# Star Cluster Evolution with Primordial Binaries

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**Abstract.** Observations and theoretical work suggest that globular clusters may be born with initially very large binary fractions. We present first results from our newly modified Monte-Carlo cluster evolution code, which treats binary interactions exactly via direct $N$-body integration. It is shown that binary scattering interactions generate significantly less energy than predicted by the recipes that have been used in the past to model them in approximate cluster evolution methods. The new result, that the cores of globular clusters in the long-lived binary-burning phase are smaller than previously predicted, weakens the agreement with observations, thus implying that more than simply stellar dynamics is at work in shaping the globular clusters we observe today.

## 1. Introduction

Observations, in combination with theoretical work, suggest that although the currently observed binary fractions in the cores of globular clusters may be small ($\sim 10\%$), the initial cluster binary fraction may have been significantly larger ($\sim 100\%$) (Ivanova et al., 2005). It has been understood theoretically for many years that primordial binaries in star clusters act as an energy source (through super-elastic scattering encounters with stars and other binaries), with a binary fraction of a few percent being enough to postpone deep core collapse for many relaxation times (see Fregeau et al., 2003, for discussion and references). In addition to playing a large part in the global evolution of globular clusters, dynamical interactions of binaries also strongly affect the formation and evolution of stellar and binary exotica (e.g. low-mass X-ray binaries, blue stragglers).

In previous studies using approximate methods (e.g. Monte-Carlo or Fokker-Planck) to simulate the evolution of star clusters, binary interactions had generally been treated using recipes culled from the results of large numbers of numerical scattering experiments—although in one case direct integration of binary interactions was performed for equal-mass stars (Giersz & Spurzem, 2003). The recipes are typically known only for equal-mass binary interactions, thus prohibiting the use of a mass function in the cluster's initial conditions. In order to model realistic clusters, which contain a wide range of masses, one must numerically integrate each binary interaction in order to resolve it properly.

In this article we present first results from our newly modified Monte-Carlo code, in which we have included for the first time exact integration of dynamical interactions of binaries with arbitrary mass members. A detailed description of all new modifications (which include physical stellar collisions and improve-
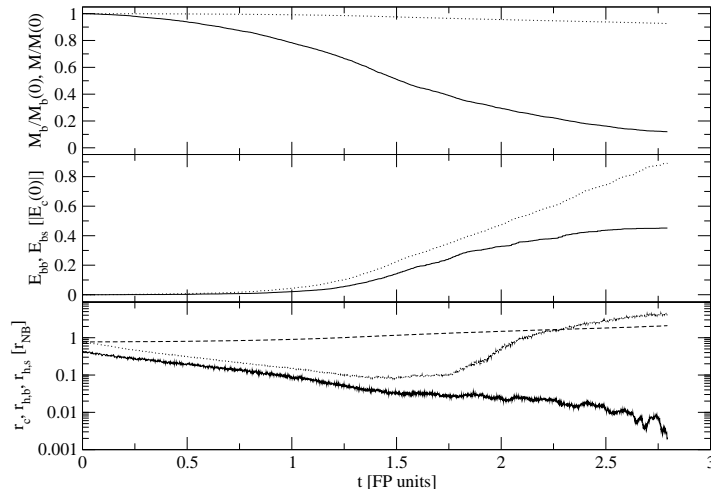
Figure 1.    Evolution of an isolated Plummer model with $3 \times 10^5$ stars and an initial 2% binary fraction. The top panel shows $M_b$, the total mass in binaries bound to the cluster (solid line), and $M$, the total mass of the cluster (dotted line), as a function of time, relative to their initial values. The middle panel shows $E_{\mathrm{bb}}$, the cumulative energy generated in binary–binary interactions (solid line) and $E_{\mathrm{bs}}$, the cumulative energy generated in binary–single interactions (dotted line) relative to $|E_c(0)|$, the absolute value of the cluster's initial mechanical energy. The bottom panel shows the evolution of $r_c$, the cluster core radius (solid line), $r_{\mathrm{h,b}}$, the half-mass radius of the binaries (dotted line), and $r_{\mathrm{h,s}}$, the half-mass radius of single stars (dashed line). The unit of time is the global cluster relaxation time, which is $\approx 10 t_{\mathrm{rh}}$.

ments to the core Monte-Carlo technique), and results, will be reported in a forthcoming paper.

## 2.    Results

In a previous paper (Fregeau et al., 2003), we simulated the evolution of clusters with primordial binaries by using recipes for the outcomes of binary interactions. Since we now treat binary interactions exactly via direct numerical integration, we compare our results with those of that work.

