THE ASTROPHYSICAL JOURNAL, 565:1251–1256, 2002 February 1

FREE-FLOATING PLANETS IN STELLAR CLUSTERS: NOT SO SURPRISING

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Received 2001 August 1; accepted 2001 October 8

ABSTRACT

We find that free-floating planets can remain bound to an open cluster for much longer than was previously calculated: of the order of the cluster half-mass relaxation timescale as opposed to the crossing time. This result is based on N-body simulations performed with the new GRAPE-6 special purpose hardware and is important in the context of the preliminary detection of a population of free-floating, substellar objects in the globular cluster M22. 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. Most planets are liberated from their parent star in, or near, the cluster core, and then drift outward on a timescale of $\sim 10^8$–10^9 yr. This still implies the existence of many (~ 100) planets per star if the M22 result is confirmed.

Subject headings: globular clusters: general — methods: n-body simulations — open clusters and associations: general — planetary systems — stellar dynamics

1. INTRODUCTION

The recent null detection of hot Jupiters in the globular cluster 47 Tucanae (Gilliland et al. 2000) is an important puzzle. This search for planetary systems was sensitive to the detection of gas-giant planets in orbits of less than five days (~ 0.05 AU) about a main-sequence parent star—the so-called "hot Jupiters." If the frequency of hot Jupiters in the solar neighborhood holds for 47 Tuc, then simulations suggested that approximately 20 should have been unearthed by the survey (Gilliland et al. 2000).

The Gilliland et al. (2000) survey has led to a number of analytical and statistical studies concerning the fate of planetary systems in star cluster environments (Bonnell et al. 2001; Davies & Sigurdsson 2001; Smith & Bonnell 2001). This is in addition to the work of Adams & Laughlin (2001), and references within. Davies & Sigurdsson (2001) estimate that only planets that form in orbits with semimajor axes, a, less than 0.3 AU will survive in a globular cluster, but that even planets with $a \sim 0.04$ AU would be broken up in the high density core. In the case of 47 Tuc, the question then seems to be, were all the surveyed stars resident in the cluster core for a significant fraction of the cluster evolution, or did the planets not form in the first place? Bonnell et al. (2001) have suggested that in the early globular cluster environment, the natal disk from which planets form may be truncated inside the region where gas-giant planets are believed to form. In the solar neighborhood, the parent stars of planets tend to be considerably richer in metals than average (Laughlin 2000). This lends support to the hypothesis that a lower abundance of metals in proto–planetary nebulae causes a lower frequency of planet formation as a result of fewer dust grains for nucleation (Gilliland et al. 2000, and references within). The metallicity of 47 Tuc is a factor of 5 less than solar (Harris 1996).

If we assume that a population of planets does form with orbital separations in the range $1 \leq a/\mathrm{AU} \leq 50$, then Smith & Bonnell (2001, hereafter SB2001) show that 50% of these planets will be liberated from their parent star in a globular cluster and 27% will be liberated in the less dense surroundings of an open cluster. *However, these authors also claim that in an open cluster only 0.5% of these liberated planets will stay in the cluster for more than a crossing time.* This increases to 30.1% for a typical globular cluster.

In the case of M22, it is the liberated or free-floating planets that are of particular interest. The microlensing of background stars by compact objects in globular clusters has been analyzed in detail by Paczynski (1994). Possible targets mentioned for a *Hubble Space Telescope* (*HST*) study are M22 with the Galactic bulge background and 47 Tuc with the Small Magellanic Clouds as background. The advantage here is that the probability of lensing is high and accurate knowledge of the distances and kinematics of the sources and lenses leads to better lens-mass estimates. Sahu et al. (2001) attribute six possible gravitational microlensing events to planetary mass objects and only one event to a star, the mass of which is $0.13\,M_\odot$, based on *HST* observations of M22. If these free-floating planetary mass objects are Jupiters, then their relative size suggests that there must be 60 Jupiters per star in M22 and, therefore, that they constitute $\sim 10\%$ of the cluster mass (Paczynski 2001). If they are Earthlike objects, then the number increases to 600 per star, but they comprise only 0.3% of the cluster mass. The central density of M22 is roughly 10^4 stars pc^{-3}, a factor of 10 less than 47 Tuc, which still places it clearly within the globular cluster regime. Factoring in the 50% liberation rate for planets (SB2001) effectively doubles the number of planets required per star. Furthermore, the relative time spent in the cluster by the liberated planets is then a critical factor in estimating the microlensing rate. Interestingly, the metallicity of M22 is a factor of 10 lower than that of 47 Tuc (Harris 1996).

