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THE PROMISCUOUS NATURE OF STARS IN CLUSTERS

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ABSTRACT

The recent availability of special-purpose computers designed for calculating gravitational interactions of *N* bodies at extremely high speed has provided the means to model globular clusters on a star-by-star basis for the first time. By endeavoring to make the *N*-body codes that operate on these machines as realistic as possible, the addition of stellar evolution being one example, we are learning much about the interaction between the star cluster itself and the stars it contains. A fascinating aspect of this research is the ability to follow the orbits of individual stars in detail and to document the formation of observed exotic systems. This has revealed that many stars within a star cluster lead wildly promiscuous lives, interacting often intimately and in rapid succession with a variety of neighbors.

Subject headings: blue stragglers — globular clusters: general — methods: *n*-body simulations — open clusters and associations: general — stellar dynamics —

1. INTRODUCTION

The rich environment of a star cluster provides an ideal laboratory for the study of self-gravitating systems. Star clusters within our Galaxy range in size from loose associations and open clusters, which contain up to tens of thousands of stars, to the large globular clusters that host a million stars or more. Globular clusters are some of the oldest objects known, and dynamically they lie in a very interesting regime. The central density of stars in a globular cluster is high enough, in comparison to the solar neighborhood (a factor of 10 million or more greater in some globular clusters), that a significant fraction of the cluster stars are likely to experience at least one close encounter with another star during their lifetime. At the opposite end of the scale, the size of a globular cluster is small enough, in comparison to a galaxy, that its dynamical relaxation timescale is less than its age. These combined considerations make a globular cluster an exciting place for a star to reside. As such, we expect the stellar populations of a star cluster, i.e., the various classes of stars and binaries, to exhibit a dynamical signature. In particular, many of the stars contained in the cluster will deviate strongly from the evolutionary paths predicted by standard stellar and binary evolution theory. This is indeed what we observe, either when pointing the *Hubble Space Telescope* (*HST*) at the centers of globular clusters or when generating star-by-star models of star cluster evolution.

2. OBSERVATIONS OF EXOTIC OBJECTS

Observational evidence for the modification of stellar populations in star clusters due to dynamical interactions between the cluster stars is found in many instances (see Bailyn 1995 for a review). A common indicator of this effect is a variation in the radial distribution of a particular stellar subpopulation within the cluster. If, for example, a certain type of exotic star is found primarily in the core of a cluster, where the number density of stars is highest and, hence, where interactions between stars are most likely, then this is taken as strong evidence that these stars have a dynamical origin.

Blue stragglers (BSs) are stars that burn hydrogen in their cores and that, according to their stellar mass, should already have evolved off the main sequence (MS) and past the red giant stage to become white dwarfs (WDs), i.e., stellar corpses. Somehow, these stars have been rejuvenated. Popular theories of the cause of this phenomenon are mass transfer from a companion star in a close binary system or the collision of two MS stars. *HST* observations of the dynamically old and metal-poor Galactic globular cluster M30 have revealed a number of BSs (Guhathakurta et al. 1998). When plotted in a cumulative radial distribution, these BSs appear concentrated toward the cluster core relative to standard MS stars. Conversely, the population of bright red giants in M30 is depleted in the core. This suggests that collisions are destroying giants, by ripping off their envelopes and reducing them to WDs, and creating BSs. Ferraro et al. (1999) used *HST* to identify 305 BSs in the high-density globular cluster M80. These are also centrally concentrated with respect to the giants in the cluster, and the suggestion is that M80 is being observed at a critical phase in its evolution, when stellar interactions are delaying the collapse of the core (Ferraro et al. 1999)—which leads to the production of collisional BSs.

Blue stragglers are not the only stars that exhibit enhanced populations in the cores of globular clusters. X-ray binaries are at least 1000 times more abundant in clusters than in the Galactic field, and they are being found in ever-increasing numbers with the *Chandra X-Ray Observatory* (Grindlay et al. 2001). Millisecond pulsars, including some in binaries or with planets (D'Amico et al. 2001), are prevalent in cluster cores. Cataclysmic binaries in clusters have been predicted and are also being found (Shara et al. 1996; Grindlay et al. 2001). A few subdwarf (sdB) stars have been located and characterized (Moehler, Heber, & Durell 1997).

