Astrophysical Supercomputing Using Particles
IAU Symposium, Vol. 208, 2003
J. Makino and P. Hut, eds.

Type Ia Supernovae and Planets in Star Clusters

Michael M. Shara and Jarrod R. Hurley

Department of Astrophysics, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024

Abstract. Star clusters are remarkably efficient (relative to the field) at making type Ia supernovae candidates: very short period, massive double-white-dwarf stars and giant-white dwarf binaries. The high frequency of these systems is the result of dynamical encounters between (mostly) primordial binaries and other cluster stars. Orbital hardening rapidly drives the degenerate binaries to periods under ~ 10 hours. Gravitational radiation emission and mergers then produce supra-Chandrasekhar objects in less than a Hubble time.

We also find that free-floating planets can remain bound to a star cluster for much longer than was previously assumed: of the order of the cluster half-mass relaxation timescale as opposed to the crossing-time. The planets in our N-body study are of Jupiter mass and are initially placed in circular orbits of between 0.05 and 50 AU about a parent star whose mass is chosen from a realistic initial mass function. This result is important in the context of the preliminary detection of a population of free-floating sub-stellar objects in the globular cluster M22.

1. Introduction

The Universe is apparently not only expanding, but also accelerating (Riess et al . 1998 & Perlmutter et al. 1999). This remarkable finding is based on observations of type Ia supernovae, whose interpretation by two teams yields the same amazing answer. It is still critical to investigate all challenges to the acceleration interpretation of the data, as detailed by Riess (2000).

Riess concludes that the primary source of reasonable doubt is evolution (could Sne Ia at z = 0.5 be intrinsically fainter than nearby Sne Ia by 25% ?). We simply don't know for certain what kind of star (or stars?) give rise to these explosions, and hence whether to expect systematic variations in SNIa luminosities with z.

Not knowing the progenitors of SNe Ia is embarrassing because of the significant empirical corrections one must apply to supernova luminosities, based on their light curves, to get distances (Phillips 1993). Two competing SNIa models exist: merging double-white-dwarfs (DWDs) and accreting single white dwarfs (ASDs) in close binary systems (see Yungelson & Livio (2000) for a review, including the pros and cons of each flavor of each model).

https://doi.org/10.1017/S0074180900207018 Published online by Cambridge University Press

It is clearly important to calculate the expected incidence of DWD and ASD in the stellar populations of the different types of galaxies where SNIa occur. This has been done for field stars, but hardly for the environs of clusters. We have begun a study of the behavior of populous star clusters using a state-of-the-art N-body code in conjunction with the powerful GRAPE-6 special purpose computer Makino (2002). Our simulations follow the individual orbits of each star in detail *and* the internal evolution of each star is also taken into account (Hurley et al. 2001). Living in a dense stellar environment leads to physical collisions, and, in the case of binaries, exchange interactions or disruptions of orbits that radically alter the fates of cluster stars. Our key result is that cluster dynamics *dramatically alters binary populations and characteristics, including those of DWD and ASD.*

2. Simulation Method

The Aarseth `NBODY4` code (Aarseth 1999 & Hurley et al. 2001) has been used to simulate the evolution of star clusters. A GRAPE-6 board located at the American Museum of Natural History hosts the code. This special purpose computer acts as a Newtonian force accelerator for N-body calculations, performing at 0.5 Tflops ($\sim$ 30 Gflop per chip). We have carried out simulations with 22 000 stars and a 10% primordial binary fraction. Initial conditions relating to the masses, positions and velocities of the stars, as well as the orbital characteristics of the binaries, are the same as for the $N = 10\,000$ star simulations described in detail by Hurley et al. (2001). The cluster is subject to a standard Galactic tidal field, and a realistic initial-mass function is used to distribute the stellar masses (Kroupa et al. 1993). The prescription used for single star evolution is described in Hurley et al. (2000) (see their Fig. 18 for WD initial-final mass relation). All aspects of standard binary evolution, i.e. non-perturbed orbits, are treated according to the prescription described in Hurley et al. 2002.

The planets in our N-body study are of Jupiter mass and are initially placed in circular orbits of between 0.05 and 50 AU about a parent star whose mass is chosen from a realistic initial mass function. The presence of the free-floating planets is the result of dynamical encounters between planetary systems and the cluster stars.

The simulation was carried out assuming a metallicity of $Z = 0.004$, and was evolved to an age of 4.5 Gyr when $\sim$ 25% of the initial cluster mass remained and the binary fraction was still close to 10%. We present here initial results for merging DWDs in one cluster simulation. Several more simulations and results for ASDs will be presented elsewhere. We also briefly describe some preliminary results on residence lifetimes of liberated planets inside star clusters.

