the average radius is $R_{ms} = 0.44R_\odot$. The average relative velocity of stars in the cluster is somewhat higher than the dispersion velocity, but capture is more efficient at lower velocities. Estimating v_{in} with the dispersion velocity σ of the cluster is therefore quite accurate. With an average mass for the neutron stars of $1.4M_\odot$ and a dispersion velocity $\sigma = 13\ km\ s^{-1}$ the central formation rate of low-mass X-ray binaries through tidal capture with main-sequence stars is $F = 1.6 \times 10^{-7} f\ yr^{-1} pc^{-3}$.

To find the ratio of tidal capture by giants with that by main-sequence stars we average the radii of the giants (taken from Rood 1972) weighing with the number of giants at each evolutionary stage:

$$\frac{F_G}{F_{ms}} = \frac{\Sigma\ N_{G,i} R_i}{N_{ms} R_{ms}} \simeq 0.07$$

Of this 0.07, 0.03 are due to subgiants, and 0.04 to giants.

To get the formation rate for the cluster as a whole, one has to integrate the formation rate over the volume of the cluster. In the absence of mass separation, a good estimate of the total formation rate can be made by multiplying the central formation rate with the core volume. To predict the number of observable low-mass

X-ray binaries one must multiply the formation rate with the expected lifetime of the X-ray binary. For systems with main-sequence stars we get

$$N_x = \frac{4}{3}\pi r_c^3 F\ T_i$$

With a core radius of 0.24 pc the predicted number of X-ray binaries is 0.9f to 4.0f, for $T_i = 0.1$ to $0.44 \times 10^9 yr$.

Systems with giants will live longer when the capture takes place at an earlier evolutionary stage. We assign to each system formed at stage i a lifetime $T_{G,i}$ equal to the time the giant takes to reach the top of the giant branch (taken from Rood 1972). Again scaling the number of systems with giants to the number of systems with main-sequence stars, we find for the ratio of the expected numbers:

$$\frac{N_{x,G}}{N_{x,ms}} = \frac{\Sigma\ F_G T_{G,i}}{F_{ms} T_i} = 0.06.$$

0.05 is due to subgiants, and 0.01 to giants on the giant branch.

In the above we have neglected mass separation. As neutron stars are more massive than the average cluster member, they will be strongly concentrated to the cluster core. Since most close encounters occur in or near the core, this will enhance the formation rate and hence the expected number of X-ray binaries. We estimate that the enhancement is approximately one order of magnitude. This would lead to an expected number of X-ray binaries in NGC 6440 of 9 f to 36 f. This cluster contains 1 X-ray transient.

5.2 The galactic system of globular clusters

From the above discussion follows that the number of expected X-ray binaries in a globular cluster is proportional to $C = \rho_o^2\, r_c^3/\sigma$ (see Eq.(3)). We use the compilation of Webbink (1985) to calculate C for the 147 clusters for which values for these parameters are available. The sum of all values of C is 0.385 $\times 10^{10} M_\odot^2 pc^{-3} s\ km^{-1}$. By comparison with the single cluster we then estimate the number of expected low-mass X-ray binaries in all galactic globular clusters together as $125f$ to $500f$ sources. This assumes that all parameters not entering C are the same in all clusters. Small variations between clusters in the parameters not used in C ($m_{co}, m_{to}, m_a, \tau$, etc) do not affect this estimate much. This means that the observed number of low-mass X-ray binaries in globular clusters can be explained with $f \simeq 0.1$, somewhat lower than our estimate in Section 3.2. Other possibilities are that a sizeable fraction of supernovae does not produce a neutron star remnant, or that the number of stars at higher mass is lower than that predicted from extrapolating the initial mass function (which after all is determined at masses an order of magnitude below the range of supernova predecessors).

Next we order the clusters with respect to their value of C, and assign space to them on a line running from 0 to 1 proportional to their value of C (Figure 1).