Even though the stellar neighborhood within an open cluster is less dense than that of a globular cluster, it is still capable of producing exotic objects. The number of BSs found in the open cluster M67 is much greater than we would expect if they are simply produced via mass transfer in binaries that exhibit the same distribution of orbital characteristics as that of binary stars found in the field. Furthermore, these BSs have a variety of living arrangements (Leonard 1996 and references therein). Some are single, while others are found with a companion. In some cases, the BS and the companion star interact in an intimate and regular manner (short-period circular orbit); in other cases, the relationship is distant (long-period orbit) and may even appear eccentric. One of the BSs is so massive, a super-BS, that it must represent the merger of three stars, and another is observed in an active triple system, a ménage-à-trois (van den Berg et al. 2001). All of this suggests that the BSs have varied formation histories and that no one mechanism is responsible for their production (Leonard 1996). In particular, the presence of a super-BS and of BSs in eccentric binaries is not predicted by standard binary evolution and points to dynamical interactions tampering with the destinies of stars.

3. SIMULATION METHODS

On a basic dynamical level, a star cluster is composed of *N* bodies that interact with each other because of the gravitational force of every other body in the system. The ideal method for following the evolution of such a system is to directly integrate the *N* individual equations of motion, the *N*-body approach. However, the cost of integrating the cluster for a relaxation time scales as N^3—N per force calculation, N^2 to integrate N bodies for one crossing (dynamical) time, and there are of order *N* crossing times per relaxation time—so the method is computationally expensive. As a result, most *N*-body simulations performed until recently, although state-of-the-art at the time, have involved a varying number of simplified and unrealistic conditions, such as including only single stars, using only equal-mass stars, neglecting stellar evolution, or assuming no external tidal field (McMillan, Hut, & Makino 1991; Heggie & Aarseth 1992). Performance has been enhanced by the development of improved computational algorithms. For example, the use of individual time steps (Aarseth 1963) enables each star to evolve on its own natural dynamical timescale rather than forcing a small time step on the entire system when only a fraction of the stars may need frequent attention. Quantizing these time steps into a series of hierarchical levels increases the efficiency of the integration (McMillan 1996). Also, regularization techniques have been developed to remove the singularities involved with compact binaries and few-body configurations, as well as to improve the accuracy of the treatment (Mikkola & Aarseth 1998).

The very nature of the large *N* effects that make the *N*-body method so computationally expensive can be used to justify the use of statistical algorithms such as the orbit-averaged Fokker-Planck equation (Hénon 1961; Giersz 2001; Joshi, Nave, & Rasio 2001). In theory, the *N*-body and Fokker-Planck methods, when applied to the same initial conditions, should give similar results in the limit of large *N* (Takahashi & Portegies Zwart 2000). Ultimately, the *N*-body approach remains the method of choice for creating dynamical models of star clusters as a minimum number of simplifying assumptions are required, and it is relatively easy to implement additional realistic features (see Meylan & Heggie 1997 for a full discussion). It is also possible to follow the journey made by a particular star as the cluster evolves.

A major impact on the suitability of *N*-body methods has been recent advances in computing power, in particular, the development of special purpose hardware. The GRAPE-4 (GRAvity PipE) system became commercially available in 1995 and was designed specifically for high-accuracy simulations of dense stellar systems (Makino & Taiji 1998). It basically acts as a Newtonian force accelerator; the host workstation supplies the GRAPE with the positions, velocities, and masses of a list of particles, and the GRAPE returns the force and its time derivative for each particle. A 96 chip GRAPE-4 board operates at a peak speed of ~50 Gflops (50 billion floating-point operations s^{-1}) and has enabled production of realistic open cluster models within a reasonable time. To be precise, a simulation of 10,000 stars with a moderate binary fraction of 10% could be completed within a week. Dealing with binary systems complicates matters because, as far as the GRAPE is concerned, it sees binaries solely as the center-of-mass particle, and the integration of the orbits of the stars within each binary system must be dealt with on the host machine. Therefore, the inclusion of a large proportion of binaries in a simulation is a potential bottleneck to the computational performance. These concerns are nontrivial because upward of 50% of the stars in any one globular cluster may be binaries and because the majority of these will be primordial (Hut et al. 1992). On the upside, Makino & Hut (1990) have shown that the computational cost of primordial binaries becomes (relatively) less of a problem when *N* is increased.

