ON THE ORIGIN OF PLANETS AT VERY WIDE ORBITS FROM THE RECAPTURE OF FREE FLOATING PLANETS

HAGAI B. PERETS 1 AND M. B. N. KOUWENHOVEN 2

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA; hperets@physics.cfa.harvard.edu
2 Kavli Institute for Astronomy and Astrophysics at Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, China; thijskouwenhoven@gmail.com

Received 2012 February 2; accepted 2012 March 1; published 2012 April 17

ABSTRACT

In recent years, several planets have been discovered at wide orbits (>100 AU) around their host stars. Theoretical studies encounter difficulties in explaining their formation and origin. Here we propose a novel scenario for the production of planetary systems at such orbits, through the dynamical recapture of free floating planets (FFPs) in dispersing stellar clusters and stellar associations. This process is a natural extension of the recently suggested scenario for the formation of wide stellar binaries. We use $N$-body simulations of dispersing clusters with 10–1000 stars and comparable numbers of FFFPs to study this process. We find that planets are captured into wide orbits in the typical range ~few × 100–10$^6$ AU and have a wide range of eccentricities (thermal distribution). Typically, 3–6 × (f$_{FFP}$/1%) of all stars capture a planetary companion with such properties (where f$_{FFP}$ is the number of FFP per star in the birth clusters). The planetary capture efficiency is comparable to that of capture-formed stellar binaries, and shows a similar dependence on the cluster size and structure. It is almost independent of the specific planetary mass; planets as well as substellar companions of any mass can be captured. The capture efficiency decreases with increasing cluster size, and for a given cluster size it increases with the host/primary mass. We also find that more than one planet can be captured around the same host through independent consecutive captures; similarly, planets can be captured into binary systems, both in circumstellar and circumbinary orbits. We also expect planets to be captured into pre-existing planetary (and protoplanetary systems) as well as into orbits around black holes and massive white dwarfs, if these formed early enough before the cluster dispersal. In particular, stellar black holes have a high capture efficiency (>50% and 5–10 × (f$_{FFP}$/1%) for capture of stars and planetary companions, respectively) due to their large mass. Finally, although rare, two FFPs or brown dwarfs can become bound and form an FFP-binary system with no stellar host.

Key words: binaries: general – planetary systems – planets and satellites: detection – planets and satellites: dynamical evolution and stability – planets and satellites: formation – stars: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

Exoplanetary systems are known to exist in a wide variety of configurations, raising many challenges to our understanding of the complex processes of planet formation. Some of these planetary systems were found to have massive planets orbiting their host stars at wide orbits (hundreds of AU; Lafrenière et al. 2008, 2011; Biller et al. 2011; Ireland et al. 2011). Such systems are not easily produced in current models of planet formation, and their origin is still debated (e.g., Dodson-Robinson et al. 2009; Boss 2011; Kratter et al. 2010; Veras et al. 2009). Microlensing observations findings show the possible existence of a large population of apparently free floating planets (FFPs; 1.8–13.9 per star; Sumi et al. 2011), i.e., they appear not to have any host star, consistent with theoretical expectations of the production of such runaway planets through various processes (e.g., Kroupa & Bouvier 2003; Veras et al. 2009; Beauge & Nesvorny 2011; Parker & Quanz 2012, and references therein). Here we suggest a novel scenario connecting FFPs with wide-orbit planets, namely, the production of wide-orbit planetary systems from the recapture of FFPs in dispersing clusters.

Recently, several studies have quantitatively shown that wide stellar binaries can form following the dispersal of a stellar cluster or stellar association (Kouwenhoven et al. 2010, hereafter Paper I; Moeckel & Bate 2010; Moeckel & Clarke 2011), and a similar suggestion was raised for the formation of Oort clouds (Levison et al. 2010). Since the majority of stars are thought to be born in star clusters (Lada & Lada 2003), the majority of planetary systems should also form and evolve in such environments. Indeed, many studies explored the evolution of planets in stellar clusters (prior to the clusters’ dispersal), showing they could be dynamically excited by encounter with other cluster stars or even be expelled from their host star to become free floating planets (e.g., Laughlin & Adams 1998; Bonnell et al. 2001; Smith & Bonnell 2001; Adams et al. 2006; Fregeau et al. 2006; Spurzem et al. 2009; Malmberg et al. 2011; Parker & Quanz 2012, and references therein). Studies of the kinematic properties of such FFPs suggest that they have similar velocity dispersion as the cluster stars (Parker & Quanz 2012). The suggested scenario for the formation of wide binaries following the cluster dispersal could therefore similarly produce wide planetary systems through the same capture process, where we assume that the FFP populations is formed prior to the cluster dispersal, which is generally consistent with the suggested origins of such FFPs.

