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Planetary dynamics in stellar clusters

Ian A. Bonnell,[1★] Kester W. Smith,[2,3] Melvyn B. Davies[4] and Keith Horne[1]

[1]*School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS*
[2]*Institut für Astronomie, ETH-Zentrum, CH-8092 Zürich, Switzerland*
[3]*Paul Scherrer Institut, Würenlingen und Villigen, CH-5232 Villigen PSI, Switzerland*
[4]*Department of Physics and Astronomy, Univeristy of Leicester, Leicester LE1 7RH*

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ABSTRACT

We investigate how the formation and evolution of extrasolar planetary systems can be affected by stellar encounters that occur in the crowded conditions of a stellar cluster. Using plausible estimates of cluster evolution, we show how planet formation may be suppressed in globular clusters while planets wider than $\gtrsim 0.1$ au that do form in such environments can be ejected from their stellar system. Less crowded systems such as open clusters have a much reduced effect on any planetary system. Planet formation is unaffected in open clusters and only the wider planetary systems will be disrupted during the cluster's lifetime. The potential for free-floating planets in these environments is also discussed.

Key words: stellar dynamics – stars: formation – planetary systems.

1 INTRODUCTION

The recent discovery of significant numbers of extrasolar planets (Mayor & Queloz 1995; Marcy & Butler 1996, 1999) has driven an outbreak in research into planet formation. Previously, our knowledge has been based entirely on one data point: our solar system.

The large increase in the number of known systems has had two major consequences for our understanding of planetary formation and evolution: firstly, it seems that planetary systems are not rare, and secondly that they need not conform to solar system type configurations. Specifically, the fact that the extrasolar planets discovered so far are gas giants commonly in close orbits was unexpected according to theories based upon the planets in the solar system (e.g. Lissauer 1993; Ruden 1999). This has led to new theories to explain how gas giants that form at distances similar to Jupiter from their central star can migrate inwards to occupy the close orbits as has been found (Lin, Bodenheimer & Richardson 1996). Forming the gas giants at such distances is seen as improbable owing to the lack of sufficient condensable material for planetesimal growth.

A further complication to planet formation may arise owing to the fact that stars are commonly found and perhaps generally formed in stellar clusters. In addition to the well known globular and open clusters, recent IR surveys have shown that most young stars are found in dense embedded clusters (cf. Clarke, Bonnell & Hillenbrand 2000). The density of these clusters range from 10^3 to $\gtrsim 10^4$ star pc^{-3} in the core of the Orion Nebular Cluster (ONC). Larger clusters such as R136 in 30 Doradus have even higher densities ($\gtrsim 10^5$) and are probably more appropriate for the early conditions of globular clusters. It is the aim of this paper to investigate how the high stellar density in such regions affect both planet formation and planetary survival. Cluster membership has other disadvantages as the proximity of massive stars can also act to impede planet formation (Armitage 2000).

2 CLUSTER EVOLUTION

In determining how relevant stellar interactions are for planets and planet formation, we have to consider not only the present cluster conditions but also the cluster's previous evolution. Although it is difficult if not impossible to determine the previous evolution in individual cases, we can estimate probable evolutionary histories by considering cluster dynamics and initial conditions. Firstly, if we consider the young (embedded) clusters found in star forming regions, they generally contain significant amounts of mass in the form of gas. For example, the ONC is believed to contain 50 per cent of its mass in gas (Hillenbrand & Hartmann 1998). As the initial mass function (IMF) and median mass are typical of field stars (Hillenbrand 1997), the majority of this mass will be ejected from the system. In general, the mass that is not accreted will help unbind the cluster. The evolution of the cluster undergoing gas removal depends critically on the gas fraction and on the removal time-scale (Lada, Margulis & Dearborn 1984; Goodwin 1997). Simulations of cluster expansion owing to gas expulsion have shown that for clusters which do survive, they generally increase their half-mass radii by factors of ≈ 3–5 (Goodwin, Pearce & Thomas 2000; Kroupa, Aarseth & Hurley 2000). This corresponds to a decrease in the mean cluster density of 10 to 100. Another way of quantifying this expansion is by comparing the youngest embedded clusters with older open clusters. Thus, from densities of 10^3 to $\gtrsim 10^4$ star pc^{-3} typical of the ONC the clusters must

★ E-mail: iab1@st-andrews.ac.uk

evolve towards densities of $\lesssim 10^2$ star pc^{-3} typical of open clusters. This is probably a lower limit as some gas removal may have already occurred in the youngest systems. Furthermore, the lower frequency of open compared to embedded clusters implies that many of the embedded clusters do not survive the expansion phase. The time-scale for this high density phase is likely to be the lifetime of the most massive stars in the system. Especially in systems with high velocity dispersions such as young globulars, multiple supernova events are the likely cause of gas removal and thus setting a time-scale of several $\times 10^6$ yr.