The next-generation machine, the GRAPE-6 (Makino 2002), became available in early 2001 and has provided a further leap forward for *N*-body methods. A single GRAPE-6 chip has an operating speed of ~30 Gflops, so that a 32 chip board represents 1 Tflops of computing power. The peak speed of GRAPE-6 is up to 100 times faster than GRAPE-4. This exciting development means that models of 50,000 stars can be simulated from formation to death, i.e., ~10 Gyr, in a week of wall-clock time. As such, it is now possible to produce realistic *N*-body models of small globular clusters for the first time. The largest Galactic globular clusters are still out of reach for a single GRAPE-6 board. However, at the University of Tokyo, where the GRAPE project is based, work is underway to link many GRAPE-6 boards in parallel and simulate systems that contain upward of 100,000 stars.[1] To tackle the million-body problem, we will have to wait for the GRAPE-8, which is expected to run at Petaflops speed.

The Aarseth NBODY4 code (Aarseth 1999) has been developed to investigate the evolution of star clusters by utilizing the GRAPE hardware. Importantly, NBODY4 incorporates algorithms for the detailed treatment of stellar evolution and the full range of possible interactions within binary stars (Hurley et al. 2001 and references therein). In the dense environment of a star cluster, it is possible for the orbital parameters of a binary to be significantly perturbed because of close encounters with nearby stars. As a result, the orbit may even become chaotic (Mardling & Aarseth 2001). Collisions may occur, and binaries can form as a result of tidal capture (Fabian, Pringle, & Rees 1975). Grav-

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[1] We refer the interested reader to http://www.astrogrape.org for further information on the GRAPE project.

itational encounters between single stars and binaries, or binary-binary encounters, can lead to an exchange interaction in which one star finds it energetically preferable to leave its current partner and become bound to another (Heggie 1975; Heggie & Hut 2002). Other possible outcomes of these *scattering* incidents include the destruction of the one (or two) binary system(s) to leave only single stars or the formation of a triple system. Rather than being instantaneous events, exchange interactions often involve a period of indecisiveness in which stars swap between partners in quick succession before choosing a companion with which to remain (see McMillan et al. 1991 for an early example of such behavior). All of these processes are accounted for in NBODY4. This allows the generation and interaction of the full range of stellar populations possible. A similar effort is represented by the kira code (Portegies Zwart et al. 2001b), which also takes advantage of the GRAPE hardware.

4. PROMISCUOUS STARS

4.1. *Cluster Models*

The use of *N*-body codes on the GRAPE hardware has already given rise to a number of important results regarding star cluster evolution. Aspects studied include the effect of dynamical evolution on the mass functions of globular clusters (Vesperini & Heggie 1997), the effect of the Galactic tidal field on the evolution of star clusters (Giersz & Heggie 1997), and the evolution of cluster morphology (Boily, Clarke, & Murray 1999). The dependence of cluster lifetimes on their size and the tidal field in which they reside was recently investigated by Baumgardt (2001), who found that the lifetimes do *not* scale with the relaxation timescale, as had previously been assumed. Portegies Zwart et al. (2001a) simulated the evolution and disruption of young compact star clusters near the Galactic center and discussed the likelihood of their being observed.

Hurley et al. (2001) demonstrated the effectiveness of the cluster environment in modifying the nature of the stars it contains by modeling the BS population of M67. Not only was the number of BSs produced twice that expected from standard binary evolution, but also formation paths for all the various types observed in M67 were created. The models of young Galactic open clusters performed by Portegies Zwart et al. (2001b) also exhibited strong dynamical activity. These studies have highlighted the importance of combining dynamics with stellar evolution.