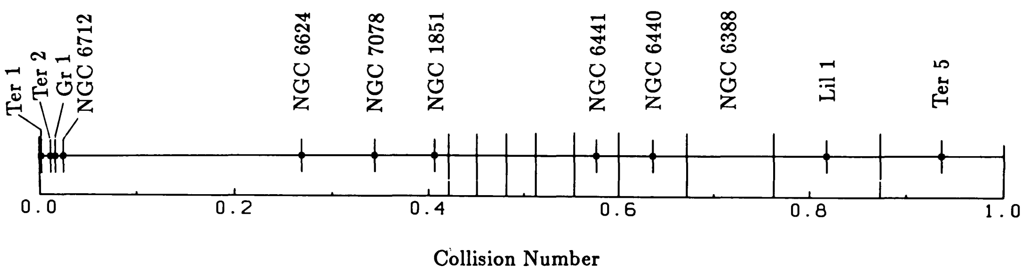

Figure 1. This Figure tests the hypothesis that low-mass X-ray binaries in globular clusters are formed through close encounters. It is made as follows: we calculate the number of close encounters C for 147 clusters listed by Webbink (1985). We order the clusters with respect to C and assign each cluster a space between 0 and 1 proportional to its value of C. For the clusters with the 9 largest C's this space is indicated in the Figure. The clusters containing low-mass X-ray binaries are marked. The source in NGC 6440 is transient, the source in Lil 1 (the rapid burster) is a recurrent transient. If sources are formed through close encounters they should be evenly distributed between 0 and 1.

This allows us to test the hypothesis that the number of low-mass X-ray binaries in a cluster is proportional to C: if this is the case the sources should be evenly distributed along the line (cf. Lightman & Grindlay 1982). For example, we expect that $\sim$ 13 % of all X-ray sources in clusters are in Ter 5. Also, whereas each individual cluster with small C is predicted to have a small probability of having an X-ray source, many of such clusters together should have some. We see from Figure 1 that 7 of the 11 sources known in globular clusters are indeed following the expected distribution, indicating that they are indeed formed by close encounters. Surprisingly, however, 4 of the sources are in clusters with a very small C. It should be noted that the values of C for individual clusters are rather uncertain, perhaps even more so in the five clusters which were studied only after an X-ray source was discovered in them (all of these clusters are located at the extremes of the C-distribution). It is therefore hard to asses the significance of the over-representation of low C clusters among the clusters containing an X-ray source. It may be worth while, however, to start looking for formation mechanisms for low-mass X-ray binaries in globular clusters which do not depend on close encounters, and to investigate whether Ter 2, Ter 1, Gri 1 and NGC 6712 are special in any respect.

6. The luminosity function and the dim sources

The sources discussed in the previous Sections all have been observed at $L_x >$

$10^{36} erg\ s^{-1}$ at some time, and therefore must contain neutron stars. These sources are all located within 2 r_c of the cluster center. With the sensitive *EINSTEIN* detectors Hertz & Grindlay (1983) discovered sources in a lower luminosity range ($L_x < 10^{34.5} erg\ s^{-1}$). No sources were discovered in the range $10^{34.5} < L_x(erg\ s^{-1} < 10^{36}$. Current theories of the evolution of low-mass X-ray binaries all predict that they have low mass-transfer rates once the mass of the secondary becomes low. The existence of a lower limit to the average luminosity of the bright sources at $L_x \simeq 10^{36} erg\ s^{-1}$ therefore indicates that low-mass X-ray binaries become transient if their mass-transfer rate drops below $\sim 10^{-10} M_\odot yr^{-1}$. It is more difficult to explain that the upper limit to the average luminosity of the globular cluster sources at $L_x \simeq 10^{37.3} erg\ s^{-1}$ is lower than the brightest galactic disk sources. The main difficulty is that the sources in the globular clusters of M 31 reach average X-ray luminosities as high as the brightest sources in our galactic disk, although the globular clusters in M 31 are very similar to the ones in our galaxy (Verbunt, Van Paradijs & Elson 1984).