The capture processes can be described as follows (see also Paper I); in an evolving star cluster, stars and FFPs may become bound to each other as the cluster expands, i.e., if the gravitational influence of the other cluster members decreases. In order to form a binary pair in this way: (1) they need to

5 We do caution that the actual fraction of FFPs is unknown; it is possible that the apparently host-less planets observed have companions too faint to be resolved or too far away. We therefore scale our results throughout this paper by the FFP fraction per star.
be sufficiently close together, (2) a star and a planet (or even two planets/brown dwarfs) need to have a sufficiently small velocity difference, and (3) the newly formed binary should not be destroyed by gravitational interaction with the remaining cluster stars, field stars or the Galactic tide. In the following we present the results of detailed N-body simulations which show that wide-orbit planetary systems around both single and binary stars can form at large numbers under realistic conditions. In addition we note that this mechanism can produce FFP-binary systems, brown-dwarf planetary systems such as been recently observed (e.g., Jayawardhana & Ivanov 2006) as well as planetary systems around compact objects (white dwarfs and black holes).

The paper is organized as follows. In Section 2 we provide a brief overview of our technique and assumptions, which are described in details in Paper I. In Section 3 we describe the results of our simulations, and in Section 4 we present and discuss our results. We summarize our conclusions in Section 5.

2. SIMULATIONS

Generally, our models follow the same scheme as described in detail in Paper I; in the following we briefly review the simulations. Following Paper I, we simulate star clusters using the STARLAB package (Portegies Zwart et al. 2001). We draw \( N \) single stars from the Kroupa (2001) mass function, \( f_M(M) \), in the mass range \( 0.1 \leq M \leq 7 M_\odot \). The lower limit corresponds to the hydrogen-burning limit. The upper limit is set to the mass of the most massive star which has not yet evolved due to stellar evolution in 50 Myr, the typical timescale at the end of our simulations. We also run simulations with higher cutoff (20 and 50 \( M_\odot \)) to probe capture by massive stars in fast dispersing clusters.

We perform simulations with varying \( N \), ranging from small stellar systems (or subclumps) with \( N = 10 \) to intermediate systems \( N = 20, 50, 100, 200, 500 \) and up to open clustered systems (\( N = 1000 \)). The cluster size which encloses all stars initially is taken to be related to the number of stars through \( R = 0.1 N^{1/3} \) pc, which corresponds to an identical initial stellar density for all the simulated clusters.

We study two sets of dynamical models to describe the cluster structure. Plummer models and substructured (fractal) models; these are described in detail in Paper I. Fractal (clumpy) models are characterized by their fractal dimension \( \alpha \), and are structured following the method used by Allison et al. (2009); we use two models, fractal clumpy clusters with \( \alpha = 1.6 \) and homogeneous systems with \( \alpha = 3 \); in this study, we explore only initially expanding clusters with \( Q = 3/2 \), where \( Q \) is the virial ratio, defined by \( Q = -E_K/E_P \), where \( E_K \) and \( E_P \) are the kinetic and potential energy of the cluster (see details in Paper I).

All simulations are performed until the clusters are completely dissolved, which is typically of the order of 50 Myr (we follow the largest clusters up to 200 Myr to ensure they completely dissolve), the timescale at which the majority of low-mass star clusters are destroyed (see, e.g., Tutukov 1978; Boutloukos & Lamers 2003; Bastian et al. 2005; Fall et al. 2005, and numerous others). Note that the lifetime of massive stars with \( M > 7 M_\odot \) could be shorter than the timescale for the cluster dispersal, and therefore black holes (BHS) and massive white dwarfs (WDs) may already form in the cluster during its dispersal. Neutron stars may also form in the cluster but are not likely to be retained in the cluster due to their natal kicks.

