GLOBULAR CLUSTER FORMATION EFFICIENCIES FROM BLACK HOLE X-RAY BINARY FEEDBACK

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ABSTRACT

We investigate a scenario in which feedback from black hole X-ray binaries (BHXBs) sometimes begins inside young star clusters before strong supernova (SN) feedback. Those BHXBs could reduce the gas fraction inside embedded young clusters while maintaining virial equilibrium, which may help globular clusters (GCs) to stay bound when SN-driven gas ejection subsequently occurs. Adopting a simple toy model with parameters guided by BHXB population models, we produce GC formation efficiencies consistent with empirically inferred values. The metallicity dependence of BHXB formation could naturally explain why GC formation efficiency is higher at lower metallicity. For reasonable assumptions about that metallicity dependence, our toy model can produce a GC metallicity bimodality in some galaxies without a bimodality in the field-star metallicity distribution.

Key words: binaries: close – globular clusters: general – X-rays: binaries

1. INTRODUCTION

The formation of bound globular clusters (GCs) takes place in an exceptionally complicated environment. A complete explanation for observed GC populations likely involves multiple physical processes (see, e.g., Portegies Zwart et al. 2010; Longmore et al. 2014), probably including galaxy merger histories (see, e.g., Kruijssen 2014). However, a common simple picture is that proto-clusters become unbound when supernova feedback (SNF) ejects the remaining cluster gas, if the gas fraction at that time is too high (\(\gtrsim 0.7\)). If true, that might suggest that GC formation is linked to regions of very high star formation efficiency (\(\gtrsim 0.3\)).

It has been argued that young clusters lose their gas too early to be consistent with that picture (see, e.g., Longmore et al. 2014 and references therein). However, the inferred ages of known gas-free clusters which are most similar to young GCs are still broadly consistent with the model we present (Bastian et al. 2014), especially given the likely uncertainty in determining their ages (see, e.g., Schneider et al. 2014). Nonetheless, if proto-GCs are shown to always lose their gas before SNF occurs then our model would not work.

In this letter we examine whether X-ray binary (XB) feedback (XBF) may affect the survival probabilities of young star clusters, since black hole (BH) XBs (BHXBs) should sometimes form before significant SNF occurs (see Justham & Schawinski 2012). BHXBs may decrease the gas fraction inside the proto-cluster, and so could increase the effective star formation efficiency before supernovae (SNe) eject the remaining gas.

XBF has already been suggested to be especially important in the epoch of galaxy formation (see, e.g., Glover & Brand 2003; Power et al. 2009; Cantalupo 2010; Mirabel et al. 2011; Justham & Schawinski 2012; Artale et al. 2015). Not only might the radiative feedback from XBs be significant (Cantalupo 2010; Jeon et al. 2012; Power et al. 2013), so might their kinetic output (Fender et al. 2005; Heinz & Grimm 2005). Some XBs directly drive very energetic kinetic outflows (see, e.g., Gallo et al. 2005; Pakull et al. 2010; Soria et al. 2014). Stochastic galaxy-to-galaxy variation in XBF may help to explain some of the diversity in dwarf galaxy populations (Justham & Schawinski 2012).

Here we argue that the influence of BHXBs on the survival of proto-GCs might explain why the GC formation efficiency—\(\eta_{\text{GC}}\), i.e., the fraction of stellar mass which stays in bound clusters—apparently increases at lower metallicity (see, e.g., Harris & Harris 2002; Forte et al. 2005). Such a change in \(\eta_{\text{GC}}\) is necessary to explain why the GCs in massive, metal-rich galaxies are predominantly metal-poor (Peng et al. 2008). The present-day observed \(\eta_{\text{GC}}\) presumably represents both formation-epoch processes and subsequent cluster disruption (see, e.g., Gnedin & Ostriker 1997 and Figure 1). Unless the other processes which affect \(\eta_{\text{GC}}\) are strongly metallicity dependent then the model we present should be able to accommodate them.

