THE EARLY STAGES OF POST-COLLAPSE CLUSTER EVOLUTION

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I. INTRODUCTION

We present here some recent (and very preliminary) findings from a study of the early stages of the post-core-collapse evolution of an isolated cluster of identical point "stars". The method used to follow the behavior of the system is the unified N-body/statistical treatment described in detail by McMillan and Lightman (1984a) and by Lightman and McMillan elsewhere in this volume. Briefly, the method combines the standard "large-N" and "small-N" approaches to the problem in the régimes where they are appropriate by treating the inner regions ($r < r_N$) exactly with a regularized Aarseth N-body code (Aarseth, 1972), while permitting stars at greater and greater radii to retain less and less of their individual identities, ultimately treating the outer portions of the system ($r > Kr_N$) in an almost purely statistical fashion.

The calculations described here may be viewed as an extension of those reported by McMillan and Lightman (1984b, hereafter referred to as ML), although this is a completely separate run with somewhat different initial conditions and operating parameters and a number of significant improvements to the computer program. The most important improvement is in the handling of close triple and higher-order encounters within the N-body code. While the regularization procedure adopted deals effectively with close two-body interactions, situations in which there is no dominant pair to regularize within a high-density "clump" of three or more stars can lead to substantial integration errors. This problem is virtually eliminated by the establishment of a "group" structure on the N-body stars. Basically, the definition of a group is such that the critical clumps of stars just mentioned can be identified and their members given special attention. The single most important step taken with group members is the shortening of their timesteps; in addition, specific troublesome configurations can be checked for and appropriate action taken. More detailed definitions and procedures for group initialization and termination will be presented in a future paper.

For this run, the system was initialized from the late-time distribution reported by Cohn (1980) with core radius equal to 0.5 r_N and around fifty stars in the core (125 N-body stars altogether). The

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interface between the exact and purely statistical radial zones had K = 6 and consisted of approximately 450 mass shells initially. The run consumed a total of 31 hours of CPU time on an FPS-164 Array Processor, almost all of the time being taken up by the N-body integration. With the above-mentioned group handling in place, typical N-body integration errors were less than two parts in 10^5 per central relaxation time.

II. RESULTS

The variation with time of the central density and the total energy (in units of the initial central mean stellar kinetic energy, E_O) "locked up" in the form of tightly bound binaries are shown in Figures 1 and 2. In each case, the time unit, t_N is the dynamical timescale, roughly one-fifth of the initial central relaxation time, and the results have been averaged over twenty dynamical times so that the long-term behavior of the system is not obscured by noise.

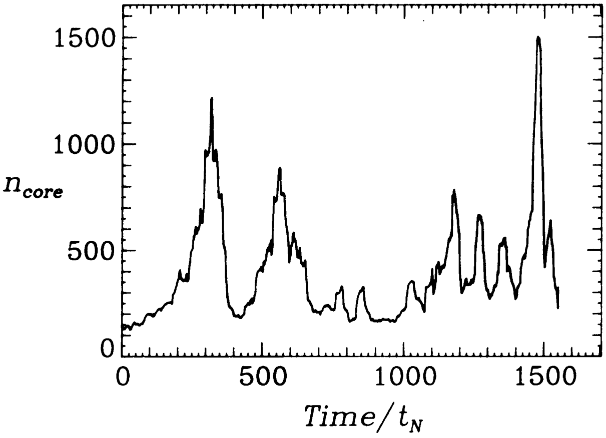

FIGURE 1. Mean density within one characteristic core radius (as defined by Aarseth, 1974) of the density center.

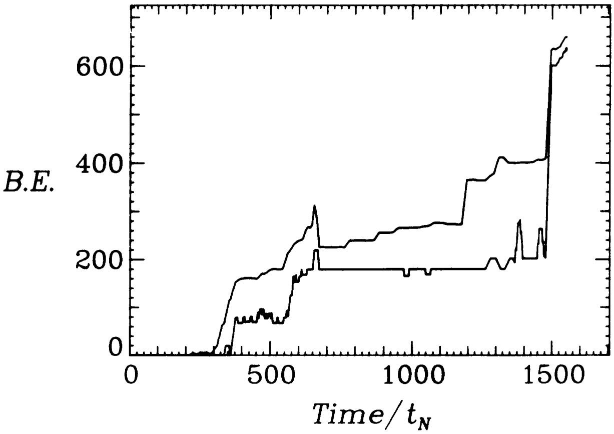

FIGURE 2. Binding energy (defined to be positive for a bound pair) stored in the form of hard binaries. The upper and lower lines represent the total energy and the energy outside the N-body region, respectively.

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These figures may be compared with the results, and discussion thereof, given by ML. Once again, we find that the projected time to complete initial collapse is around one hundred initial central relaxation times. Several cycles of the core oscillations reported by ML can be seen. The claim that the oscillations are regulated by binary formation, hardening and ejection from the core is strongly supported by the facts that (i) with one notable exception (at around 1350 t_N), the termination of each collapse phase is associated with a significant increase in total binary binding energy, and (ii) the magnitude of each increase may be shown to be comparable with the core kinetic energy around the time of the density maximum. In addition, in many cases, the subsequent ejection of the binary from the N-body region can easily be seen in Figure 2.

At the end of the run, there were five very hard binaries in the system, with binding energies ranging from 15 E_o to 400 E_o. Again as conjectured by ML, binary-binary (and even binary-binary-binary!) interactions became quite frequent at late times; however, the effects of these encounters have not yet been analyzed in any detail.

III. DISCUSSION

It is not clear whether the apparent decay of the oscillations is real or just a chance phenomenon. The edge of the central isothermal region (Heggie's (1984) R_*) is rather hard to determine precisely, but if we assume that R_* lies between ten and twenty core radii at the time of maximum collapse, it may be shown (ML) that the decay timescale associated with the increase in R_* is between 1500 and 6000 t_N, suggesting that we might indeed be seeing the precursor to a steady reexpansion phase. Two other interesting findings are (i) binary lifetimes and maximum energies seem to be much larger than expected (indeed, the hardest binary in the system at the end was formed in the initial collapse, but was ejected only during the final oscillation) and (ii) there appears to be a substantial "non-diffusive" flux of stars ejected directly from the core to quite large radii. An explanation of the longevity may be that many energetic encounters seem to occur within groups of stars; by absorbing some of the liberated energy, these groups could reduce the binary recoil velocities. These facts clearly affect the arguments given in ML and warrant considerably closer scrutiny.

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