Binary systems and multiple systems (where the masses can be stellar or planetary) are identified recursively. We impose that the systems must be stable. The internal stability is partially guaranteed by the fact that they survive 50 Myr in the simulations. Furthermore, we impose the stability criterion by Valtonen et al. (2008). In our simulations we account for the tidal field of the galaxy at the solar neighborhood (following Kroupa et al. 2001; we adopt a distance of 8.5 kpc from the Galactic center and take \( M_{gal} = 5 \times 10^{10} M_\odot \)). Jiang & Tremaine (2010) show that binaries can survive in the Galactic tidal field if their separations are smaller than the Jacoby radius

\[
r_J \sim \left( \frac{G(m_1 + m_2)}{4\Omega A} \right)^{1/3} \sim 1.7 \left( \frac{m_1 + m_2}{2 M_\odot} \right) \text{ pc},
\]

where \( G \) is the gravitational constant, \( \Omega \) is the angular velocity of the Galaxy at the solar circle, \( A \) is Oort's \( A \)-constant, and \( m_1 \) and \( m_2 \) are the masses of the components. The value of 1.7 pc is valid for the canonical values for the Galactic constants and individual masses of \( 1 M_\odot \). We do not follow the binaries longer than the simulation time, and therefore some of the widest systems formed in the simulation that we consider as bound would be slowly disrupted in the Galactic field, later on. Nevertheless, \( \sim 90\% \) of all the capture-formed systems we find are within their Jacoby radius, consistent with the expectations. Note that wide binaries are also likely to be destroyed through encounters with other field stars or giant molecular clouds; these are not included in our simulations.

The most important difference from previous simulations is the addition of a population of FFPs. We simulated FFP populations with one planet per star, \( f_{FFP} = N_{FFP}/N_\star = 1 \), and a more limited number of simulations with \( f_{FFP} = 0.5 \) and 2. For simplicity, we always make use of single mass FFPs, taken to be Jupiter mass; \( m_{FFP} = m_J \). Since the binding potential of a planet and a star are completely dominated by the stellar mass, the specific choice of the planetary mass is typically not important for their capture around stars, as long as \( m_p \ll M_\star \), where \( m_p \) and \( M_\star \) are the typical masses of the FFPs and the cluster stars, respectively. Nevertheless, we also ran simulations with lower mass, 50 Earth mass planets, \( m_{FFP} = 50 M_\oplus \), to verify this.

The parameters of the various cluster models are summarized in Table 1. Throughout the paper we refer to models by their parameters, e.g., model F_N20_P0.5_M0.16 corresponds to a fractal cluster of 20 stars and 10 FFPs \( (f_{FFP} = 0.5) \) of mass \( 0.16 M_J \); if not explicitly written, \( f_{FFP} = 1 \) and \( M_{FFP} = M_J \).

### Table 1

| Parameter | Value |
|-----------|-------|
| Structure | Fractal (F; \( \alpha = 1.6 \)), Homogeneous (H; \( \alpha = 3 \)) |
| Number of stars (\( N_\star \)) | 10, 20, 50, 100, 200, 500, 1000 |
| Planet to star ratio (\( f_{FFP} \)) | 0.5, 1, 2 |
| Mass function | Kroupa MF, truncated at \( m = 7 M_\odot \) |
| Planetary mass | \( M_J, 50 M_\odot \) |
| Cluster radius (\( R \)) | 0.1 \( N^{1/3} \) pc |
| Simulation time | 50–200 Myr |
3. RESULTS

In the following we describe the various populations of planetary systems we obtain for the different cluster models we explore. Table 2 summarizes the results for the total fractions of multiple systems formed in our simulations.

### 3.1. Fractions of Capture-formed Systems

As can be seen in Figure 1, the fractions of capture-formed stellar binaries and planetary systems follow similar dependence on cluster sizes and cluster structure (homogeneous versus fractal). The binary fraction in homogeneous clusters is inversely proportional to the number of stars in the cluster, but shows a weaker dependence \( f_{\text{cap}} \propto N^{-0.15} \) on the cluster size than suggested by the theoretical expectation of \( f_{\text{cap}} \sim 1/N \) from the theory of soft binaries freeze-out (Moeckel & Clarke 2011). This model predicts a single binary to form per cluster, independent of the number of stars in the cluster. The fractal clusters also show a decrease in capture efficiency with increasing cluster size, with a stronger dependence, \( f_{\text{cap}} \propto N^{-0.35} \).

We can now integrate the observed fractions (from our simulations) together with the observed cluster mass function \( dN/dN_\star \propto N_\star^{-2} \) (Lada & Lada 2003) in the range \( 10 \leq N_\star \leq 1000 \), and calculate an overall expected fraction of capture-formed systems. For the homogeneous clusters we find fractions of \( f_{\text{bin}}^{\text{cap}} \sim 0.069 \) and \( f_{\text{planet}}^{\text{cap}} \sim 0.058 \) for the stellar and planetary

![Figure 1. Capture efficiency as a function of cluster size (N\_\star). The fraction of capture-formed systems is a decreasing function of the cluster size/mass, as expected from theoretical models; however, the dependence is weaker than the 1/N\_\star dependence predicted by models of soft binaries freeze-out (Moeckel & Clarke 2011). The H and F models correspond to homogeneous and fractal models, respectively.](image_url)
systems, respectively; similarly, for the fractal clusters, we get $f_{\text{bin}}^{\text{cap}} \sim 0.055$ and $f_{\text{planet}}^{\text{cap}} \sim 0.036$.