3. Double White Dwarfs

The key result is that DWD formed in clusters are significantly hardened by interactions with passing stars. This greatly increases the number of DWD which merge in less than a Hubble time. Table 1 lists the characteristics of the merging DWDs formed during one cluster simulation: star ID, epoch of formation, types of white dwarf, component and system masses, orbital period at formation epoch, gravitational inspiral timescale, and whether the binary is primordial or due to an exchange. All of these objects will merge in less than a Hubble time, creating a supra-Chandrasekhar object which may be a type Ia supernova.

We expect about 10 DWDs to be present at any one time amongst a field binary population of 2000 systems. Of these, only 0.3 is expected to be a "loaded gun", i.e. to have a combined mass $M_{\rm b} > M_{\rm Ch}$ *and* a merger timescale less than the age of the Galaxy (Hurley et al. 2002). From Table 1 we see that there are eight loaded guns per 2000 binaries, which is 26 times more than expected in a binary population unaffected by dynamical interactions. Later simulations with better statistics indicate that the enhancement is closer to a factor of 13.

Table 1. Double-WD systems that are Type Ia candidates. To qualify the system must have a combined mass in excess of the Chandrasekhar mass, $1.44 M_\odot$, and a gravitational radiation merger timescale less than the age of the Universe, $\sim 1.2 \times 10^{10}$ yr. The time at formation for the double-WD (DWD) system, Myr units, is given in Column 1. The types of the WDs are listed in Column 2. Three types of WD are distinguished: helium composition (He), carbon-oxygen (CO), and oxygen-neon (ONe). The individual masses of the two WDs are given in Columns 3 and 4 respectively, and the combined mass is given in Column 5. All masses are in solar units. The period of the binary is given in Column 6 in units of days. Column 7 gives an estimate of the time it will take the DWD system to merge, in yrs, owing to angular momentum loss from gravitational radiation. This estimate comes from integrating eq. (18) of Hurley et al. 2002. Column 8 summarizes the history of each system using the following code: primordial binary (PRIM); exchange interaction (EXCH); perturbation before (PB), or after (PA), Double-WD formed; subsequent escape from cluster (ESC); subsequent disruption in dynamical encounter (DISR). Note that perturbations to the orbit are only recorded if they lead to a change in the evolution path of the binary.

$T_{\rm form}$	Types		M_1	M_2	$M_{\rm b}$	Period	$T_{\rm grav}$	Legend
225	CO	ONe	0.72	1.24	1.96	3.3884×10^{-1}	4.112×10^{9}	EXCH
186	CO	CO	0.99	0.66	1.65	1.0715×10^{-1}	2.259×10^{8}	PRIM-PB-ESC
229	CO	CO	0.97	0.67	1.64	1.1482×10^{-1}	2.991×10^{8}	PRIM-PA-DISR
334	ONe	CO	1.06	0.57	1.63	1.0715×10^{-1}	2.270×10^{8}	PRIM-PA
370	CO	CO	1.09	0.54	1.63	2.4547×10^{-1}	2.343×10^{9}	PRIM-PA
221	CO	CO	0.92	0.64	1.56	4.3652×10^{-2}	2.187×10^{7}	PRIM-ESC
375	CO	CO	0.83	0.67	1.50	1.1220×10^{-1}	2.997×10^{8}	PRIM
149	CO	CO	0.83	0.66	1.49	8.7096×10^{-3}	3.350×10^{5}	PRIM-PB-ESC

The color-magnitude diagram of the cluster we have simulated is shown in Figure 1. In addition to the single star and binary main sequences, several blue stragglers and cataclysmic binaries (below and to the left of the main sequence) are visible in each simulation. Most remarkable are the DWDs, seen in profusion

https://doi.org/10.1017/S0074180900207018 Published online by Cambridge University Press

above the white dwarf cooling sequence, and the loaded guns shown as circled diamonds in each of the figures.

Figure 2 illustrates the spatial distribution within the cluster at several epochs for the single stars, binaries and DWD. This clearly demonstrates that equipartition of energy is dominating the dynamical evolution. The DWD are much more centrally concentrated than the other binaries or the single stars.

An overly simple prediction based on this work is that we might expect to see many or most Type Ia supernovae erupting in star clusters, often in their cores. There are two reasons to be cautious with this prediction. First, open star clusters disperse, usually on a $1 - 6$ Gyr timescale. Second, we don't know what fraction of stars are created in star clusters, and what fraction of those escape during the earliest stages of cluster life.