Fig. 1 shows the evolution of an isolated Plummer model with an initial 2% binary fraction. In this model all stars had the same mass. This can be compared directly with Fig. 3 of Fregeau et al. (2003), in which we used recipes for binary interactions. The evolution of the two models is quite similar, with both showing the binaries starting to get kicked out of the core (as evidenced by $r_{\mathrm{h,b}}$) around $t/t_{\mathrm{rh}} \approx 17$, entering deep core collapse at $t/t_{\mathrm{rh}} \sim 25$, showing roughly the same rate of binary mass loss (due to binaries getting disrupted or kicked out of the cluster), and roughly the same rate of energy generation in binary interactions. However, we find that although the simple recipes reproduce the energy generation in binary–single interactions reasonably well, they over-
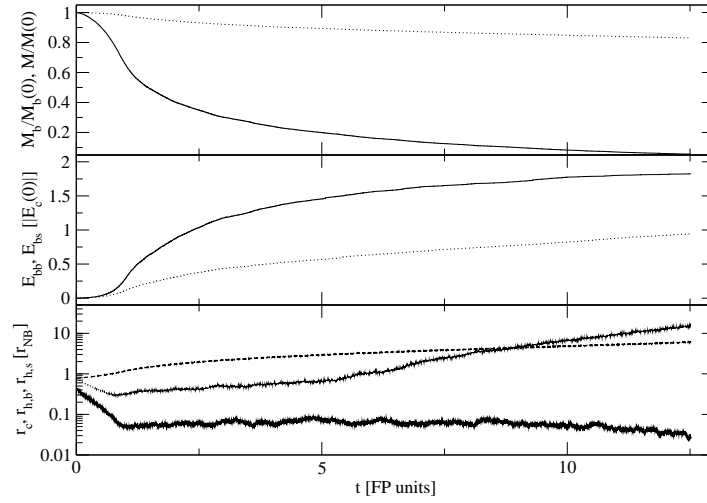
Figure 2.     Same as Fig. 1, but for an initial binary fraction of 10%.
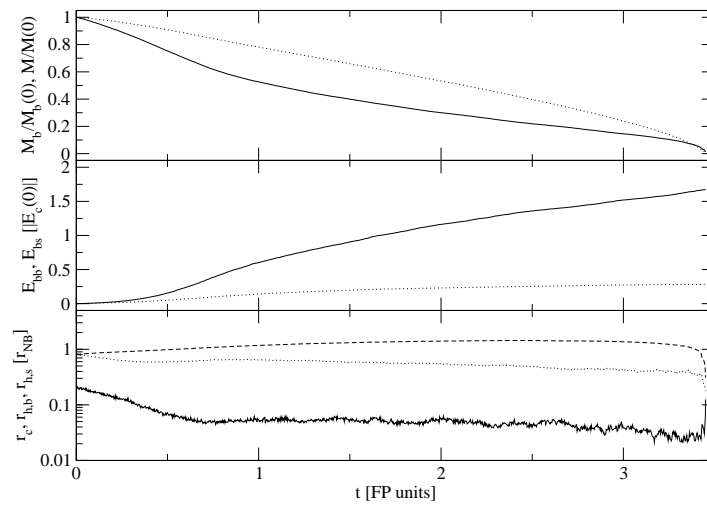


Figure 3.     Same as Fig. 1, but for a tidally-truncated $W_0 = 7$ King model
with an initial binary fraction of 20%.

estimate the rate of energy generation in binary–binary interactions by a factor of two relative to exact integrations. The same disagreement between recipes and exact integrations for binary–binary interactions was found by Giersz & Spurzem (2003) in their models. Another point of note is that with direct integrations the approach to deep core collapse is much noisier, with what appear to be many "mini" gravothermal oscillations.

Fig. 2 shows the same as Fig. 1, but for an initial binary fraction of 10%. This can be compared directly with Fig. 4 of Fregeau et al. (2003). Again we find that the energy generation rate due to binary–single interactions is comparable between recipes and direct integrations. For binary–binary, integrations predict a rate that is roughly 60% of what recipes predict.

Finally, in Fig. 3 we show the evolution of an initial $W_0 = 7$ King model with 20% primordial binaries, which can be compared directly with Fig. 11 of Fregeau et al. (2003). Just as in that paper, the cluster is disrupted by the tidal field of its host galaxy before core collapse, at a time of roughly $t/t_{\rm rh} \sim 35$–40. Looking more closely at the figures, we see that the evolution of $M_b$, $M$, $r_{\rm h,s}$, and $r_{\rm h,b}$ is quite similar between the two models. Again, we find that with integrations the binary-burning rate is smaller. One major difference between the two is that with integrations the core radius shrinks, then remains at a constant value once the steady binary-burning phase is reached. With recipes, the core appears to expand from the start. The discrepancy is no doubt caused by the larger rate of binary-burning in the model with recipes.

## 3.   Conclusion

Although our models for evolving globular clusters are somewhat simplified— since they include the effects of two-body relaxation and binary interactions, but ignore the effects of stellar evolution—we can still reach some conclusions by comparing with observations. In Fregeau et al. (2003) we found that the values of cluster half-mass radius to core radius, $r_h/r_c$, predicted by models using recipes for binary interactions were in reasonably good agreement with observations. Our new models, which treat binary interactions exactly, predict a significantly lower core energy generation rate, and a consequently smaller core, yielding values of $r_h/r_c$ up to an order of magnitude larger. This disagreement suggests that processes other than simply stellar dynamics—such as stellar evolution— may play a very important role in shaping the clusters we observe today.

## References

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