After gas removal, the cluster will continue to expand owing to a combination of mass segregation, tidal interactions with the Galaxy, which removes stars from the cluster (e.g. Terlevich 1987), and binaries, which absorb a large fraction of the binding energy. The combination of all these effects can typically increase the cluster's radius substantially and thus decreases the stellar density. Simulations of post core-collapse clusters including the effect of binaries have shown a decrease in density of ≈ 10 (Giersz & Heggie 1997) when not filling their tidal radius.

From these considerations, we can estimate that cluster densities generally decrease by factors of 10 to $\gtrsim 100$ (or possibly up to 1000 in some cases) over their evolution. Although these higher density phases may have occurred over much shorter time-scales, they could potentially have had dramatic effects on any planetary systems.

3 CLUSTER PROPERTIES

The clusters we consider here range from the low density open clusters in the stellar neighbourhood to the globular clusters such as 47 Tuc and the possible precursers of both of these types of systems. Open clusters generally have stellar densities of $\lesssim 10^2$ star pc^{-3} and ages of $\lesssim 10^9$ yr with low velocity dispersions, $v_{\rm disp} \lesssim 1$ km s^{-1}. Based on the above discussion, precursers of such systems probably had densities of $\gtrsim 10^3$ to 10^4 (possibly as high as 10^5) star pc^{-3} with still low velocity dispersions of a few km s^{-1}.

Globular clusters commonly have densities of $\approx 10^3$ star pc^{-3}, ages of $\lesssim 10^{10}$ yr and velocity dispersions of ≈ 10 km s^{-1}. Precursers of present-day globular clusters, again based upon expectations from gas expulsion and later evolution, are likely to have had densities of $\gtrsim 10^5$ to $\approx 10^6$ star pc^{-3} over their first few million years.

4 PLANET FORMATION

The first potential effect of the stellar environment on any planetary systems is on their potential for formation. Most theories for the formation of gas giant planets involve the slow growth of planetesimals through collisional processes in the circumstellar disc. This process requires sufficient condensible material in the disc which in most disc models only exist beyond a few au from the star. In this scenario, any gas giant closer to the parent star has to undergo an inward migration, possibly owing to the torques from the accretion disc (Lin et al. 1996).

The growth from planetesimals to a planetary core can take up to a million years, while the subsequent gas accretion to build a giant planet can take up to 10 million years (e.g. Lissauer 1993; Pollack et al. 1996). Thus, if extrasolar planet formation occurs in an analogous fashion to that believed to have occurred in our solar system, then the primary requirement is that the circumstellar disc is present and relatively stable over such time-scales. In a crowded region, any stellar encounters can perturb this disc and thus suppress its planet forming potential. In addition, any encounter which occurs before the planet has migrated is likely to eject the planet from the system.

Investigations of stellar encounters including non-self-gravitating circumstellar discs have shown that the encounters generally remove any material exterior to one third of the periastron distance (Hall, Clarke & Pringle 1996). So, for example, if a star passes within 10 au of another, this will remove all disc material exterior to ≈ 3 au.

If we assume that any giant planets form at separations typical of the gas giants in the solar system, then any encounters within 10 au will suppress the formation of gas-giant planets. Alternatively, encounters within 50 au will truncate the circumstellar disc to ≈ 15 au, which will impede some planet formation and possibly affect the subsequent migration of any inner planets. For a given star in the cluster, the mean time interval, $t_{\rm enc}$, between encounters within a distance $R_{\rm enc}$ is (Binney & Tremaine 1987):

$$\frac{1}{t_{\rm enc}} = 16\sqrt{\pi} n v_{\rm disp} R_{\rm enc}^2 \left(1 + \frac{GM_*}{2 v_{\rm disp}^2 R_{\rm enc}}\right), \qquad (1)$$

From equation (1) we can see that the time-scale for an encounter depends on both the stellar density n and the velocity dispersion $v_{\rm disp}$ in addition to the interaction length $R_{\rm enc}$. The first term in brackets on the right-hand side represents the contribution of the geometric cross-section of the target and the second term represents the effect of gravitational focusing. Fig. 1 plots the time-scale for encounters within 0.5, 10 and 50 au for clusters containing 240 and 5×10^5 stars as a function of the stellar density ($v_{\rm disp}$ is chosen to ensure that the clusters are virialized). We see that for encounters within a disc radius to occur within the planet formation time-scales, $\lesssim 10^7$ yr, requires relatively high stellar densities ($\gtrsim 10^4$ star pc^{-3}). The required densities are lower for larger clusters owing to their larger velocity dispersions. In order for encounters to seriously affect planet formation ($\lesssim 10^7$ yr), cluster densities of $\gtrsim 10^5$ star pc^{-3} are required. Such densities are high relative to today's globular clusters but are not unreasonable for the earliest phase of a globular cluster's lifetime before expansion resulting from gas expulsion.