A large fraction of the stars that we observe are found in gravitationally bound star clusters. In fact, it is entirely possible that most stars were born in a star cluster of some sort (Kraft 1983; Lada, Strom, & Myers 1993). Clusters are crowded stellar environments, ranging in density from 10^2 stars pc^{-3} to as high as 10^7 stars pc^{-3} in the cores of the densest globular clusters, which complicates matters for the evolution of their members. Encounters between stars can lead to collisions and, in the case of binary stars or

TABLE 1

Parameters of the N-body Simulations Presented in This Work

Run	Z	N_p	a_{min}	a_{max}
1......	0.004	2000	1.00	50.0
2......	0.004	3000	0.05	50.0
3......	0.020	3000	0.05	50.0

Notes.—The simulation ID number, metallicity, number of planetary systems, and the minimum and maximum of the planetary orbital separation distribution are listed. Each simulation involved 22,000 stars, comprised of 18,000 single stars and 2000 binaries, so the total number of particles in each simulation is $22{,}000 + N_p$.

planetary systems, an exchange interaction or disruption of the orbit. For this reason among others, it is desirable to model the evolution of a star cluster using a direct N-body method in which the individual orbits of each star are followed in detail *and* the internal evolution of each star is also taken into account (Hurley et al. 2001).

We have instigated a study of the behavior of planetary systems in star clusters using a state-of-the-art N-body code in conjunction with the powerful GRAPE-6 special purpose computer (Makino 2001). This detailed project will ultimately involve a large number of N-body simulations covering a wide range of initial conditions, e.g., metallicity, binary fraction, stellar number density, and multiple planets per star. However, for now we have simply looked at the case of Jupiters in single-planet systems within moderate-density cluster conditions. Furthermore, we do not consider whether planets should form at all in star clusters (e.g., Armitage 2000), especially in low-metallicity and/or high density environments, but simply ask the question, what happens if they do? Even though this project is in its infancy, the possible discovery of free-floating planets in M22 (Sahu et al. 2001) makes publication of the initial results very timely.

2. SIMULATION METHOD

To model the evolution of star clusters, we use the Aarseth NBODY4 code (Aarseth 1999; Hurley et al. 2001). Simulations are performed on a prototype GRAPE-6 board located at the American Museum of Natural History. This special purpose hardware, which acts as a Newtonian force accelerator for N-body calculations, performs 0.5 Tflops (~ 30 Gflops per chip). It represents a factor of 100 increase in computing power compared to its predecessor, the GRAPE-4 (Makino, Kokubo, & Taiji 1993), and has brought the possibility of modeling globular clusters on a star-to-star basis within reach for the first time.[1]

The simulations performed so far have involved 22,000 stars with 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). In particular, a realistic initial mass function is used to distribute the stellar masses (Kroupa, Tout, & Gilmore 1993), and the cluster is subject to a standard Galactic tidal field. The distribution of orbital separations for the primordial binaries is lognormal with a peak at 30 AU and spans the range $\sim 6\,R_\odot$ to 30,000 AU. The eccentricity of each binary orbit is taken from a thermal distribution (Heggie 1975). Positions and velocities of the stars are assigned according to a Plummer model (Aarseth, Hénon, & Wielen 1974) in virial equilibrium.

We include the outcome of three simulations in the results presented here (see Table 1). The first had a metallicity of $Z = 0.004$ relevant to 47 Tuc and included 2000 planets of Jupiter mass. Each planet was placed in a circular orbit about a randomly chosen single star at a separation taken from a uniform distribution between one and 50 AU. The second simulation involved 3000 Jupiters with the lower limit of the separation distribution reduced to 0.05 AU, and the final simulation differs from this only in the use of $Z = 0.02$. Each simulation 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%. Typically, the velocity dispersion of the stars in these model clusters was 2 km s^{-1} with a core density of 10^3 stars pc^{-3}. The density of stars at the half-mass radius is generally a factor of 10 less than this.