The observed wide binary fraction (with semimajor axis, SMA, $a > 10^4$ AU) is $\sim 0.02$ (Raghavan et al. 2010; Moeckel & Clarke 2011); recent observations focusing on binaries at larger separations suggest that the fraction could be even higher (Shaya & Olling 2011), if these are accounted for. In the simulations a large fraction ($\sim 80\%$ and $\sim 50\%$ for the homogeneous and fractal clusters, respectively) of the capture-formed multiple stellar systems reside in this range. We therefore conclude that the observed fraction of wide binaries in our simulations is generally consistent with observations. Taken at face value, we may therefore expect the efficiency of planetary systems formation to be in the range of $0.036 \leq f_{\text{planet}}^{\text{cap}} \times (f_{\text{FFP}}/1) \leq 0.058$, comparable to that of capture-formed stellar systems.

Observations of the Taurus–Auriga star-forming region show a wide binary frequency of $\sim 5\%–10\%$ in the range 1000–5000 AU (Kraus et al. 2011), which is 2–3 times larger than found in the fractal models, and even higher compared with the homogeneous models. Note, however, that for stars at these separations, other processes beside dynamical capture are also likely to contribute to binary formation, and therefore direct comparison should be taken with caution.

### 3.2. Properties of Capture-formed Systems

In the following, we discuss the distributions of various properties of the capture-formed planetary and stellar systems. For simplicity, we only present results from simulations of $N_* = 100$ clusters, which generally provide a good representation of the overall distributions we observe.

**Eccentricity distribution.** We find the eccentricities of both planetary systems and stellar binaries to follow a thermal distribution (see Figure 2), $dN/de = 2e$.

**Inclination distribution.** In higher multiplicity systems, we can explore the relative inclinations between inner and outer binaries of hierarchical systems. We find that the inclination distribution appears to be isotropic (uniform in $\cos i$).

**Mass function.** Figure 3 shows the fraction of captured-formed systems as a function of the primary-component mass. As can be seen, the fraction is a monotonically increasing function of mass (which becomes saturated at high masses), for both stellar and planetary systems.

**SMA and closest approach distributions.** The detailed distributions of SMAs and pericenter approach for various models are shown in Figure 4. The orbits of captured stellar binaries and FFPs both follow quite similar distributions. The majority of the systems have SMAs in the typical range of few $10^2–10^6$ AU, with thin tails extending toward lower and larger SMAs. Binaries with separations larger than $\sim 10^6$ AU are likely to be dissolved by the Galactic tide on timescales longer than our simulation, or through encounters with other field stars. Such systems are generally rare. The typical capture-formed planetary systems found in our homogeneous cluster simulations follow an almost log-normal distribution with a tail at low SMAs, and an upper cutoff mostly due to the Galactic tide, as mentioned above. The fractal cluster show a log-constant distribution at the mid-range ($10^3.5$–$10^5.5$ AU), i.e., a uniform distribution per logarithmic bin (Ópik-like distribution). Figure 4(b) shows the pericenter distribution, which extends as close as a few AU from the host stars (though these extreme cases are rare). Planets and stars captured into such close approaches can have a significant dynamical interactions with pre-existing planetary/protoplanetary systems even in dynamical timescales following their capture.

We note that there is a weak trend in the dependence of the SMA and pericenter distribution on cluster sizes. We find that closer binaries/planetary systems are formed in larger clusters (not shown); the overall distribution is generally well represented by the shown distribution in Figure 4.

### 4. DISCUSSION

The cluster dispersal scenario for the formation of wide-orbit planetary systems is a natural extension for a similar model used to explain the origin of wide binaries. Our simulation results verify that FFPs can be captured through this process, with comparable efficiency. The capture process depends on both the cluster properties, as well as the masses of the specific stars. We find that the general properties of the wide planetary systems follow the same behavior as wide binaries, which was explored in detail in Paper I and in Moeckel & Clarke (2011). In the following, we focus on the specific implications for planetary systems.