We do not examine the formation of multiple stellar populations in GCs. Leigh et al. (2013) have done so when considering single stellar-mass BHs which accrete from the proto-cluster gas. If BHXBs can affect the formation epoch of GCs, then they might somehow help to resolve this problem.\footnote{By contrast, as we were finalizing this manuscript, Cabrera-Ziri et al. (2015) speculated that XBs might have ejected gas from some young clusters, thereby reducing the opportunity for second-generation star formation.}

Section 2 presents the background to this scenario. Sections 3 and 4 investigate the idea of using toy models.

2. FEEDBACK FROM XBS IN EMBEDDED YOUNG CLUSTERS

A key property of BHXBs for proto-GC survival is that BHXBs can be formed before SNe eject the cluster gas. This is possible if BHs can form relatively quietly, from stars more massive than those which dominate the energetic SNF (see, e.g., Heger et al. 2003; Justham & Schawinski 2012 and references therein).

Rappaport et al. (2005) find young BHXBs turn on \(\approx 4\) Myr after a starburst; their models match the observed luminous XB distribution in the Cartwheel galaxy. The expected time
available for such BHXBs to act before strong SNF depends on whether BH formation “by fallback” is sufficiently quiet to avoid sudden gas ejection, or only formation of BHs by direct collapse. Those options roughly correspond to initial single-star masses above $\approx 25M_\odot$ and $\approx 40M_\odot$, respectively (a more complete picture would be metallicity-dependent—see, e.g., Heger et al. 2003—and binarity adds further complexity). Nonetheless, by the time SNe explosively eject gas from the proto-GC, one or more BHXBs might well have had $\approx 1-5$ Myr to reduce the gas fraction inside the cluster, which is a significant qualitative difference between those proto-clusters in which an early BHXB does form and those in which one does not (Justham & Schawinski 2012).

There are exceptions to the above broad statements. For example, Belczynski & Taam (2008) predict that $\sim 0.1\%$ of NSs form within 5 Myr of star formation due to binary interactions, presumably in energetic SNe. Even rarer are BH-forming events probably associated with long-duration gamma-ray bursts (see, e.g., Podsiadlowski et al. 2004 and references therein), and classes of “super-luminous” SNe (see, e.g., Gal-Yam 2012). Our toy models neglect these unusual events, although they may be sufficiently common to affect detailed cluster demographics.

Another complication is the possibility of age spreads larger than $\approx 1$ Myr within cluster stellar populations. Since the expectation is that denser clusters should have smaller age spreads (Elmegreen 2000; Tan et al. 2006; Parmentier et al. 2014), this may make gas ejection by BHXBs relatively less important for less dense clusters than for proto-GCs.

\[ \eta_{\text{formation}} \times (1 - \eta_{\text{disruption}}) \times \eta_{\text{survival}} = \eta_{\text{GC}} \]

\[ \frac{E_{\text{bind}}}{E_{\text{XBF}}} \sim \frac{1}{30} \left( \frac{L_{\text{XBF}}}{10^{38} \text{ erg s}^{-1}} \right)^{1/2} \]

\[ \left( \frac{\Sigma_H}{1 \text{ g cm}^{-2}} \right) \sim \left( \frac{M_H}{10^5 M_\odot} \right) \left( \frac{R_{\text{GC}}}{10 \text{ pc}} \right)^{-2} \]

**2.2. Column Density**

Another argument in favor of the importance of XBF in young GCs is that the gas-rich environments of embedded clusters might be Compton-thick. This would help to trap the accretion luminosity. We take a column density of $10^{24}$ cm$^{-2}$ as sufficient for Compton-thickness, or a surface density $\Sigma_H$ of slightly above 1 g cm$^{-2}$. Scaling to this value, we find

\[ \left( \frac{\Sigma_H}{1 \text{ g cm}^{-2}} \right) \sim \left( \frac{M_H}{10^5 M_\odot} \right) \left( \frac{R_{\text{GC}}}{10 \text{ pc}} \right)^{-2} \]

where $M_H$ is the hydrogen gas mass. So for gas fractions of $\approx 90\%$ ($99\%$), proto-clusters with initial stellar masses above $\approx 10^5 M_\odot$ ($10^4 M_\odot$) may well be Compton-thick.

Zezas et al. (2002) reported six heavily obscured luminous X-ray sources consistent with being inside dense, gas-rich, star-forming clouds in the Antennae. Those may well represent less extreme examples of such embedded systems.
Here we assume that the formation of those pre-SNF BHXBs can be treated as a Poisson process.