Other intriguing suggestions from this work are that distant DWD and cataclysmic variables should be rather commonplace in open clusters, and likely segregated towards the cluster centers. We encourage observers to survey for such objects.

4. Planets

The recent null detection of hot Jupiters in the globular cluster 47 Tucanae (Gilliland at al. 2000) (20 should have been unearthed by the HST survey), and the claim of planetary-induced microlensing events in M22 (Sahu et al. 2001) demonstrate the intense interest in this field. If confirmed, the M22 result suggests the presence of more planets in the cluster than stars.

We find in our simulations a weak preference for planets in wide orbits to be liberated from their parent star: planetary systems with a 50 AU separation are 10 times more likely to be broken-up than those with 1 AU.

Planetary systems primarily escape from a cluster owing to stripping of stars in the outer cluster regions by the Galactic tidal field. As a natural consequence of mass-segregation there is a preference for systems with low parent star mass to escape. Planetary systems of all orbital separations are equally likely to escape (as planets just "tag along for the ride"). Stars are ejected from the cluster due to close encounters with other stars or binaries but in the case of planetary systems the encounter more likely results in liberation of the planet.

We find that a large fraction of the liberated planets are retained in the cluster for much longer than a crossing-time. The typical crossing-time for these simulations is $2 - 10$ Myr. The planets are preferentially liberated in the cluster core and 46% are liberated with a velocity less than the cluster escape velocity. They generally begin their free-floating existence deep within the potential well of the cluster and then drift outwards, driven by the effect of two-body relaxation. The initial orbital separations for planetary systems that are broken up during the simulation are shown in Figure 3.

Because the timescale for mass-segregation is inversely proportional to stellar mass we might naively expect the planets to take much longer to reach the tidal boundary of the cluster than low-mass stars. The picture is somewhat more complicated for the planets because the core population is replenished over time and their velocity distribution is detached from that of the stars. Our simulations show that the average position of the free-floating planet population