#### 4.1. Planets and Brown Dwarfs at Wide Orbits

The most basic result of our suggested FFP-capture scenario, verified in the detailed simulations, is the robust production of wide-orbit planetary systems following cluster dispersal which include FFPs. The fraction of capture-formed wide planetary systems in our simulations is dependent on the their yet unknown original number fraction in the birth clusters. The recent microlensing finding of FFPs, as well as theoretical predictions, suggest that these fractions are high: 0.5–2 FFPs per cluster star (Sumi et al. 2011). The FFP-recapture mechanism could therefore play a major role in the production of wide-orbit planetary system. Such planets can regularly form around stars at small separation, then be ejected from the system, likely through scattering with other planets, and then be captured by another cluster star following the birth-cluster dispersal.
between pairs of stars of any two objects in the birth cluster (e.g., related metallicity). The relation between such recaptured planets and their new hosts could therefore be quite arbitrary. In particular, the pairing of stellar and planetary properties such as metallicity, masses/sizes, and spin-orbit relations should generally be random, or at most reflect correlations that may exist between the properties of any two objects in the birth cluster (e.g., related metallicity). Even if the latter case is true, the random pairing should be smeared out compared with the likely stronger correlation between pairs of stars/planets originally formed in the same system.

Planets could be captured into orbits of any eccentricity (through high eccentricities are preferred, through the thermal eccentricity distribution observed in our simulations), and a wide range of orbits, with typical SMAs extending over the range of few $\times 10^2$–$10^5$ AU. At apocenter the most eccentric orbits could have twice as large separation as their SMA, and could therefore be more susceptible to disruption by the Galactic tide over time, if their SMA is comparable to their Jacoby radius (Equation (1)). Systems with the smallest separation and/or the highest eccentricities, the pericenter approach, $a(1 - e)$, can become comparable to the separations of regularly formed planets at up to a few tens of AU. Objects on such orbits may strongly interact with any pre-existing planetary/protoplanetary system (see also the next section).

In situ formation of planets (and particularly massive gas giants) at wide orbits as found in our simulations, where the mass density in the protoplanetary disk becomes very small, is unlikely in the core-accretion model (Dodson-Robinson et al. 2009). Ejection of planets from inner orbits to wide separations is possible. Such orbits would initially be very eccentric and flyby encounters with other stars would be required in order to put them into more circular orbits (similar to the formation and evolution of the Oort cloud; Duncan et al. 1987). In comparison, the capture scenario can naturally produce both low and high eccentricity orbits. Planets at wide orbits, however, are not likely to survive in a cluster environment where close encounters with other stars can destroy the system (e.g., Parker & Quanz 2012 and references therein). If such systems survive, or scattering occurs after the cluster dispersal it might be more difficult to currently distinguish between such a scenario and the suggested capture scenario introduced here. Nevertheless, our models provide specific predictions for the dynamical properties of such systems, and moreover, connect them to wide binary systems and population of free floating planets. The models therefore provide a wealth of potential signatures, which can distinguish them from different models (e.g., Veras et al. 2009). A smoking gun signature for the capture scenario may exist in the form of binary FFPs (see Section 4.4), and the existence of planets in wide orbits around low mass stars, which are unlikely to form through in situ planet formation scenarios. In the gravitational instability model for planet formation (Boss 2006) massive gas planets may possibly form at wider orbits than in the core-accretion scenario, but it is not clear if the process could be efficient up to the very large separations as observed in our simulations. In any case, such processes are not likely to form low mass rocky planets at these separations. To summarize, in the FFP-recapture model we expect a planet of any mass to be captured into very wide orbits—systems which would be difficult to form in the currently suggested planet formation models. We also note that the fraction of capture-formed planetary systems, as well as the planetary masses distribution reflect the FFP fraction and mass distribution in the birth-clusters, and are likely to show similar orbital properties as wide stellar binaries.

### 4.2. Multiple Planets at Wide Orbits

In principle, more than a single planet can be captured into the same planetary system, through independent captures. The fraction of such multiple captured-planet systems is therefore expected to be proportional to the probability for multiple independent captures, i.e., $f_{2p} = f_p^2$ for capture of two planets. Table 2 show the fraction of planetary systems with $n = 1, 2$ and 3, which is generally consistent with the expectation. Capture of high (>2) multiplicity stellar systems is expected to follow the same behavior; however, capture of an additional star also contributes to the total mass of the system, and therefore the likelihood of a consecutive capture is somewhat increased. This is verified in the higher fraction of high multiplicity.
stellar systems in comparison to the planetary systems (when normalized to the fraction of binary/single planet systems).