At solar metallicity we take the mean population from the calculations of Rappaport et al. (2005), using the predicted number of BHXBs more luminous than $10^{39}$ erg s$^{-1}$ at an age of $\approx 5$ Myr. At that time, for a population which will eventually produce $10^6$ core-collapse SNe, their least optimistic model predicts $\approx 1$ such BHXB, and their more optimistic models $\approx 10$ of them. We adopt an intermediate value of 3 (simply normalized to 100$M_\odot$ of stars per core-collapse SN), so models allow at least half an order-of-magnitude of freedom in either direction in this BHXB frequency.

At “low metallicity”—roughly below 0.1 $Z_\odot$—we assume that the incidence of suitable luminous young BHXBs is 10 times higher than at $Z_\odot$. Observational evidence of a similar increase has become increasingly convincing (see, e.g., Mapelli et al. 2010; Prestwich et al. 2013; Brorby et al. 2014; Douna et al. 2015), and an increase was strongly expected by models (e.g., Belczynski et al. 2004; Dray 2006; Linden et al. 2010; Justham & Schawinski 2012; Fragos et al. 2013). This metallicity dependence likely does not only arise from a change in which single stars would form BHs, since other effects are important in forming a system containing a BH in a close binary. In particular, early envelope loss—with respect to the nuclear evolution of the stellar core—can lead a massive star to leave a NS remnant rather than a BH (see, e.g., Wellstein & Langer 1999; Brown & Lee 2004; Belczynski & Taam 2008).

However, at sufficiently low metallicity, massive stars burn helium before expanding to become giants, hence their common-envelope phases tend to happen later in their nuclear evolution, hence they are more likely to form BHs in close binaries. This effect may produce a sudden increase in suitable BHXB formation below the appropriate threshold metallicity (which might be significant for Section 4). Observational results from Prestwich et al. (2013) and especially Douna et al. (2015) also suggest a sharp increase in the frequency below a transition metallicity (below $12 + \log(O/H) \approx 8$ for the calibrations used, though conversion to an absolute metallicity scale is non-trivial).

3. SURVIVAL PROBABILITIES AND FORMATION EFFICIENCIES

We now use toy models to demonstrate potential consequences of this scenario. These adopt a very simple set of assumptions, including that star formation efficiency is so low that SN-driven ejection of the remaining gas would normally unbind a young cluster. So a cluster survives to become a GC if and only if a BHXB acts first. In the terminology of Figure 1, we assume that all stars form in clusters ($\eta_{\text{formation}} = 1$; though some clusters may have very low mass), and that if a BHXB is formed before SNF the cluster remains bound ($\eta_{\text{XBF}} = (1 - \eta_{\text{disruption}})$).

3.1. Toy Model without Later Evolution

First we neglect later disruption processes ($\eta_{\text{XBF}} = \eta_{\text{GC}}$). Then the probability of a cluster remaining bound is the Poisson probability of that mass of stars forming one or more BHXBs before SNF (taken from Section 2.3). In the statistical limit, this probability is also the fraction of clusters which remain bound with that particular initial mass (and metallicity).

Figure 2 presents outcomes from such probability calculations. The upper panel shows survival fractions for given initial cluster masses, and the lower panel the effect on a population of clusters with a given initial cluster mass function (ICMF). The “initial cluster masses” are stellar masses, not including gas. Since the survival fraction is very low below the mass range which typically produces GCs we conclude that, if this toy model is inappropriate below the mass range which produces GCs, it would only moderately affect broad predictions.

Figure 3 compares integrated survival efficiencies to present-day inferred $\eta_{\text{GC}}$ values (from Forte et al. 2005). The upper and lower panels demonstrate the effect of varying the uncertain upper and lower bounds of the integral over the ICMF. The values predicted for $\eta_{\text{GC}}$, along with the difference between $\eta_{\text{GC}}$.
for metal-rich and metal-poor clusters, appear at least order-of-magnitude consistent with observationally derived values in most of the parameter space.