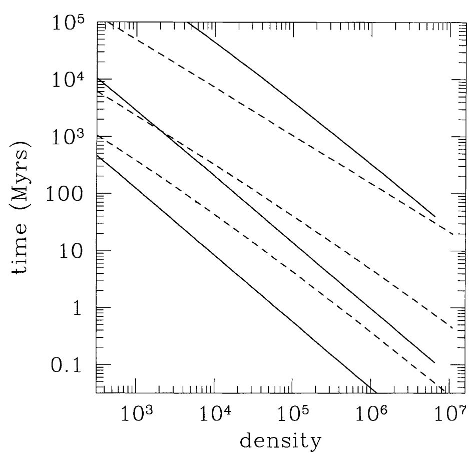

Figure 1. Encounter time-scale versus density for clusters of 240 (dashed) and 5×10^5 (solid) stars for (from top to bottom) 0.5, 10 and 50 au separations. The velocity dispersion is taken such that the clusters are virialized.

It is interesting to note that encounters within 0.5 au are not expected to occur on reasonable time-scales for most clusters and even a high density phase would have to be very long ($\gtrsim 10^8$ yr) in order to have appreciable numbers of encounters that close to the parent star. Thus, the disruption of close-in gas giant planets is unlikely to occur owing to encounters in a stellar cluster. In this context, in order to explain the lack of close-in giant planets in 47 Tuc (Brown et al. 2000; Gilliland et al. 2000) requires that either the giant planets did not form or that they did not migrate.

Fig. 2 plots the necessary conditions in terms of cluster density and velocity dispersions for encounters within 10 and 50 au (of a 1.0-$M_\odot$ star) to occur on time-scales of two and 10 million years. The time-scale decreases with increasing density and, weakly, for increasing velocity dispersion. For example an encounter within 10 au will occur in 10 million years for clusters with densities $\gtrsim 2 \times 10^5$ star pc^{-3} and velocity dispersion of $\gtrsim 10$ km s^{-1}, whereas clusters with densities of $\gtrsim 8 \times 10^5$ star pc^{-3} and velocity dispersion of $\gtrsim 10$ km s^{-1} will have similar encounters within one million years. The dotted lines in Fig. 2 show the possible evolutions in density–velocity space of clusters with 4×10^3 and 5×10^5 stars, as they expand (assuming virialized conditions).

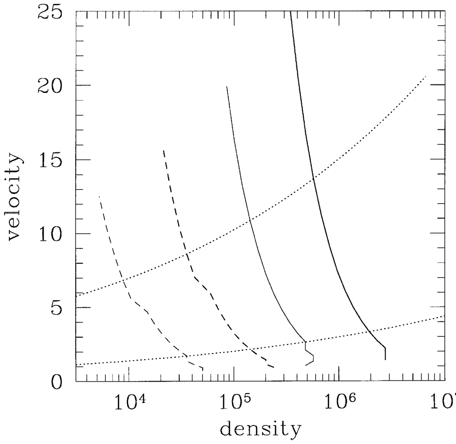

Figure 2. The cluster conditions in density–$v_{\rm disp}$ space in order to have mean encounter time-scales of two (heavy lines) and 10 (light lines) million years for an encounter within 10 au (solid lines) and 50 au (dashed lines) of a 1.0-$M_\odot$ star. Probable evolutionary sequences are plotted (dotted lines) for a cluster of 5×10^5 and 4×10^3 stars.

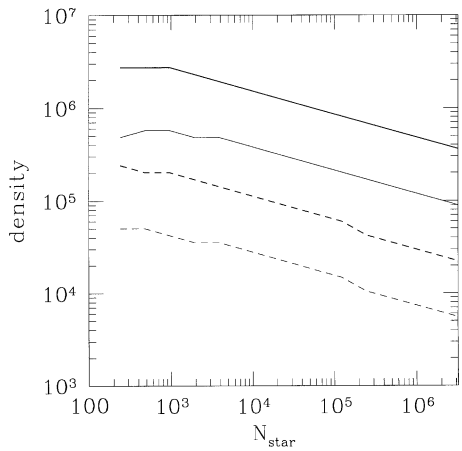

Figure 3. Same as Fig. 2, but as a function of the number of stars and the stellar density in the cluster.

Thus, if the planet formation time-scale is $\gtrsim 5 \times 10^6$ yr, stars in a cluster of 3×10^5 stars with densities $\gtrsim 3 \times 10^5$ star pc^{-3} will typically have their discs stripped through stellar interactions before they are able to form gas giant planets.

The effect of the number of stars on the necessary cluster conditions can be seen in Fig. 3 which shows the critical densities for encounters within 10 and 50 au (of a 1.0-$M_\odot$ star) on time-scales of two and 10 million years as a function of the number of stars in the cluster. The decrease in critical densities in larger-N systems is because of the larger velocity dispersions in such systems. From this, it can be seen that densities $\gtrsim 10^4$ start to become interesting for disrupting some outer planets or the outer disc, whereas densities $\gtrsim 10^5$ are required to affect planets that form at distances of ≈ 5 au.

Combining the expected evolution of clusters of different numbers of stars and the expected encounter time-scale, we expect that encounters within 10 au can occur within the planet forming time-scale in the large-N globular clusters but not in the smaller-N open (embedded) clusters. This difference is mainly because of the expected densities in the earliest stages of the cluster evolution combined with the higher critical densities for encounters in the low-N systems.