Though this scenario can explain even multiple planet systems at wide orbits, it is unlikely to form a large number of such systems, given the rapidly decreasing probability for such occurrence. It is also unlikely to form planetary systems in mean motion resonance, which require a continuous migration of planetary orbits through phase space; these are likely to form through migration in disks.

Naturally, stars hosting primordial in situ formed planetary systems or protoplanetary disks can capture additional planets following the cluster dispersal. Given the random orientation of the capture processes, these additional “guest” captured planets are likely to be misaligned with any existing protoplanetary disk or pre-existing planetary system. In some cases, the capture of an additional object into a wide orbit may lead to the perturbation or even the destabilization of an existing planetary system. In particular, an object captured at high inclination may induce long term secular evolution of the inner pre-existing system (e.g., through Kozai–Lidov evolution; Kozai 1962; Lidov 1962), and potentially even destabilize them (though the latter possibility is far more likely in the case of a stellar capture).

4.3. Planets in Binary Systems: Circumstellar and Circumbinary Orbits

Primordial binaries existing before the cluster dispersal could themselves capture additional stellar or planetary objects, forming high multiplicity stellar systems of binary planets. This mechanism is not much different from the capture of planet around single stars (aside from the potentially much higher mass of the system, in the case of binary stars, which induces a higher capture probability; see Figure 3). Nevertheless, three body systems could become unstable, and therefore the capture of additional objects by a binary may limit the range of orbital phase-space available, at least in those cases where the initial binary is wide. The current simulations presented here did not include primordial binaries, which would be a natural extension of our models. We expect such systems to generally have a higher capture efficiency due to their higher mass.

Binary planets could also form through a double capture, either a planet capture followed by a stellar capture or a stellar capture, forming a binary, followed by a planetary capture. The planetary capture in the latter case follows a similar evolution as planetary capture around primordial binaries; however, the inner stellar binary would be typically much wider than primordial binaries in the birth cluster. The former process where a planet is captured first may lead to a circumstellar binary planet, as the stellar binary could be captured at a much wider orbit, not perturbing the inner planetary orbit. In this case, circumbinary planetary systems is less likely to form, as a close single-binary encounter of a star within the planetary orbit (i.e., where the binary is the star–planet system) would more likely lead to its ejection process (typically the lowest mass objects are ejected in such encounters). Table 2 shows the fraction of binary planets (combining both circumstellar and circumbinary orbits) formed in our simulations.

4.4. Free Floating Planet Binaries

Larger stellar masses allow for binding of companions with higher relative velocities, as reflected in the higher capture rate by more massive stars. Nevertheless, planets could capture companion planets without any host stars. These free floating double planets or FFP binaries are generally rare (see Table 2). The formation of such systems (or similarly, planet capture around brown dwarfs) through typical planet formation scenarios rather than through dynamical capture processes is unlikely (current models require the existence of a host stars around which planet forms in a massive enough protoplanetary disk; see also discussion on planet and star formation at wide orbits in Béjar et al. 2008 and Kraus & Hillenbrand 2009). Therefore, the finding of even a single such system could serve as a potential smoking gun signature of the planetary capture scenario discussed.

Figure 4. Semimajor axis and pericenter distribution function of capture-formed stellar and planetary systems, in \( N_\ast = 100 \) clusters. Top: the main figure shows the cumulative SMA distribution, and the inset shows the differential SMA distribution. Capture-formed systems from the fractal clusters (F) are characterized by a log-uniform distribution (equal fraction in logarithmic bins), whereas the homogeneous clusters (H) give rise to a more log-normal distribution. Bottom: the same for closest approach (pericenter) distributions. Note different axis scales. The distribution of different cluster sizes behaves similarly with a general trend for the distribution in more massive clusters to peak at smaller separations.

(A color version of this figure is available in the online journal.)
here. Given the increased capture probability with system mass, and the better detectability of more massive planets, the most likely FFP binaries to be observed would lie in the higher end of the planetary mass regime. Most interestingly, Jayawardhana & Ivanov (2006) discovered such a systems of two planetary mass companions of a few × 10 M\(_{\odot}\) at wide, 240 AU separation, followed by the discovery of similar even wider systems by other groups (Béjar et al. 2008; Biller et al. 2011). Our suggested scenario can provide a natural explanation for these otherwise puzzling systems.