Where the predicted \( G_C \) appears too high, this allows freedom for unclustered star formation and additional GC disruption mechanisms. So it seems preferable if the ICMF flattens or truncates at a few hundred solar masses or more. This constraint would relax slightly if suitable BHXBs are more common than we have assumed; we repeat that in BHXB models there is at least half an order-of-magnitude of freedom to allow this.

3.2. Toy Model Including Later Evolution

To our earlier assumptions we now add a parameterized version of later cluster evolution (due to Fall & Zhang 2001, via Jordán et al. 2007). For this we use a Monte Carlo approach, randomly drawing clusters from a Schechter-function ICMF and deciding whether each cluster remains bound based on the same BHXB formation probabilities as above. Each of the surviving clusters is then assumed to lose a mass \( \Delta \) after the formation epoch (Fall & Zhang 2001; Jordán et al. 2007).

Due to the large dynamic ranges, for the distributions in Figure 4 we drew \( 10^{11} \) primordial clusters from the ICMF. Over the mass range in Figure 4, assuming \( M_{105} = \epsilon \) reduces \( G_C \) by a factor of a few. This reproduces the GCMF turnover within our earlier model uncertainties.

3.3. The Upper Slope of the Cluster Luminosity Function

Jordán et al. (2007) found that the bright end of the GC luminosity function is steeper for GC populations around less massive host galaxies (which correlates with more metal-poor GC populations). Figure 4 displays the power law index \( \beta \) inferred by Jordán et al. (2007) for the upper mass function of those presumed metal-rich and metal-poor populations (\( \beta = 1.7 \) and 3.0, respectively). The correspondence with this model seems at least intriguing.

This qualitative effect also arises in our simplest toy model, as Figure 2 predicts that the upper mass function of bound GCs should be steeper for low-metallicity clusters.

4. CLUSTER METALLICITY DISTRIBUTIONS

If the formation of appropriate BHXBs has a suitable metallicity dependence, then this scenario might explain the metallicity bimodality of Galactic GCs. It is not certain whether the commonly observed color bimodality of extragalactic GCs indicates a similar metallicity bimodality (Yoon et al. 2006; Blakeslee et al. 2012). A metallicity-dependent \( \eta_{GC}(Z) \) would produce a GC metallicity bimodality when the host galaxy’s stellar metallicity distribution \( \mu(Z) \) was appropriate—i.e., only function ICMF and deciding whether each cluster remains bound based on the same BHXB formation probabilities as above. Each of the surviving clusters is then assumed to lose a mass—denoted by \( \Delta \)—after the formation epoch (Fall & Zhang 2001; Jordán et al. 2007).

Due to the large dynamic ranges, for the distributions in Figure 4 we drew \( 10^{11} \) primordial clusters from the ICMF. Over the mass range in Figure 4, assuming \( \Delta = 10^5 M_{\odot} \) reduces \( \eta_{GC} \) by a factor of a few. This reproduces the GCMF turnover within our earlier model uncertainties.

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if $\mu(Z) \times \eta_{\text{GC}}(Z)$ leads to a bimodal distribution. Unfortunately, robust $\mu(Z)$ distributions for entire galaxies, including their halo populations, are difficult to obtain.

Here we show that a simple $\eta_{\text{GC}}(Z)$ function, guided by our model, could reproduce a GC metallicity bimodality from a non-bimodal $\mu(Z)$. We assume two regimes of constant $\eta_{\text{GC}}$—one at low $Z$ and one around $Z_\odot$—matched by a transition region, expressed as

$$\log \left( \frac{\eta_{\text{GC}}(Z)}{\eta_{\text{GC}}(Z_\odot)} \right) = \frac{R}{2} \left[ 1 + \tanh \left( S \left[ T - \log \left( \frac{Z}{Z_\odot} \right) \right] \right) \right]$$

where $R$ represents the amount by which $\log(\eta_{\text{GC}})$ increases at low-$Z$, $S$ gives the “sharpness” of the transition between the $Z_\odot$ and low-$Z$ regimes, and $T$ indicates the metallicity around which that transition occurs.