3. FREE-FLOATING PLANETS

Table 2 shows, as a function of time, the number of planets that are liberated from their parent stars during the

TABLE 2

Averaged Results for the Planet Population at 1.0 Gyr Intervals

	Liberated					
Time (Myr)	Total (%)	Kept (%)	Current (%)	Escaped (%)	Swallowed (%)	Exchanged (%)
1000.0......	5.6	69.8	48.4	11.7	0.4	1.0
2000.0......	7.7	66.8	33.1	31.4	0.8	1.7
3000.0......	9.1	66.5	22.4	51.1	0.9	2.3
4000.0......	10.4	64.0	12.7	65.8	1.0	3.6

Notes.—The percentage of all planets liberated from their parent star, the percentage of these that remain in the cluster for more than a crossing-time, and the percentage in the cluster at that time, are given in columns 2-4. The percentage that have escaped attached to their parent star is given in column 5. Columns 6 and 7 give the percentages of planets that have been engulfed by their parent star, and those that have been exchanged into orbit about another parent star, respectively.

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

simulation, the number of planetary systems that escape from the cluster, and the number of planets that are exchanged from their original orbit into orbits about another parent star. Also shown is the number of planets swallowed by their parent star simply as a result of nuclear-driven expansion of the stellar envelope. These are averaged results from the three simulations.

We find a weak preference for planets in wide orbits to be liberated from their parent star; i.e., planetary systems with a 50 AU separation are 10 times more likely to be broken up than those with 1 AU (see Fig. 1). Heggie, Hut, & McMillan (1996) showed that the cross section for a binary to undergo an exchange interaction, which also serves as a likelihood-of-disruption indicator, scales linearly with the orbital separation. This has been confirmed by Davies & Sigurdsson (2001) in the case of planetary systems. The fact that we do not observe this relation is primarily a result of the large fraction of escaping systems, which deprives the cluster of orbits to break up. Another factor is the relatively weak binding energy of the planetary systems compared to that of the binaries. It is evident from Figure 1 that we are limited at this stage to a fairly low number of systems per orbital separation bin, and not until we can saturate the distribution with a large number of systems, all situated in the core of the cluster, will we be able to fully test the statistical results mentioned above.

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" (see Fig. 1). It is also possible for stars to be 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. Figure 2 shows the distribution of time spent in the cluster by the free-floating planets. The planets are preferentially liberated in the cluster core and 46% are liberated with a velocity less than the escape velocity at the cluster surface (see Fig. 3). We note that the effective escape velocity at the position within the cluster where the planet is liberated will actually be higher than this (SB2001). The velocity dispersion of the free-floating planets is approximately twice that of the cluster stars. We expect this to have only a minimal effect on the determination of the lensing mass in M22 (Sahu et al. 2001). So the planets generally begin their free-floating existence deep within the potential well of the cluster and will then journey toward the outer regions of the