Within each of these open cluster size simulations, there exist numerous interactions between stars that are often glossed over when discussing the simulation result. However, each of these interactions is interesting in its own right, and we now take the opportunity to illustrate some of these fascinating tales in detail.

4.2. *Lurid Examples*

The first documentation of the behavior of a particular star in an *N*-body simulation involving stellar evolution, and the motivation for this paper, was presented by Hurley et al. (2001). This star began life as a 1.33 $M_\odot$ single star. Four exchange interactions and one tidal capture event later, involving a total of four collisions within eccentric binaries, its mass (after 4100 Myr of cluster evolution) had grown to 7.7 $M_\odot$, which is an amazing factor of 6 greater than the MS turnoff mass at that time. At various intervening points in its evolution, this star would have been observed as a single super-BS, a super-BS in a binary, a BS in an eccentric binary, or a BS in a triple system. *What we want to emphasize here is that such promiscuous behavior is not at all rare.*

Consider a similar case involving BS formation that arose in a recent simulation on GRAPE-6 aimed at modeling the evolution of planetary systems in star clusters (Hurley & Shara 2002). At the beginning of the simulation, the star of interest had a mass of 0.99 $M_\odot$ and was in a primordial binary with a period of $P = 6513$ yr and eccentricity of $e = 0.73$. The companion star had a mass of 0.54 $M_\odot$, and the binary was situated just beyond the cluster half-mass radius. The metallicity of the stars in this simulation was $Z = 0.004$. After 40 Myr, the orbital parameters of this wide binary had been reduced to $P = 63$ yr and $e = 0.13$ because of perturbations resulting from weak gravitational encounters with nearby stars. At $T \simeq 490$ Myr, the binary had drifted inside the cluster half-mass radius and was involved in an exchange interaction with a 0.29 $M_\odot$ star. Subsequently, the low-mass interloper was ejected from the three-body system, which left the original binary intact. Following this tumultuous but short-lived relationship, the binary partners remained quietly monogamous until becoming involved in a five-body interaction at $T = 3463$ Myr, by which time the binary had sank farther toward the cluster center, through mass segregation, lying slightly outside of the core. The other participants in this encounter were a 1.12 $M_\odot$ single star and a binary with component masses of 1.17 and 0.32 $M_\odot$ and $P = 58$ yr. Initially, the 0.54 $M_\odot$ star was ejected, destroying the primordial binary, and a quasi-stable four-body system remained. Shortly afterward, the 0.32 $M_\odot$ star was also ejected, and the 0.99 and 1.12 $M_\odot$ stars formed a binary with $P = 51$ yr and $e = 0.95$ in a triple system with the 1.17 $M_\odot$ star. The presence of the third body gradually drove the eccentricity of the inner binary up to 0.99, at which point ($T = 3515$ Myr) the two MS stars collided to form a 2.11 $M_\odot$ BS, which did not remain bound to the third star. Figure 1 documents this interaction, and all subsequent interactions involving the initially 0.99 $M_\odot$ star, in terms of the masses of the stars involved. We note that the 0.54 $M_\odot$ star actually escaped from the cluster with a velocity exceeding the stellar velocity dispersion by a factor of 3—approximately 10 Myr after it was removed from its primordial companion—but as a direct result of the energy exchanged in that interaction.

The BS (now significantly more massive than the average cluster star) quickly sank inside the core of the cluster in which, at $T \simeq 4000$ Myr, it was involved in an exchange interaction with a 2.2 $M_\odot$ single star and a primordial binary. The single star, itself a BS formed via the coalescence of two MS stars in a semidetached binary, formed a bound pair with the original BS. This BS-BS binary had a period of 487 yr and an eccentricity of 0.72. Its orbit was perturbed by interactions with a 1.2 $M_\odot$ star at $T = 4049$ Myr and with a 0.9 $M_\odot$ star at $T = 4092$ Myr, which increased the eccentricity to 0.98. The orbit then became chaotic, and at $T = 4162$ Myr the BSs collided to form a 4.31 $M_\odot$ super-BS. At $T = 4180$ Myr, the super-BS exchanged itself into a binary comprising a 1.11 and a 1.52 $M_\odot$ star and left bound to the more massive of the two, also a BS. Then, in a final showdown, this binary formed a four-body system with another binary, and at $T = 4210$ Myr, the 4.31 $M_\odot$ super-BS and the 1.52 $M_\odot$ BS