For the upper row of Figure 5, we assume a $\mu(Z)$ constructed to approximate the $\mu(Z)$ distribution of NGC 1399 in Figure 5 of Forte et al. (2005). There we keep $\mu(Z)$ fixed, and show cluster metallicity distributions for different values of $R$, $S$, and $T$. Our adopted values of $R$ and $T$ are similar to those which we have previously suggested are expected (i.e., $\approx 1$ and $\approx -1$, respectively; see Section 2.3). From this $\mu(Z)$ we can recover a bimodality in cluster metallicity, and the qualitative result is not affected by small variations in $S$. The gradual metallicity dependence from Fragos et al. (2013) for generic high-mass XBs would not produce a bimodality, as shown in the central panel. However, the systems involved in our scenario are a very specific subset of young BHXBs. Moreover, there are indications that a sharp transition is at least plausible (see Section 2.3 and Douna et al. 2015).

The bottom row of Figure 5 demonstrates changing $\mu(Z)$ with fixed model parameters ($R = 0.7$, $S = 5$, $T = 1$). This illustrates that the model does not predict that every galaxy must have a bimodal cluster metallicity distribution (for which see, e.g., Usher et al. 2012), and that the peaks of the GC metallicity distribution are affected by the underlying $\mu(Z)$.

When future observations provide reliable $\mu(Z)$ distributions for a significant sample of galaxies, this should enable strong

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{For given star formation $Z$-distributions ($\mu(Z)$; the dotted curves), we demonstrate how a toy model may recover a bimodal distribution in cluster metallicity (solid curves). Upper row: the fixed $\mu(Z)$ is intended to be broadly representative of common $\mu(Z)$ distributions. Each panel varies one of the model parameters, with different curves labeled with the relevant parameter value. The dashed curve in the center panel shows the outcome when applying the metallicity dependence for generic HMXBs from Fragos et al. (2013). Lower row: for fixed parameters ($R = 0.7$, $S = 5$, $T = 1$), we show results from varying $\mu(Z)$; in the left-hand panel, the black curves are for the same $\mu(Z)$ as in the top row.}
\end{figure}
constraints on our model. If Equation (4) provides a good functional form for ηGC(Z)—and if ηGC is only a function of metallicity—then the parameters R, S and T should be universal constants. However, we expect that reality is more complicated. For example, this simplified model assumes that γXMB—and hence ηGC—has only two regimes (Z_≤ and low-Z). At higher metallicities ηXMB might well decrease further. Indeed, for metallicities significantly above solar then single stars might no longer leave BH remnants at all (see, e.g., Heger et al. 2003).

5. PROTON-CAPTURE REACTIONS AND ABUNDANCE ANTICORRELATIONS

Since the Na–O and Mg–Al anticorrelations are exclusively associated with star clusters which stay bound, it would be elegant if these anticorrelations could be explained by the BHXBs which—in this model—allow clusters to stay bound. This speculation arose since the relevant nuclear reactions are high-energy proton capture reactions (see, e.g., Izzard et al. 2007), and many BHXBs may be prolific sources of high-energy protons (see, e.g., Heinz & Sunyaev 2002; Fender et al. 2005).

Unfortunately, even for assumptions which we expect are extremely optimistic, we have been unable to convince ourselves that a single BHXB would explain the observed abundance anomalies in an entire GC.

Nonetheless, variations on this mechanism may deserve further examination, perhaps involving other proton accelerators in these dense stellar systems.

6. CONCLUSIONS

We have investigated a scenario in which young stellar clusters are able to survive as bound GCs only when feedback from BHXBs gradually decreases the gas fraction inside the cluster before energetic SNe suddenly eject the remainder of the gas. Several potential complications are ignored by our toy model. However, as long as the other processes which affect ηGC are largely metallicity-independent, this scenario may well have sufficient freedom to include them without losing its positive features. A minimal set of assumptions, combined with input numbers estimated from population models for suitable BHXBs, produces predictions consistent with observationally inferred ηGC, including the increase in ηGC at low metallicity. We therefore suggest that more detailed study of early feedback from BHXBs in proto-GCs may be important for trying to understand GC populations.