The nature of the dim ($L_x < 10^{34.5} erg\ s^{-1}$) sources is the subject of some debate. Hertz and Grindlay (1983) argue that these sources are cataclysmic variables. Cataclysmic variables are expected to be formed in globular clusters by close encounters between white dwarfs and main-sequence cluster members (Hut & Verbunt 1983). Verbunt, Van Paradijs & Elson (1984) agree that the sources at the low end of the luminosity distribution of the dim sources, some of which are located far outside the cluster core, are presumably cataclysmic variables, but note that the brightest of the dim sources, all located in the cluster cores, seem too bright to be cataclysmic variables, and propose that they are transient low-mass X-ray binaries in quiescence.

Two *EXOSAT* observations shed new light on this debate. An observation of ω Cen indicates that some dim sources have very soft spectra ($kT \simeq 40eV$). For these sources the luminosities derived by Hertz & Grindlay, who assume $kT = 5keV$, may be an order of magnitude too high (Verbunt et al. 1986). In order to determine whether the brightest of the dim sources are too bright to be cataclysmic variables it is necessary to measure their temperatures.

The other *EXOSAT* observation concerns a source in the galactic disk: the soft X-ray transient Cen X-4. This source was detected at a level of $L_x \simeq 10^{32} - 10^{33} erg\ s^{-1}$, the first unambiguous detection of a soft X-ray transient in quiescence (Van Paradijs, Verbunt & Shafer, in preparation). This shows that transients in quiescence can indeed have luminosities in the range of the dim sources in globular clusters, and strengthens the case for identification of some dim sources with quiescent transients.

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Note: Some time after the conference a paper by S. Djorgovksi & I.R. King appeared (Astrophys. J. Letters **305**, L61; 1986) which presents evidence that Ter 1 and Ter 2 have undergone core collapse. This seems to support the suggestion of Grindlay at the conference that the four bright X-ray sources in clusters with low (present) encounter rates have formed during core collapse. On the other hand, NGC 6712 shows no sign of core collapse.

DISCUSSION

A. Blaauw: Your scenario first forms by capture, a binary which becomes the X-ray source. Is it possible that encounters, not close enough to lead to (semi-permanent) binaries, yet rather close, contribute to explaining observed X-ray sources?

F. Verbunt: Such sources would live a very short time, a day or a week or so. The observed sources are much more long-lived.

J. Grindlay: I wish to clarify what appears to be a misunderstanding of my talk based on the comments of the speaker, who stated that the number of CVs per LMXB in the plane is very different than in globular clusters. In fact the number of CVs per highest luminosity LMXB (i.e. the ~10 GX sources with luminosities ~10^{38} erg/s) is ~10^4 both in the field and in globulars. On this basis, I argued that accretion-induced-collapse (A.I.C.) of both CVs in globular and in giant-fed systems in the bulge are occurring. Secondly, it was apparently not clear that the neutron star formation by A.I.C. in globulars produces subsequently "re-cycled" X-ray sources by exchange collisions in the dense cluster cores so that they are predominantly observed as bursters with main sequence companions

F. Verbunt: This comment does not alter my opinion that direct close encounters between neutron stars and field stars are by far the most efficient way to make low-mass X-ray binaries in globular clusters. The comment is wrong in the sense that not a single globular cluster contains a source as bright as the bright galactic bulge sources.

J. Grindlay: I showed on a viewgraph (but did not mention) that formation of neutron stars in globulars from collapse of single massive stars may lead to the problem of escape from the cluster but also to a problem of "pollution" of the cluster with too many metals (from the many SN-II). Yet neutron stars are formed (in abundance) in metal poor clusters like M15. Globular cluster high luminosity sources (bursters, except M15) have the same luminosity distribution as bursters in the field (cf., Grindlay 1985, Proc. Japan-US Seminary on X-ray Sources). In contrast to your statement that none of the X-ray clusters appear to have undergone core collpase, this is not true for both NGC 6624 and M15, which show central cusps and possibly also NGC 6712, which may show an enhanced number of binaries (produced at core collpase) as indicated in my talk.

F. Verbunt: I agree. I don't think it affects any of my arguments. The main statement I make is that there is to my knowledge no evidence that Ter 1, Ter 2, Gr 1 or NGC6712 have undergone core-collapse. Further, there are several clusters that do show evidence of core-collapse that have much higher densities than the four just mentioned, and that do not contain low-mass X-ray binaries.