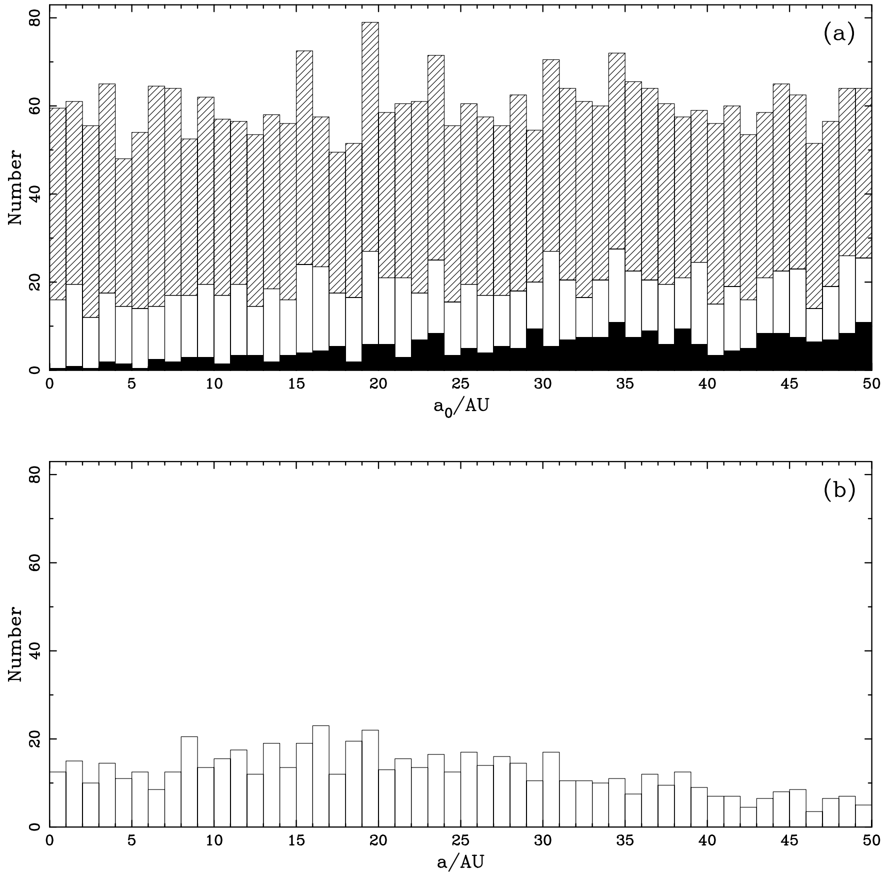

FIG. 1.—Histograms relating to the planetary system separations: (*a*) total of distribution represents the initial planetary systems, the solid region represents those that have been broken up, and the hatched region shows the number of planetary systems that have escaped; (*b*) distribution of separations for planetary systems that remain in the cluster when the simulation ended. Differences between the unshaded regions in (*a*) and (*b*) are attributed to exchange interactions, orbital changes owing to mass loss or weak perturbations, and mergers of planets with their parent star. Note that only results from the second and third simulations are presented in this figure. Numbers in each bin are averaged over these two simulations.

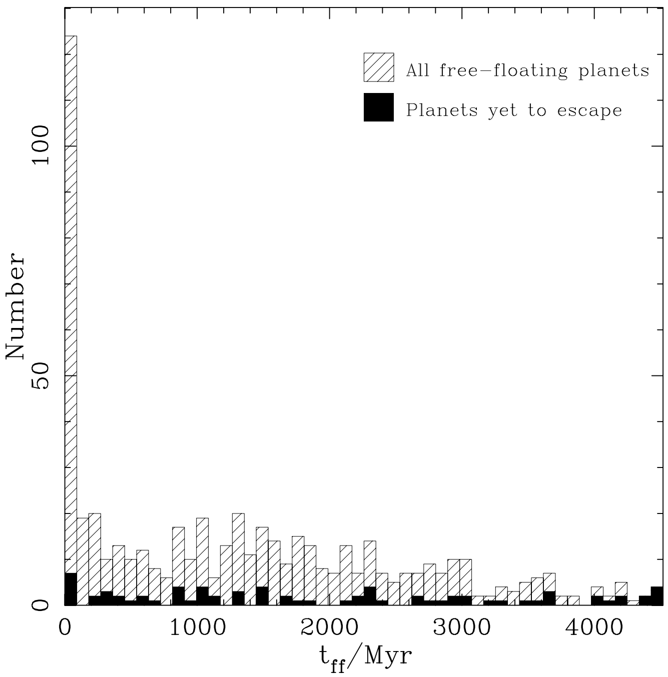

FIG. 2.—Histogram showing the distribution of the time spent in the cluster by free-floating planets subsequent to liberation from their parent star (*hatched region*). Distribution for the subset of planets that remain in the cluster when the simulation was halted is also shown (*solid region*). For these planets, the data represent a lower limit to the time spent in the cluster.

cluster, driven by the effect of two-body relaxation. Chernoff & Weinberg (1990) derive the timescale for mass segregation to be directly related to the relaxation timescale of the cluster, but with an inverse dependence on stellar mass. Therefore, we would expect the planets to take much longer to reach the tidal boundary of the cluster than low-mass stars.

This is not what we see in Figure 4, which illustrates the average position within the cluster over time for various mass groups. As expected, the 0.5–1.0 $M_\odot$ group, which always contains the average stellar mass, shows little movement. For the remaining stellar mass groups, there is a strong correlation between deviation from the average stellar mass and the rate of mass segregation, whether it be inward for high mass or outward for low mass. This clearly demonstrates that equipartition of energy is dominating the dynamical evolution. The picture is complicated for the planets because, in this case, the core population is replenished over time and their velocity distribution is detached from that of the stars. From Figure 4, we see that the average position of the free-floating planet population 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.

For the nonescaping planetary systems, we find that marginally more planets are liberated than suggested by SB2001 (~30% compared to 27%) and that a much larger fraction of free-floating planets are retained (~64% compared to 0.5%). If this trend continues into the globular cluster regime, and we expect that it will, then these early results have an important bearing on the interpretation of the M22 observations. In particular, it strengthens the