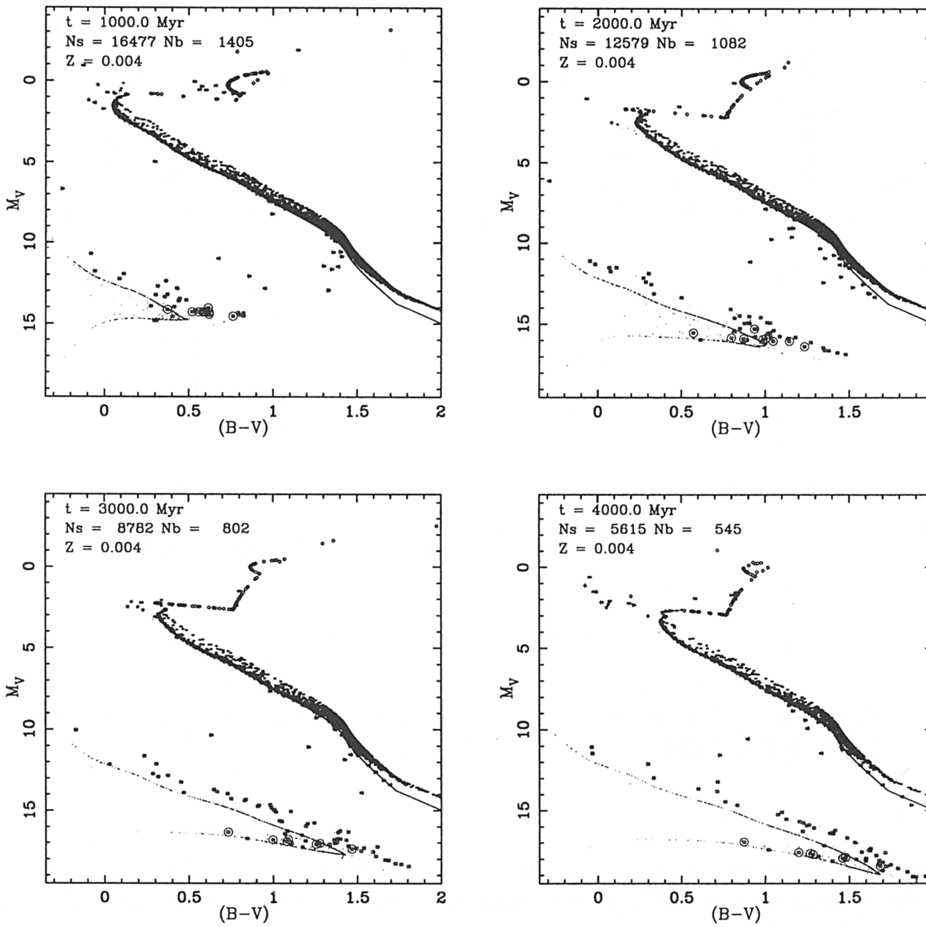

Figure 1. Colour-magnitude diagram for a $Z = 0.004$ star cluster at 1, 2, 3 and 4 Gyr. The results of two simulations have been added to improve statistics. Main-sequence stars (dots), blue stragglers (stars), sub-giants, giants and naked helium stars (open circles) and white dwarfs (dots) are distinguished. Binary stars are denoted by overlapping symbols appropriate to the stellar type of the components, with main-sequence binary components depicted with filled circles and white dwarf binary components as diamonds. Type Ia candidates are circled. Bolometric corrections computed by Kurucz (1992) from synthetic stellar spectra are used to convert theoretical stellar quantities to observed colours. These corrections are strictly not valid for WDs and extremely cool giants.

https://doi.org/10.1017/S0074180900207018 Published online by Cambridge University Press

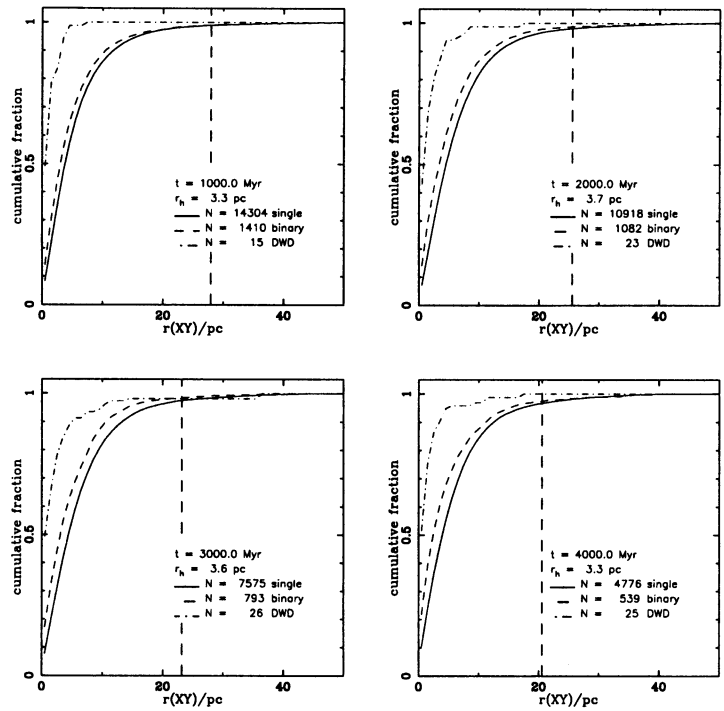

Figure 2. Population gradients for single stars, binaries and double-WDs in the simulations of Figure 1.

remains roughly constant, lying just outside the half-mass radius. The planets take approximately 200 Myr, comparable to the half-mass relaxation timescale of the cluster, to move from inside the core to outside the half-mass radius.

A significant number of planetary orbits are altered during the simulations. Orbits of all sizes expand when the parent star evolves off the main-sequence and begins to lose mass non-conservatively in a stellar wind. Weak perturbations from passing stars can cause the orbital period to decrease: this affects roughly 15% of systems with $a > 10$ AU. We do not see any orbital migration of planetary systems with initial orbital separations less than this. The changes in orbital separations of planets and stars are shown in Figure 3.

5. Conclusions

We find a greatly increased rate of production of loaded guns - Supra-Chandrasekhar DWD with inspiral ages shorter than a Hubble time - in star clusters relative to the field. The same is true of ASD. Orbital hardening, often preceded by exchange interactions are the responsible mechanisms for the enhanced rates.

The results are based on studies of open cluster size N-body simulations, but we expect the effect to be even stronger in the case of globular clusters.

Contrary to recent claims (Bonnell et al. (2001) and Smith & Bonnell (2001)) we find that free-floating planets can form a significant population in stellar clusters. This is based on the results of open cluster size N-body simulations but is expected to be even more likely in the case of globular clusters.

Acknowledgments. We are extremely grateful to Jun Makino and the University of Tokyo for the loan of the GRAPE-6 board. MS thanks Ken Nomoto for very helpful discussions and suggestions. We thank Fred Rasio and Vicky Kalogera for organizing the 2001 Aspen Center for Physics meeting on Compact Objects in Dense Star Clusters where some of the ideas for this paper were clarified.