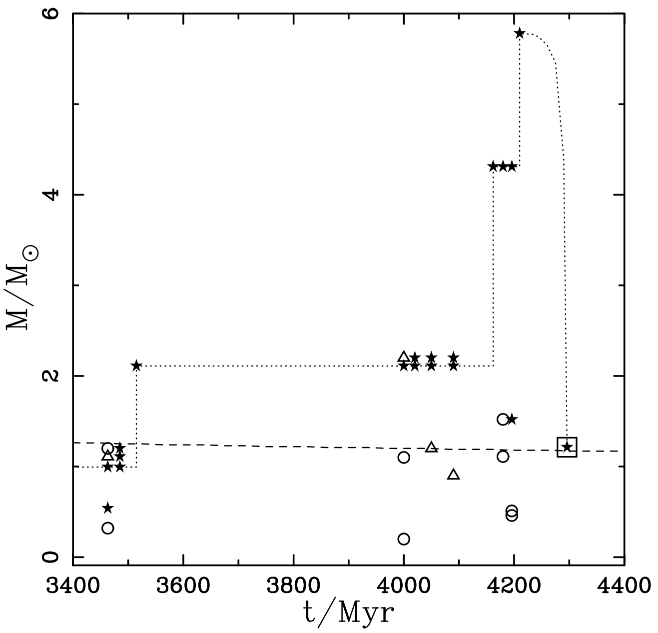

FIG. 1.—Mass as a function of time for the 0.99 $M_\odot$ star that becomes a 5.78 $M_\odot$ blue straggler and the various stars and binaries that it interacts with along the way. The promiscuous star is represented as a solid star symbol, as is its companion in any binaries that it forms, and its path is traced out by the dotted line. Interacting single stars (*triangles*) and binaries (*circles for each component*) are distinguished. The boxed symbol at 4296 Myr represents the 1.21 $M_\odot$ oxygen-neon WD that the 5.78 $M_\odot$ blue straggler evolves to at that time (via a giant phase). The main-sequence turnoff mass is also represented (*dashed line*).

collided to form a 5.78 $M_\odot$ super-BS. Being as massive as it was, almost 5 times greater than the MS turnoff mass at the time, this promiscuous star quickly evolved off the MS and shortly afterward lost its envelope on the asymptotic giant branch to become an oxygen-neon WD.

This lurid example, and the one presented by Hurley et al. (2001), highlights an important point. Although the possibility of any particular star becoming a BS as a result of a dynamical encounter is quite random, *once a star does become a BS and, hence, one of the most massive stars in the cluster, subsequent interactions are almost inevitable.* They also show that if a binary emerges from the indiscriminate and short-lived relationship that is an exchange interaction, then it will more often than not comprise the two most massive stars involved in the interaction; i.e., in this society it is desirable to be heavy.

In a typical GRAPE-6 simulation with $N = 20{,}000$, initially composed of 18,000 single stars and 2000 binaries in which the evolution was followed for 5 Gyr, the number of exchange interactions observed was ~500. These involved 730 different stars, with some stars taking part in multiple interactions. The number of stars that swapped partners once was 494, twice was 105, three times was 48, four times was 27, and 14 stars swapped partners on five occasions. Amongst these were a number of remarriages in which a "star changed its mind" and returned to its original partner. The component stars of one particularly flirtatious binary were actually involved in 22 exchange interactions, including 10 remarriages.

The total number of merger events observed during the entire simulation was 104. Of these, mass transfer in a primordial binary accounted for 46 cases, while 13 mergers came from mass transfer in a binary formed via an exchange interaction. The remainder were the result of collisions in eccentric binaries; 21 were in primordial systems in which the orbit was strongly perturbed by nearby stars.