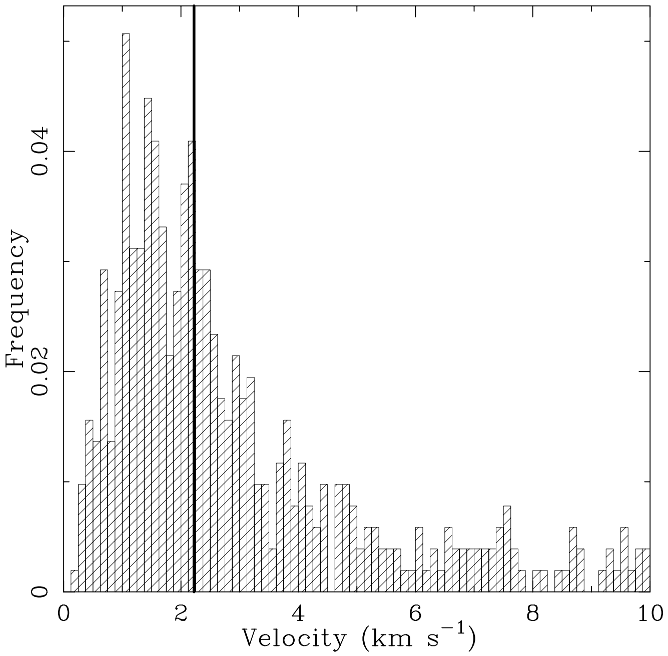

FIG. 3.—Distribution of velocities for free-floating planets immediately after being liberated from their parent star. Distribution is normalized to the total number of liberated planets. Average cluster escape velocity is also shown (*solid vertical line*): 46% of planets are liberated at speeds lower than the cluster escape velocity. Tail of distribution is truncated at 10 km s^{-1}, which excludes the 10% of the liberated planets with velocities extending out to 70 km s^{-1}.

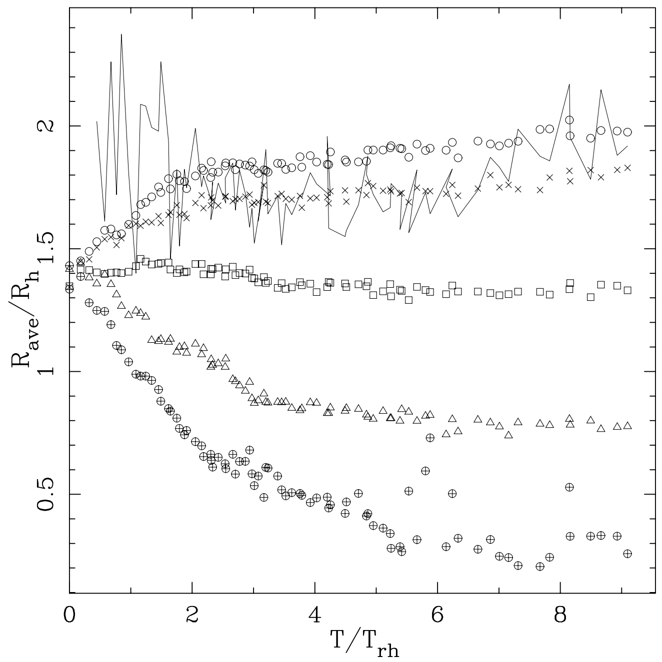

FIG. 4.—Average radial position, scaled by the cluster half-mass radius, of various mass groups as a function of time, scaled by the current half-mass relaxation timescale, T_{rh}. Mass groups identified are: $0.1 - 0.2M_\odot$ ($\circ$), $0.2 - 0.5M_\odot$ ($\times$), $0.5 - 1.0M_\odot$ ($\square$), $1.0 - 1.6M_\odot$ ($\triangle$), $1.6 - 3.0M_\odot$ ($\oplus$), and the free-floating planets (*solid line*). Planet group contains fewer members, approximately 50 at any one time, which explains the increased noise in its data, while data for the most massive group become noisy after about 300 Myr when its members start to evolve off the main sequence. Half-mass relaxation timescale is typically within the range of 200–400 Myr during cluster lifetime.

possibility raised by SB2001 that a significant number of free-floating planets may exist in a globular cluster such as M22. What is surprising is that many free-floating planets may also be found in open clusters.

If there are an estimated 60 free-floating Jupiters per star in M22 and the liberation rate of planets is 50% with a cluster retention rate of 30% (SB2001), then this implies ~ 400 planets per star originally. However, if the retention rate is actually 64% (and possibly higher still in the globular cluster regime), the number of planets required per star is only ~ 200 (or less).