5 PLANETARY SYSTEM DISRUPTION OWING TO STELLAR ENCOUNTERS

Planetary systems that do succeed in forming in a stellar cluster are then subject to disruptions from stellar encounters. Once a planet has formed, and possibly migrated to its final separation from the parent star, the probability of a disruptive encounter depends on this separation and on the cluster properties. In order to quantify this probability we performed simulations of the evolution of a population of planets in various cluster conditions.

The initial distribution of planetary orbits was taken to be flat in log separation, and spanned a range of 0.01 to 100 au. Two main cluster types were investigated, globular clusters and open clusters. For the globular cluster case, we chose a velocity dispersion of 10 km s^{-1}. For the open cluster case, the velocity dispersion is 2 km s^{-1}. We then used equation (1) to calculate the probability of encounters within various time intervals and cluster densities (see Figs 4 and 5). In each case, the total time interval was split into smaller time-steps, so that multiple encounters were possible.

The effect of an encounter on a planetary system was determined as follows. Where the kinetic energy of the perturber was greater than the binding energy of the planet, the planetary system was assumed to be destroyed (or 'ionized'). Where the kinetic energy of the perturber was less than the binding energy of the planetary system, the planet was assumed to lose energy and move closer to its parent star (the system is 'hardened'). This hardening was taken to be 25 per cent, based on average values obtained in binary–single star scattering experiments (Sigurdsson & Phinney 1993; Davies 1997). In the former case, the system is termed 'soft', while in the latter, it is said to be 'hard'. The hard–soft boundary is given by

$$R_{\rm hard} = \frac{GM_1M_2(M_1 + M_2 + M_3)}{M_3(M_1 + M_2)v_{\rm enc}^2}, \tag{2}$$

where M_1, M_2 and M_3 are the masses of the primary, secondary (in this case planet) and of the perturber star. The encounter velocity, $v_{\rm enc}$, is essentially the velocity dispersion, $v_{\rm disp}$, of the cluster.