4.5. Wide-orbit Planets Around Compact Objects

The timescales for cluster dispersal could be relatively short, and much shorter than the main-sequence lifetimes of most stars. Nevertheless, the lifetime of stars more massive than \(\sim 5 M_{\odot}\) could be comparable to the dispersal time scales of the host cluster. These stars could therefore become compact objects before the cluster disperses, and can later capture planets like any other cluster star. Note, however, that this is likely to be true only for black holes and white dwarfs; the natal kicks of neutron stars are likely to eject them from their host cluster upon their formation. The mass loss of stars prior to the formation of the compact object can eject pre-existing planets at wide orbits (e.g., Veras et al. 2011), especially in the case of prompt mass loss in a supernova. The capture channel suggest that even such objects could host wide-orbit planetary systems. Interestingly, the dispersal timescale of a cluster defines a lower limit on the mass of WD progenitors that could acquire planetary/binary companions through capture. Lower mass WDs with such wide orbit companions would have had to capture them while still on the MS, and would have a higher chance of losing these companions as they evolve and lose mass. The age cutoff may therefore be reflected by a lower fraction of low mass WDs with wide-orbit stellar or planetary companions. Masses of stellar black holes could typically be in the range of 5–15 M\(_{\odot}\); given the higher probability for planetary and stellar capture for massive stars (see Figure 3), we expect more than half of all stellar black holes to have a wideorbit-captured stellar companion, and more than 5–10 \((f_{\text{FFP}}/1)\)% of them to host a planetary companion (our additional simulations of clusters containing stars as massive as 20 M\(_{\odot}\), not shown here, suggest that the capture probability for stellar companions could approach unity for \(m_*>10 M_{\odot}\)). Massive white dwarfs \((m_{\text{WD}} \sim 1 M_{\odot})\) are expected to capture \(\sim 0.2\) less companions compared with stellar black holes.

5. SUMMARY

In this paper we presented a novel channel for the formation of planetary systems at very wide orbits (typically \(\sim \text{few} \times 10^{5}–10^{6}\) AU), through the dynamical recapture of free floating planets during cluster dispersal. This mechanism, originally suggested as a route for the formation of wide-orbit binaries, was extended to the planetary regime. We simulated dispersing clusters with a population of FFPs, and followed the formation of planetary systems in the simulations. We find that the efficiency of capture-formation of planetary systems ranges between 1% and 9% depending on cluster size and structure. We predict an overall fraction of 3–6 \((f_{\text{FFP}}/1)\)% of all stars (accounting for the birth cluster size distribution) to host a wide-orbit planetary companion at separations > 100 AU, comparable to the expected fraction of wide stellar binaries. The orbital properties of capture-formed planetary systems resemble those of wide binaries. The fraction of capture-formed planetary systems (as well as capture-formed binaries) increases with the host mass. Future searches for wide-orbit planetary companions should therefore favor more massive stars. Although captures are biased toward higher mass hosts, planets can be captured around hosts of any mass (with stars like our Sun having a 3%–5% probability to have captured a wide-orbit planet). In fact, we find that, although rare, planets could even be captured around other planets (or brown dwarfs) to form free floating planet binaries. In addition, planets can be captured around compact objects, if these formed prior to the cluster dissolution; we find stellar black holes may have a high probability of capturing stellar and planetary companions in wide orbits. Finally, we note that the properties of captured planets should not correlate with their host star; single and multiple planets could be captured into arbitrary orbits that are generally non-coplanar with each other (or with the stellar host spin, or pre-existing planetary system). Nevertheless, some secondary planet–host star metallicity correlation may still exist due to the common origin of the stars from same birth cluster.

H.B.P. is a CfA and BIKURA (FIRST) fellow. M.B.N.K. was supported by the Peter and Patricia Gruber Foundation through the IAU-PPGF fellowship, by the Peking University One Hundred Talent Fund (985), and by the National Natural Science Foundation of China (grants 11010237, 1105010414, 11173004). The authors thank Michael Ireland, Nathan Kaib, Sally Dodson-Robinson, and the anonymous referee for helpful comments that helped improve this manuscript.