We note that SB2001 only considered equal-mass stars; they studied cases of $0.7\,M_\odot$ and $1.5\,M_\odot$ separately. In this respect, the velocity distribution shown in Figure 3 is more representative of the real picture and this goes some way toward explaining our vastly different results for the retention of planets. SB2001 also note that changes in the planet mass can critically affect the velocity distribution. Table 2 shows that the current number of planets in the cluster is decreasing with time but the escaping planetary systems are distorting the results. For the same reason, our numbers concerning the liberation of planets must be taken as lower limits. However, when comparing these numbers to the work of SB2001, we note that they used a separation distribution uniform in log space for their planetary systems and therefore we have a higher proportion of initially wide orbits. The effect of escaping systems must be addressed in future simulations, possibly by placing planets primarily around stars with mass close to the average for the cluster stars.

4. PLANETARY ORBITS

A 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 nonconservatively in a stellar wind. Weak perturbations from passing stars can cause the orbital period to decrease, affecting 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. A *hard* system is defined as having an orbit with a binding energy greater than that of the mean kinetic energy of the cluster stars (Heggie 1975). It is then expected that owing to close encounters during the cluster evolution, hard systems will become harder, i.e., orbital migration inward, and *soft* systems will be broken up. The hard/soft limit for binaries in our cluster simulations is roughly 60 AU, and for the planetary systems it is more like 0.1 AU. Considering this in conjunction with the relatively low number density of stars in the simulations performed so far, it is not surprising that we have yet to observe hardening of close planetary orbits. Exchange interactions alter the observed distribution of orbital characteristics in a fairly random manner, although it is more likely for a wide system to be involved in such an event.

5. CONCLUSIONS

Contrary to recent claims (Bonnell et al. 2001; Smith & Bonnell 2001) we find that free-floating planets can form a significant population in open star clusters. This is based on the results of open-cluster size N-body simulations, but it is expected to be even more likely in the case of globular clusters. While it should be stressed that the detection of free-floating planets in M22 is preliminary, and also speculative, it suggests that at least 100 planets were formed for every star. This may sound implausible but is in fact supported by recent simulations. Ida & Kokubo (2001) have shown that in a proto–planetary disk where the surface density of the solid component is low, the isolation mass of planets is small and many terrestrial planets can form. It is also possible that proto–planetary disks, having lower metallicity than solar, would form many earthlike planets—perhaps 50–100 per star (S. Ida 2001, private communication). A population of free-floating substellar objects has also been detected in the young cluster σ Orionis (Zapatero-Osorio et al. 2000). The possibility has been raised that these may be formed as such (Boss 2001), i.e., not attached to a parent star.

We agree with Davies & Sigurdsson (2001) that subsequent surveys for planetary systems should be conducted in clusters less dense that 47 Tuc, such as metal-rich open clusters. Observations of a metal-rich globular cluster should help determine whether the lack of planetary systems in 47 Tuc is due to the metallicity of the cluster or dynamical interactions. We note that a planet has been detected within a binary pulsar system in M4 (Thorsett et al. 1999) which is metal-poor compared to 47 Tuc (Harris 1996).

Observational constraints on the binary fraction in open clusters are often uncertain because the number of stars is small and membership can be difficult to determine. Typically a fraction of $\sim 25\%$ is found (Mermilliod & Mayor 1990; González & Lapasset 2000), rising to as high as 50% in some cases (Fan et al. 1996), so obviously the value of 10% used in our N-body simulations is a lower limit. This modest fraction was chosen mainly because the integration of binary orbits is performed on the host workstation, not on the GRAPE board, so that the presence of many binaries has the potential to dramatically increase the simulation time (see Hurley et al. 2001 for a full discussion). Davies & Sigurdsson (2001) find that the effective cross section for the break up of planetary systems via encounters is increased by as much as a factor of 5 when considering binaries rather than single stars. Thus, it will be important to experiment with a higher binary fraction in future simulations.

As we expand the parameter space of our N-body study, many of the interesting issues regarding planetary systems in star clusters will be addressed. Of particular importance will be the inclusion of systems with multiple planets per star (Murray & Holman 2001). Full realization of the capabilities of the GRAPE-6 hardware when the 1-Tflop board becomes available will allow larger particle numbers, and consequently more planetary systems, to be studied per simulation. This will improve the statistical significance of our results considerably. Moving to simulations that operate at globular cluster number densities will make it possible to look for orbital migration in small-period planetary systems. Hence, this study will have implications for future planet searches in globular clusters, especially if hot Jupiter planetary systems cannot form directly in such an environment.

We are extremely grateful to Jun Makino and the University of Tokyo for the loan of the GRAPE-6 board. We thank David Zurek, Shigeru Ida, and Rosemary Mardling for helpful discussions. We also thank the referee (Kester Smith) for a number of insightful comments that improved the quality of this manuscript.

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