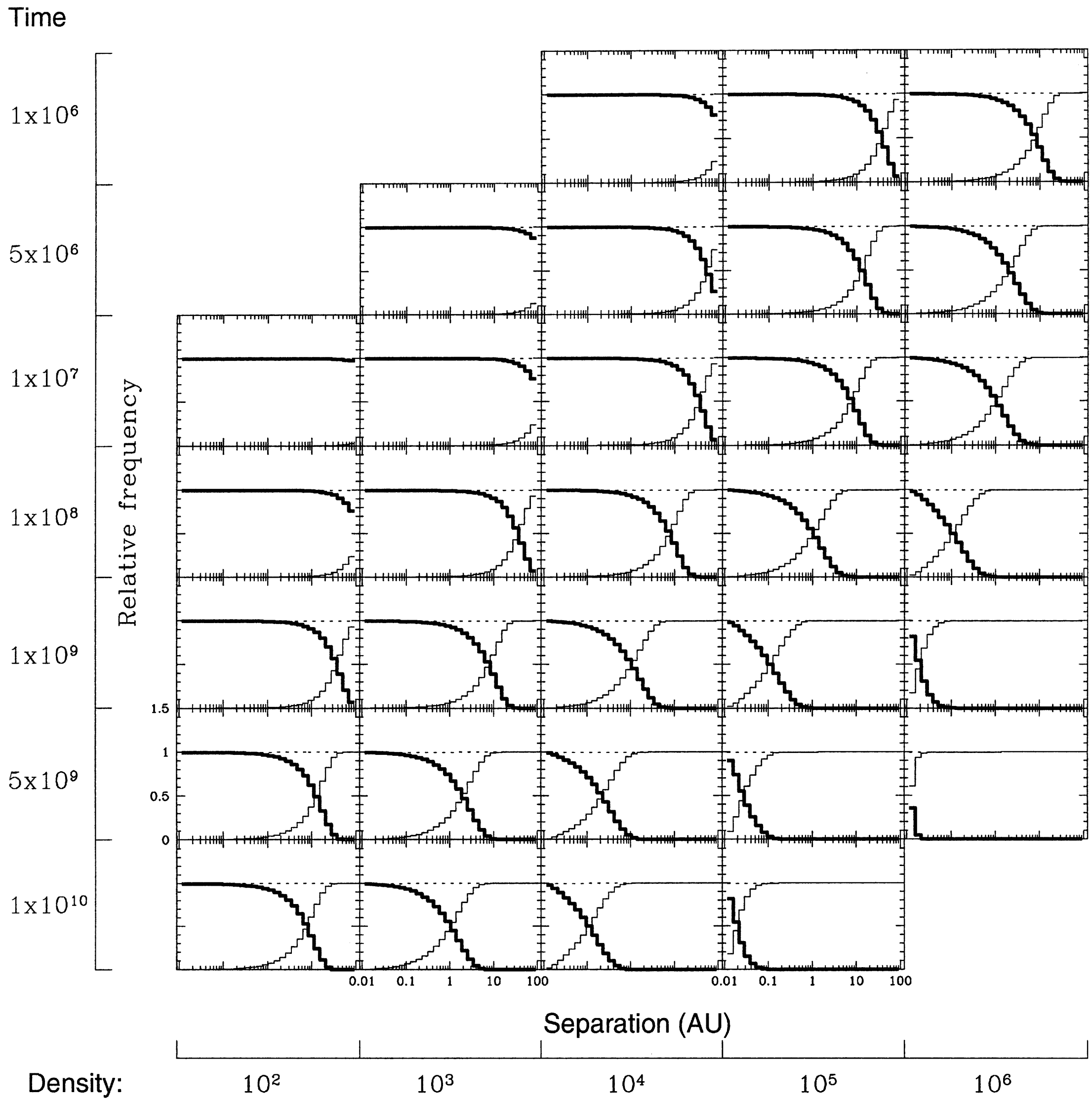

Figure 4. Separation distributions for populations of planetary systems exposed to different globular cluster environments. In each case, $M_1 = M_3 = 0.5\,\mathrm{M}_{\odot}$, $M_2 = 0.001\,\mathrm{M}_{\odot}$ (i.e. one Jupiter mass). The density of the cluster varies between 10^2 to $10^6\,\mathrm{star\,pc^{-3}}$ along the *x*-axis and the total time-scale of the simulation varies from 10^6 to 10^{10} yr down the *y*-axis. The dotted line is the initial population while the final population is the heavy solid line. The lighter solid line represents the ionized systems. The velocity dispersion is $10\,\mathrm{km\,s^{-1}}$, typical for a globular cluster.

From equation (2) we see that most planetary systems, where M_2 is small, are 'soft' and will easily be ionized through encounters. The question of hardenning is therefore not crucial to our conclusions. In addition, encounters can drive eccentricity into the planetary system, and thus potentially further instability (Davies & Sigurdsson 2000).

The results from our simulations are divided into two sections depending on the chosen velocity dispersion. First we present the results appropriate for globular clusters with $v_{\mathrm{disp}} = 10\,\mathrm{km\,s^{-1}}$, then those for open clusters with $v_{\mathrm{disp}} = 2\,\mathrm{km\,s^{-1}}$.

5.1 Planetary disruption in globular clusters

Fig. 4 presents the results for the planetary systems in clusters where the velocity dispersion is $\approx 10\,\mathrm{km\,s^{-1}}$. The figure is broken up into different panels each appropriate for a specific stellar density and for a specific amount of time. Globular clusters have typical core densities of $\approx 10^4\,\mathrm{star\,pc^{-3}}$, mean densities of $\approx 10^3\,\mathrm{star\,pc^{-3}}$ and lifetimes which extend to the age of the Galaxy ($10^9 \lesssim t \lesssim 10^{10}$ yr). The cluster densities increase from left to right and the time increases from top to bottom. The dotted lines give the initial planetary distribution while the heavy solid lines give the final planetary distribution. The light solid lines indicate the fraction of planetary systems, and their initial separations, which have been ionized.

The overall result is that the wider (softer) systems are more easily disrupted than are the tighter systems. Their larger cross-section for an encounter results in lower critical densities and in shorter encounter time-scales. Tighter systems require higher stellar densities in order to ensure a reasonable time-scale for an encounter. Furthermore, a cluster of given stellar density will disrupt increasingly tighter systems with time until reaching the hard–soft boundary. Thus, wide systems are disrupted in most clusters although they do require longer time-scales in the least dense clusters. In contrast, the tighter systems are only disrupted in sufficiently old, dense, clusters.