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REFERENCES

Artale, M. C., Tissera, P. B., & Pellizza, L. J. 2015, MNRAS, 448, 3071
Bastian, N., Hollyhead, K., & Cabrera-Ziri, I. 2014, MNRAS, 445, 378
Belczynski, K., Sadowski, A., & Rasio, F. A. 2004, ApJ, 611, 1068
Belczynski, K., & Taam, R. E. 2008, ApJ, 685, 400
Blakeslee, J. P., Choi, H., Peng, E. W., et al. 2012, ApJ, 746, 88
Brotherton, M., Kaaret, P., & Prestwich, A. 2014, MNRAS, 441, 2346
Brown, G. E., & Lee, C.-H. 2004, NewA, 9, 225
Cabrera-Ziri, I., Bastian, N., Longmore, S. N., et al. 2015, MNRAS, 448, 2224
Cantalupo, S. 2010, MNRAS, 403, L16
Douma, V. M., Pellizza, L. J., Mirabel, I. F., & Pedrosa, S. E. 2015, A&A, 579, A44
Dray, L. M. 2006, MNRAS, 370, 2079
Elmegreen, B. G. 2000, ApJ, 530, 277
Fall, S. M., & Zhang, Q. 2001, ApJ, 561, 751
Fender, R. P., Maccarone, T. J., & van Kesteren, Z. 2005, MNRAS, 360, 1085
Forte, J. C., Faifer, F., & Geisler, D. 2005, MNRAS, 357, 56
Fragos, T., Lehner, B. D., Naoz, S., Zezas, A., & Basu-Zych, A. 2013, ApJL, 776, L31
Fujita, Y., & Griem, H. J. 2005, ApJ, 633, 384
Heinz, S., & Sunyaev, R. 2002, A&A, 390, 751
Izzard, R. G., Lugrano, M., Karakas, A. I., Illidis, C., & van Raai, M. 2007, A&A, 466, 641
Jeon, M., Pawlik, A. H., Greif, T. H., et al. 2012, ApJ, 754, 34
Jordán, Á., McLaughlin, D. E., Coté, P., et al. 2007, ApJS, 171, 101
Justham, S., & Schawinski, K. 2012, MNRAS, 423, 1641
Krijssen, J. M. D. 2014, CQGra, 31, 244006
Leigh, N. W. C., Böker, T., Maccarone, T. J., & Perets, H. B. 2013, MNRAS, 429, 2997
Linden, T., Kalogera, V., & Sipkins, J. F., et al. 2010, ApJ, 725, 1984
Longmore, S. N., Krijssen, J. M. D., Bastian, N., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 291
Mapelli, M., Rimondini, E., Zampieri, L., Colpi, M., & Bressan, A. 2010, MNRAS, 408, 234
Mirabel, I. F., Dijkstra, M., Laurent, P., Loeb, A., & Pritchard, J. R. 2011, A&A, 528, A149
Miralta, W. S., & Motch, C. 2010, Natura, 466, 209
Parmentier, G., Pfalzner, S., & Grebel, E. K. 2014, ApJ, 791, 132
Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJL, 607, L17
Poggio, Zwart, S. F., McMillan, S. L. W., & Gieles, M. 2010, ARA&A, 48, 431
Power, C., James, G., Combet, C., & Wynn, G. 2013, ApJ, 764, 76
Power, C., Wynn, G. A., Combet, C., & Wilkinson, M. I. 2009, MNRAS, 395, 1146
Prestwich, A. H., Tsantaki, M., Zezas, A., et al. 2013, ApJ, 769, 92
Rappaport, S. A., Podsiadlowski, P., & Pfahl, E. 2005, MNRAS, 356, 401
Schneider, F. R. N., Izzard, R. G., de Mink, S. E., et al. 2014, ApJ, 780, 117
Soria, R., Long, K. S., Blair, W. P., et al. 2014, Sci, 343, 1330
Tan, J. C., Krumholz, M. R., & McKee, C. F. 2006, ApJ, 641, L121
Usher, C., Forbes, D. A., Brodie, J. P., et al. 2012, MNRAS, 426, 1475
Wellstein, S., & Langer, N. 1999, A&A, 350, 148
Yoon, S.-J., Yi, S. K., & Lee, Y.-W. 2006, Sci, 311, 1129
Zezas, A., Fabiano, G., Rots, A. H., & Murray, S. S. 2002, ApJ, 577, 710