References

Aarseth, S. J. 1999, PASP, 111, 1333

Bonnell, I. A., Smith, K. W., Davies, M. B., & Horne, K. 2001, MNRAS, 322, 859

Gilliland, R. L., et al. 2000, ApJ, 545, L47

Hurley, J.R., Pols, O.R., & Tout, C.A. 2000, MNRAS, 315, 543

Hurley, J. R., Tout, C. A., Aarseth, S. J., & Pols, O.R. 2001, MNRAS, 323, 630

Hurley, J.R., Tout, C.A., & Pols, O.R. 2002, MNRAS, accepted

Kroupa, P., Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545

Makino, J. 2002, in ASP Conf. Ser. XX, Stellar Collisions, Mergers and their Consequences, ed. M. M. Shara (San Francisco: ASP), in press

Perlmutter, S., et al. 1999, ApJ, 517, 565

Phillips, M.M., 1993, ApJ, 413L, 105

Riess, A.G. et al. 1998, AJ, 116, 1009

Riess, A.G. 2000, PASP, 112, 1284

Sahu, K. C., Casertano, S., Livio, M., Gilliland, R. L., Panagia, N., Albrow, M. D., & Potter, M. 2001, Nature, 411, 1022

Smith, K. W., & Bonnell, I. A. 2001, MNRAS, 322, L1

Yungelson, L., Livio, M., ApJ, 528, 108

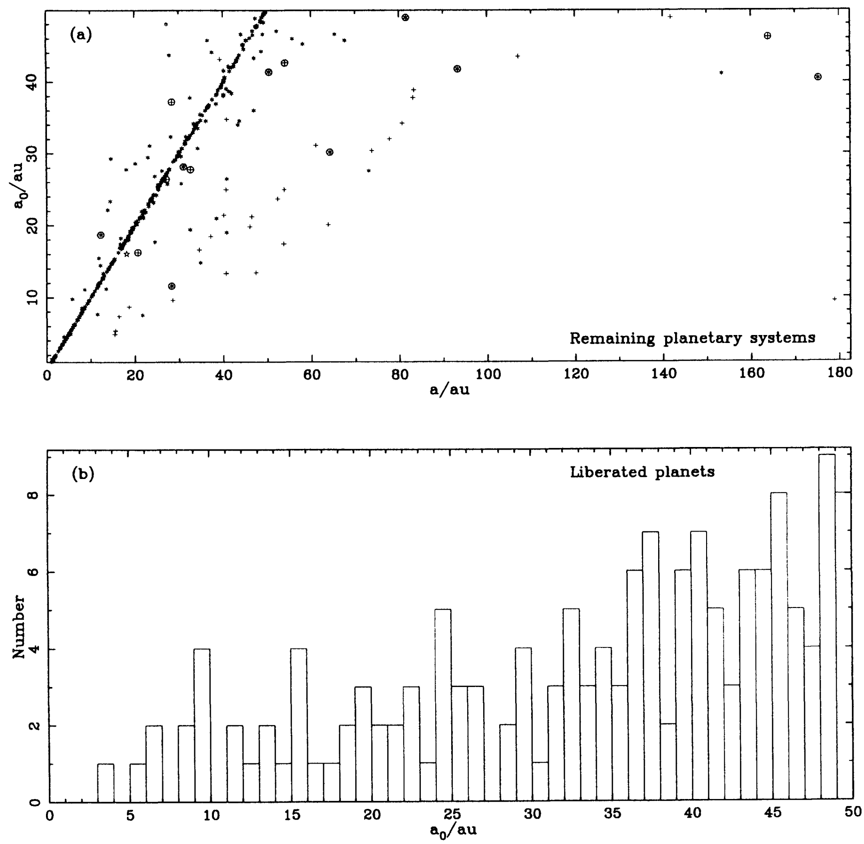

Figure 3. Results relating to the orbital separations of planetary systems in an N-body simulation of an open cluster (Hurley & Shara 2002). The simulation began with 16 000 single stars, 2 000 binaries and 2 000 planetary systems. Each planetary system comprised a Jupiter mass planet in a circular orbit about a parent star, with mass randomly chosen from a realistic initial mass function, at a separation chosen from a uniform distribution between the limits of 0.05 – 50 AU. The upper panel plots the initial orbital separation against the corresponding value after 4.5 Gyr of cluster evolution. Planetary systems with a MS ($*$), giant (open star), or WD ($+$) parent star are distinguished. Orbits resulting from an exchange interaction are circled. The lower panel shows the distribution of initial orbital separations for planetary systems that are broken-up during the simulation.