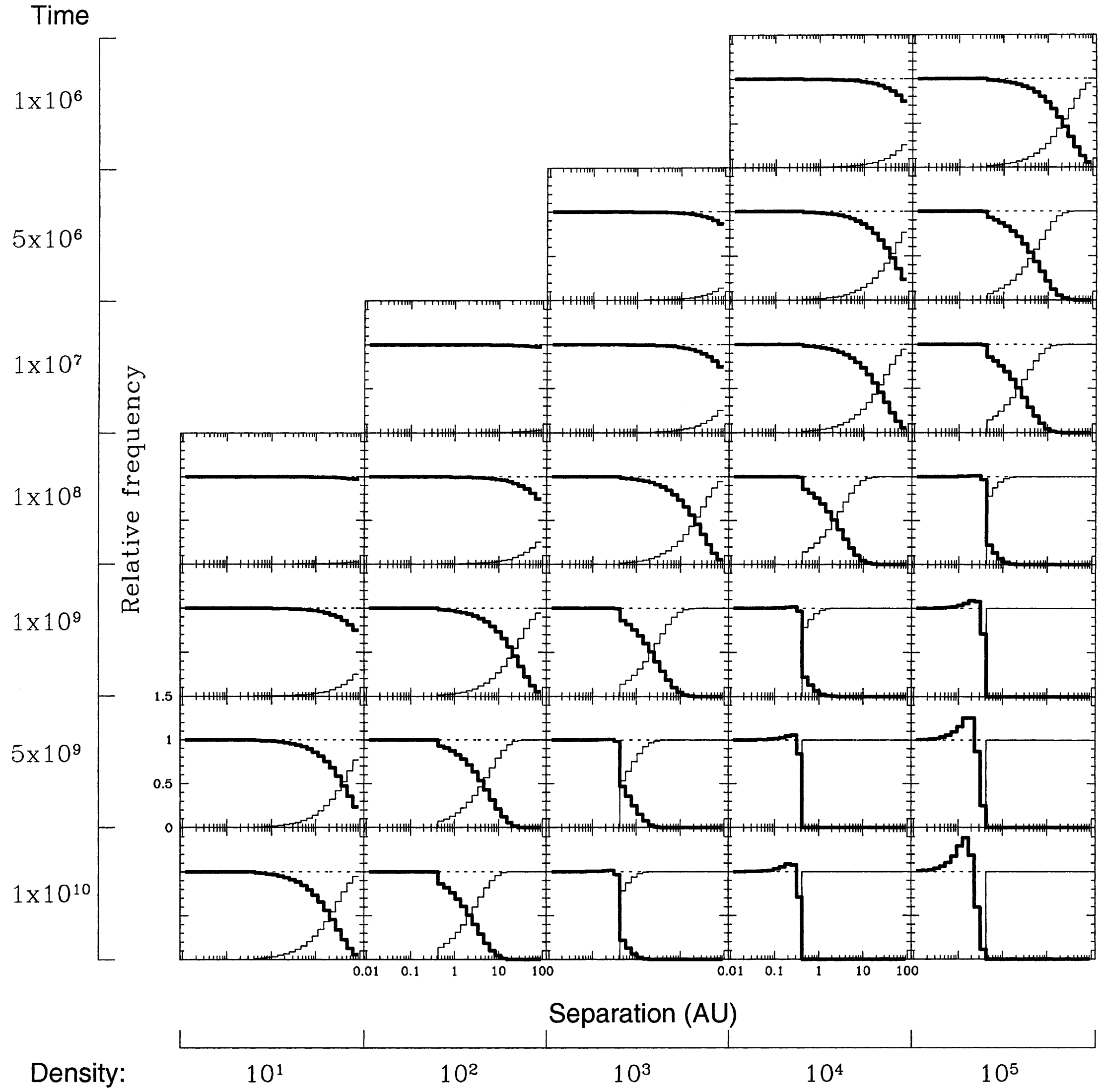

Figure 5. Same as Fig. 4, but with a velocity dispersion (of $2\,\mathrm{km\,s^{-1}}$) and densities typical for an open cluster.

It can be seen that in the case of $v_{\mathrm{disp}} = 10\,\mathrm{km\,s^{-1}}$, all systems are soft. There is no hardening (moving planets to smaller separations) and any system which is perturbed is disrupted. This occurs as the hard–soft boundary is at $R_{\mathrm{hard}} \approx 0.02$ au or $4\,\mathrm{R_{\odot}}$ (smaller than the separations considered here). Thus some hardening can be expected of only the tightest of planetary systems.

It should be noted that probable evolutionary paths (based on the discussion of Section 2) of a globular cluster through this diagram will be from the upper right (gas-rich cluster) towards the lower left. In general, any high density phase, will last for $t \lesssim 10^7$ yr whereas subsequent phases will last successively longer as the cluster evolves on a relaxation time-scale. It is also worth noting that the long time-periods that a cluster spends in the less dense phases can actually be more destructive of the relatively short-period planetary systems than are the short-lived high-density phases.

Present day globular clusters such as 47 Tuc have mean stellar densities (near the half-mass radius) and ages that put them in the lower-left part of Fig. 4 (densities of $\approx 10^3\,\mathrm{star\,pc^{-3}}$ and ages of $\lesssim 10^{10}$ yr). Thus, any planetary systems with separations $\gtrsim 1$ au are likely to have suffered a disruptive encounter and no systems with separations greater than 10 au should still exist. In the core of such a cluster with densities $\gtrsim 10^4\,\mathrm{star\,pc^{-3}}$, even those systems as tight as 0.1 au are likely to be disrupted and only those with separations $\lesssim 0.01$ au are completely safe. Even these systems can be disrupted if the core density is as high as $10^5\,\mathrm{star\,pc^{-3}}$. Lower densities typical of the halo of the cluster will leave wider systems ($\lesssim 10$ au) intact.

Planetary systems with very small separations $\lesssim 1$ au are generally unaffected by stellar encounters in globular clusters unless the cluster density was extremely large ($\gtrsim 10^5$) for the majority of the cluster's lifetime ($t \gtrsim$ few 10^9 yr). Thus, the only way to destroy tight planetary systems in globular clusters is to destroy the disc before the planet forms and before it has a chance to migrate inwards. If the planet forms *in situ*, then stellar encounters are not a promising way of disrupting the system.