BS formation as a result of a hyperbolic collision is rare in simulations of open clusters but does occur. One example involved a 0.32 $M_\odot$ star that began life in the core of the cluster and slowly drifted out to the half-mass radius because of mass segregation, where at 1300 Myr it collided with a 0.93 $M_\odot$ star. The relative velocity of the two stars at infinity was 2.8 km s^{-1}, and the collision product was assumed to be a fully mixed 1.25 $M_\odot$ MS star. When the cluster was 3850 Myr old, this star first appeared as a BS, and by 4500 Myr, when the simulation ended, it had sank inside the cluster core. The incidence of direct collisions will be greater in the higher density conditions of a globular cluster simulation. However, these are abrupt encounters and much less interesting than the sociable nature of exchange interactions and the binary systems they produce. The presence of binaries also acts to magnify the chance of collisions, because in the case of a binary, it is the semimajor axis that sets the relevant cross section for collision, rather than the stellar radius that is used in the case of single stars. Here, we have to be careful with the terminology used. If a binary is involved in a hyperbolic *interaction*, then any *collision* that results will occur in a two-step process and will not be *direct*; first, a (resonant) capture may produce a hierarchical system, and subsequently, a collision can occur within this system.

Interesting cases of stellar interactions are not limited to BS formation alone. Consider the case of the primordial binary composed of MS stars of 0.6 and 1.5 $M_\odot$ with an eccentricity of 0.42 and an orbital period of ~270 yr that was part of the same GRAPE-6 simulation mentioned above. Residing in the core of the cluster, this binary suffered a series of weak perturbations to its orbit, which drove the eccentricity up to 0.95. After the 1.5 $M_\odot$ star became a subgiant, it was involved in two exchange interactions, finally settling into a 33 yr orbit with eccentricity of 0.9 about a 1.4 $M_\odot$ MS star after 2130 Myr of evolution. The subgiant then evolved onto the giant branch (GB), and by $T = 2160$ Myr tidal forces within the binary had circularized the orbit, which resulted in a separation of 250 $R_\odot$. While on the GB, the 1.5 $M_\odot$ star filled its Roche lobe, and a phase of common envelope evolution began. This stripped the envelope of the giant and left a helium WD and a MS star separated by 52 $R_\odot$. The MS star subsequently evolved to the GB, filled its Roche lobe, and another common envelope event ensued, which resulted in a pair of 0.4 and 0.3 $M_\odot$ helium WDs with an orbital period of 0.7 days. Because of gravitational radiation, this system would easily merge within 10^{10} yr to possibly form a blue subdwarf star (Iben 1990), i.e., a helium-burning object with a thin hydrogen envelope.

The final case that we choose to highlight involves the formation of a Thorne-Żytkow object (TZO; Thorne & Żytkow 1977). Although TZOs have not been directly observed, they are thought to result from stellar mergers involving either a neutron star or a black hole in which the merger product is unstable and rapidly ejects all of the material involved other than the neutron star or black hole, which remains. The system of interest began as a primordial binary with component masses 10.8 and 5.3 $M_\odot$, an eccentricity of 0.87, and a period of 1870 days. After 20 Myr of evolution, the orbital period had been reduced to 1350 days due to perturbations that had *hardened* this already *hard*[2] binary. A few Myr later, the more massive of the two stars evolved onto the subgiant branch, and, as the region of convection within its envelope grew, tidal forces began to circularize the orbit. At $T = 23$ Myr, the primary star filled its Roche lobe and began transferring mass to the companion. When the primary evolved onto the giant branch, the rate of mass transfer accelerated so that the giant quickly overfilled the Roche lobes of both stars to leave the 2.42 $M_\odot$ helium core of the giant and the 5.31 $M_\odot$ MS star contained within a common envelope. Orbital friction then caused these two objects to spiral toward each other, and the energy released was enough to drive off the envelope before they coalesced. This left a naked helium star and a MS star in a circular orbit with a 4.3 day period. The helium star then evolved onto the helium GB and filled its Roche lobe. A period of stable mass transfer ensued until the envelope of the helium star had been removed and it became a 1.42 $M_\odot$ WD of oxygen-neon composition. The orbital period at that stage was 10 days, and the companion star was now a 6.07 $M_\odot$ BS. At $T = 74$ Myr, the BS evolved off the MS onto the subgiant branch and filled its Roche lobe, which lead to another common envelope event and the formation of a naked helium star in an orbit of $P = 0.1$ days with the oxygen-neon WD. When this helium star evolved onto the helium GB, it also filled its Roche lobe and began transferring mass to the WD. It was assumed that the helium-rich material would be accepted by the WD and steadily burned on its surface. This quickly caused the mass of the WD to reach the critical Chandrasekhar mass, 1.44 $M_\odot$, at which point it underwent an accretion-induced collapse to form a neutron star. The neutron star remained bound to the helium giant with an orbital period of 0.04 days. At $T = 94$ Myr, the helium giant again filled its Roche lobe, which lead to a third phase of common envelope evolution and the formation of a TZO.