REFERENCES

Adams, F. C., Proszkowski, E. M., Fatuzzo, M., & Myers, P. C. 2006, \textit{ApJ}, 641, 504
Allison, R. J., Goodwin, S. P., Parker, R. J., et al. 2009, \textit{ApJ}, 700, L99
Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, \textit{A&A}, 431, 905
Beauge, C., & Nesvorny, D. 2011, \textit{arXiv}:1110.4392
Béjar, V. J. S., Zapatero Osorio, M. R., Pérez-Garrido, A., et al. 2008, \textit{ApJ}, 673, L185
Biller, B., Allers, K., Liu, M., Close, L. M., & Dupuy, T. 2011, \textit{ApJ}, 730, 39
Bonnell, I. A., Smith, K. W., Davies, M. B., & Horne, K. 2001, \textit{MNRAS}, 322, 859
Bocca, A. P. 2006, \textit{ApJ}, 637, L137
Boss, A. P. 2011, \textit{ApJ}, 731, 74
Bouloubous, S. G., & Lamers, H. J. G. M. 2003, \textit{MNRAS}, 338, 717
Dodson-Robinson, S. E., Veras, D., Ford, E. B., & Beichman, C. A. 2009, \textit{ApJ}, 707, 79
Duncan, M., Quinn, T., & Tremaine, S. 1987, \textit{AJ}, 94, 1330
Fall, S. M., Chandar, R., & Whitmore, B. C. 2005, \textit{ApJ}, 631, L133
Fregeau, J. M., Chatterjee, S., & Rasio, F. A. 2006, \textit{ApJ}, 640, 1086
Ireland, M. J., Kraus, A., Martinache, F., Law, N., & Hillenbrand, L. A. 2011, \textit{ApJ}, 726, 113
Jayawardhana, R., & Ivanov, V. D. 2006, \textit{Science}, 313, 1279
Jiang, Y.-F., & Tremaine, S. 2010, \textit{MNRAS}, 401, 977
Kraus, A. L., Ireland, M. J., Martinache, F., & Hillenbrand, L. A. 2011, \textit{MNRAS}, 404, 1835
Kozai, Y. 1962, \textit{AJ}, 67, 591
Krautter, K. M., Murray-Clay, R. A., & Youdin, A. N. 2010, \textit{ApJ}, 710, 1375
Kraus, A. L., & Hillenbrand, L. A. 2009, \textit{ApJ}, 703, 1511
Kraus, A. L., Ireland, M. J., Martinache, F., & Hillenbrand, L. A. 2011, \textit{ApJ}, 731, 8
Kroupa, P. 2001, \textit{MNRAS}, 322, 231
Kroupa, P., Aarseth, S., & Hurley, J. 2001, \textit{MNRAS}, 321, 699
Kroupa, P., & Bouvier, J. 2003, \textit{MNRAS}, 346, 369
Lada, C. J., & Lada, E. A. 2003, \textit{ARA&A}, 41, 57
Lafrenière, D., Haywardana, R., Janson, M., et al. 2011, \textit{ApJ}, 730, 42
Lafrenière, D., Jayawardhana, R., & van Kerkwijk, M. H. 2008, \textit{ApJ}, 689, L153
Laughlin, G., & Adams, F. C. 1998, \textit{ApJ}, 508, L171
Levison, H. F., Duncan, M. J., Brasser, R., & Kaufmann, D. E. 2010, *Science*, 329, 187
Lidov, M. L. 1962, *Planet. Space Sci.*, 9, 719
Malmberg, D., Davies, M. B., & Heggie, D. C. 2011, *MNRAS*, 411, 859
Moeckel, N., & Bate, M. R. 2010, *MNRAS*, 404, 721
Moeckel, N., & Clarke, C. J. 2011, *MNRAS*, 415, 1179
Parker, R. J., & Quanz, S. P. 2012, *MNRAS*, 419, 2448
Portegies Zwart, S. F., McMillan, S. L. W., Hut, P., & Makino, J. 2001, *MNRAS*, 321, 199
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, *ApJS*, 190, 1
Shaya, E. J., & Olling, R. P. 2011, *ApJS*, 192, 2

Smith, K. W., & Bonnell, I. A. 2001, *MNRAS*, 322, L1
Spurzem, R., Giersz, M., Heggie, D. C., & Lin, D. N. C. 2009, *ApJ*, 697, 458
Sumi, T., Kamiya, K., Bennett, D. P., et al. 2011, *Nature*, 473, 349
Tutukov, A. V. 1978, *A&A*, 70, 57
Valtonen, M., Mylläri, A., Orlov, V., & Rubinov, A. 2008, in IAU Symp. 246, Dynamical Evolution of Dense Stellar Systems, ed. E. Vesperini, M. Giersz, & A. Sills (Cambridge: Cambridge Univ. Press), 209
Veras, D., Crepp, J. R., & Ford, E. B. 2009, *ApJ*, 696, 1600
Veras, D., Wyatt, M. C., Mustill, A. J., Bonsor, A., & Eldridge, J. J. 2011, *MNRAS*, 417, 2104