5.2 Planetary disruption in open clusters

Fig. 5 shows the contrasting case more typical of open clusters where the velocity dispersion is a few $\mathrm{km\,s^{-1}}$. The first difference

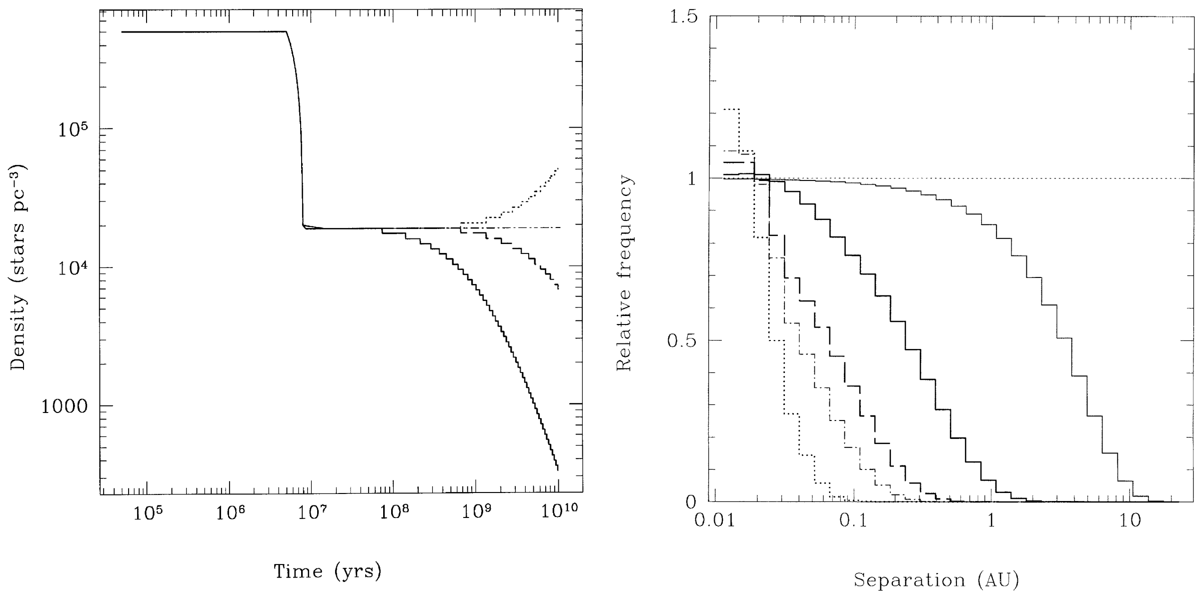

Figure 6. The left panel shows the assumed density evolution in a model cluster containing 5×10^5 stars. The evolution starts from a density of 5×10^5 star pc^{-3} which expands after a few $\times 10^6$ yr owing to gas loss. Further expansion of the cluster is taken to occur on one (solid line), 10 (dashed line) and ∞ (dot-dashed line) $t_{\rm relax}$. A possible increasing density, as one might expect as the cluster evolves towards core collapse, is also modelled (dotted line). The right panel shows the resultant surviving planetary system distributions after the initial expansion owing to gas loss and after 10^{10} yr for each model. They are from left to right the increasing density model (dotted), the constant density model (∞ $t_{\rm relax}$, dot-dashed), the 10 $t_{\rm relax}$ evolution (dashed) and the one $t_{\rm relax}$ evolution (solid). The second solid line represents the evolution after the gas-expansion phase whereas the horizontal dotted line is the initial distribution of the planetary systems.

to note is that the hard–soft boundary for planetary systems is significantly further out ($\approx$0.6 au) and that a cluster with large densities for long time periods could experience significant hardening. Typical densities and lifetimes of open clusters (10^2 star pc^{-3} and $t \lesssim 10^9$ yr), precluding significant hardening of planetary systems as the probability of encounters near the hard–soft boundary, is not very high. In general, most planetary systems are not adversely affected by stellar encounters in open clusters. Significant disruption only occurs for systems with separations $\gtrsim$10 au. Even an early high density phase is unlikely to be sufficiently dense or long-lived to cause much disruption to any but the widest of planetary systems.

5.3 Model cluster evolutions

In order to illustrate how the cluster evolution might affect the planetary populations, we have repeated the simulations of Sections 5.1 and 5.2 but with time-dependent parameters (density and velocity dispersion), designed to mimic a simple cluster evolution model. An example of this is included in Fig. 6 for a cluster containing 5×10^5 stars. We assume an initial stellar density of 5×10^5 star pc^{-3} during the gas-rich phase, which persists for several $\times 10^6$ yr. Once the gas is expelled, the density decreases rapidly to 2×10^4 star pc^{-3}. The subsequent evolution has four possibilities. First a constant density representing a non-evolving cluster. Secondly a cluster that continues to expand on its relaxation time-scale or, thirdly, on 10 relaxation times. These model evolutions include, in a heuristic way, the effects expected from relaxation (Chernoff & Weinberg 1990) and from binary heating (Giersz & Heggie 1997). Lastly, a model where the cluster density contrasts increase on 10 relaxation times is included to illustrate the effects of core collapse on any planetary systems in the cluster core. It should be noted that the different evolutionary models can be taken to represent different parts of the cluster.