In this particular instance, dynamical interactions were not crucial to the outcome of the evolution; without perturbations to its orbit, this binary would still have formed a TZO. However, we do see examples of similar systems being disrupted by encounters with other stars in the cluster so that the ultimate fate of the system is altered. Such occurrences include the orbit being so strongly perturbed that the stars merge while both are on the MS. Alternatively, a perturbation takes place just prior to the onset of a common envelope phase, in a way that leads to coalescence of the two stars, rather than the formation of a close binary.

The examples given here represent only a small fraction of the wealth of information regarding stellar interactions and populations that is generated by realistic *N*-body simulations of star clusters. Much of this information is quickly discarded if it is not of direct relevance to the initial purpose of that particular simulation. With GRAPE-6 increasing the *N* that can be simulated within a reasonable time frame, a distinct possibility exists that those working in the *N*-body field will rapidly be overwhelmed with data. Therefore, the creation of an archive for the results of *N*-body simulations that is accessible to all members of the scientific community is crucial (see Teuben et al. 2002 for a related discussion). This database will complement the *HST* stellar populations archive (D. Zurek: *HST* Proposal AR-9225) currently under construction at the American Museum of Natural History.

It should also be noted that these interactions are not simply interesting; they also have wide-reaching implications. Take, for example, the case of Type Ia supernovae, which are important standard candles in cosmology and have recently been used to demonstrate that the expansion of the universe is accelerating (Perlmutter et al. 1999). Short-period double-degenerate binaries in which the component WDs have a combined mass in excess of the critical Chandrasekhar mass and that will merge within a Hubble time are thought to be possible progenitors of Type Ia supernovae. Close inspection of the results of *N*-body simulations performed on GRAPE-6 have shown that the production rate of these systems is remarkably enhanced—over an order of magnitude in open clusters and likely much more in globular clusters—relative to the field (Shara & Hurley 2002).

5. SUMMARY

The introduction of the GRAPE-6 hardware, coupled with *N*-body codes that have the capability to produce realistic cluster models, places the astrophysicist in the position of knowledgeable voyeur. An exciting aspect of this is the capability to investigate and understand the range of stellar populations that are observed and how these are affected by dynamical interactions between cluster stars. As we move to full utilization of the GRAPE-6 and the simulation of globular clusters, the fascinating tales of promiscuous stars in clusters will become very graphic indeed!

We are extremely grateful to Piet Hut and Jun Makino for their efforts in instigating and maintaining the GRAPE program. Immense gratitude is extended to Sverre Aarseth for his tireless work in producing state-of-the-art *N*-body codes. We also thank Peter Eggleton, Rosemary Mardling, Steve McMillan, Seppo Mikkola, Onno Pols, and Christopher Tout for important contributions made to the development of realistic *N*-body codes. Thanks to Simon Portegies Zwart and David Zurek for many stimulating discussions relating to the interactions of stars in clusters, and to the referee (Piet Hut) for a number of highly constructive suggestions. The generous support of Doug Ellis and the Cordelia Corporation has enabled the American Museum of Natural History to purchase new GRAPE-6 boards, and we are most grateful for that.

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[2] For a binary to be termed "hard," the magnitude of its binding energy must be greater than the mean kinetic energy of the cluster stars; otherwise it is "soft." In stellar dynamics, it is found that hard binaries will become harder, and soft binaries will be broken up, as a result of encounters with other stars.

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