Each model is evolved up to 10^{10} yr, while the velocity dispersion is adjusted such that the cluster is virialized. We see that the initial high density phase can disrupt any systems (or discs) that extend to several (to 10) au or more. Systems with smaller separations are disrupted during the following less-dense phases owing to their longer time-scales. The fastest evolving model destroys the fewest planetary systems but still leaves only those closer than $\lesssim$1 au with a 50 per cent chance of survival at $\approx$0.3 au. The model which evolves on 10 relaxation times destroys almost all systems $\gtrsim$0.2 au whereas the constant density model removes systems $\gtrsim$0.1 au. The model with increasing density, such as occurs in a core collapse, removes systems $\gtrsim$0.05 au with a 50 per cent survival rate interior to 0.03 au. It is interesting to note that these last two evolutions include significant hardening inside 0.02 au ($\approx 4\,R_\odot$). Thus in this simplified model there should still be some gas giants on very tight orbits.

5.4 The Sun's natal environment

An interesting question to pose is what can we deduce of the probable natal environment of the Sun and whether such an environment would leave a detectable trace in the solar system. The existence of the planets in the solar system and beyond them of the Kuiper belt to $\approx$50 au (Jewitt & Luu 2000) implies that any stellar encounters must have been more distant than that. Thus, it is unlikely that the Sun spent a significant fraction of its lifetime in a high density environment. Alternatively, the apparent lack of Kuiper belt objects beyond 50 au (Hahn 2000) could imply a stellar encounter which truncated the solar system at that radius (see also Ida, Larwood & Burkert 2000). If this is the correct interpretation, we can deduce from Fig. 5 the probable cluster properties in order to have a significant probability of such an encounter. Thus, the Sun could have been a member of an open cluster with a mean density of $\approx 10^2$ star pc^{-3} for $t > 10^8$ to nearly 10^9 yr, or alternatively, that the cluster had an earlier high-density phase with either a density of $\approx 10^3$ star pc^{-3} for $t > 10^7$ to nearly 10^8 yr or a density of $\approx 10^4$ star pc^{-3} for $t \approx$ a few $\times 10^6$ yr. The existence of the Oort cloud beyond the limit of the Kuiper belt implies that any interaction would have had to happen before the bulk of the Oort cloud was ejected from the solar nebular disc, thus within a few 10^7 yr. This is possible if the Sun was born in a cluster with a density of $n \gtrsim 10^3$ star pc^{-3} which dissolved, or evolved to a lower density, within $\approx 10^8$ yr.

6 FREE-FLOATING PLANETS

One of the implications of stellar encounters disrupting planetary systems in stellar clusters is that there should then be a population of free-floating planets. Such a population, owing to stellar encounters, is unlikely to be significant in most open clusters as these clusters are not sufficiently long-lived. Even fewer free-floating planets are expected in the young clusters owing to the disruption of planetary systems. Alternatively, the more frequent disruption of planetary systems in globular clusters should result in a population of free-floating planets. For example, in clusters with ages $\approx 10^{10}$ yr and densities $\gtrsim 10^3$ star pc^{-3}, any planetary systems with separations $\gtrsim 1$ au should have been disrupted and these planets liberated into the cluster. If such systems resemble our own, then a number of planets would be liberated per event. The likelihood for finding free-floating planets depends on their velocities. In open clusters any free-floating planets are likely to have velocities after disruption well in excess of the escape speed (Smith & Bonnell 2001). In contrast, post-disruption velocities in globulars are more likely to be comparable or less than the higher escape speeds there (Smith & Bonnell 2001). In either case, owing to their low-mass, subsequent two-body encounters will increase their velocity dispersion and thus limit their lifetime in the cluster.

7 CONCLUSIONS

We have shown that young planetary systems similar to the Solar system have a good chance of surviving their early years if they have the good fortune to form in an open cluster environment. Planetary systems formed in globular clusters, on the other hand, face two major obstacles to their reaching adulthood. First, the natal disc from which planets could form must survive for at least a few million years. If the earliest stages of a globular cluster include a high-density phase ($\gtrsim$ few 10^5 star pc^{-3}) then the circumstellar disc can be truncated inside the region where gas-giant planets are believed to form. Such a high density phase is consistent with expectations based on the efficiency of star formation in nearby embedded (young) stellar clusters and on subsequent cluster dynamics. This could explain the recent find of a lack of close planets in 47 Tuc (Brown et al. 2000; Gilliland et al. 2000).

Secondly, the planetary systems must endure a constant bombardment from neighbouring star systems. These interactions will destroy most planetary systems beyond about 0.3 au over the lifetime of the cluster. We conclude that giant planet formation may be made more difficult in a globular cluster and that any which do form are unlikely to survive unless their orbits are $\lesssim 0.3$ au.

The planets thrown out by interactions would be expected to form a population of free substellar bodies in the cluster. The velocity obtained by them from the initial disruption and subsequent encounters are likely to be higher than the escape velocity of the cluster and thus free-floating planets should not form a significant population in stellar clusters.

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