CONFIGURATIONS OF BOUNDED AND FREE-FLOATING PLANETS IN VERY YOUNG OPEN CLUSTERS

HUI-GEN LIU, HUI ZHANG, AND JI-LIN ZHOU

School of Astronomy and Space Science & Key Laboratory of Modern Astronomy and Astrophysics in Ministry of Education, Nanjing University, Nanjing 210093, China; huigen@nju.edu.cn

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ABSTRACT

Open clusters (OCs) are usually young and suitable for studying the formation and evolution of planetary systems. So far, only four planets have been found with radial velocity measurements in OCs. Meanwhile, a lot of free-floating planets (FFPs) have been detected. We utilize N-body simulations to investigate the evolution and final configurations of multi-planetary systems in very young open clusters with an age <10 Myr. After an evolution of 10 Myr, 61%–72% of the planets remain bounded and more than 55% of the planetary systems will maintain their initial orbital configurations. For systems with one planet ejected, more than 25% of them have the surviving planets in misaligned orbits. In the clusters, the fraction of planetary systems with misalignment is >6%, and only 1% have planets in retrograde orbits. We also obtain a positive correlation between the survival planet number and the distance from the cluster center r; planetary systems with a larger r tend to be more stable. Moreover, stars with a mass >2.5 \( M_\odot \) are likely unstable and lose their planets. These results are roughly consistent with current observations. Planetary systems in binaries are less stable and we achieve a rough criterion: most of the binary systems with \( \theta_0 (1 - e_0^2) > 100 \) AU can retain all the initial planets. Finally, 80% of the FFPs are ejected out of the clusters, while the rest (~20%) still stay in host clusters and most of them are concentrated in the center (<2 pc).

Key words: binaries: general – open clusters and associations: general – planetary systems – planets and satellites: dynamical evolution and stability

Online-only material: color figures

1. INTRODUCTION

In current star formation theories, stars initially form in clusters or groups. The same initial mass function (IMF) between field stars and young embedded clusters provides direct evidence of this (Lada & Lada 2003). More than 70% of stars originated from clusters or groups according to a survey of embedded clusters (Lada & Lada 2003; Lada 2010). By reviewing solar system properties, Adams (2010) concluded that our Sun most likely formed in an environment with thousands of stars.

Stars in clusters have basically homogenous parameters (i.e., ages, [Fe/H], etc.); thus, searching for planets in clusters, especially in young open clusters (hereafter YOCs), is very important to understand the formation and evolution of planetary systems. However, nearly all the detected planets are around field stars, while only four planetary systems are found in open clusters (hereafter OCs) with radial velocity measurements. Although many groups attempted to find planets by traniting, most of them had no results (see Zhou et al. 2012 for a review and references therein).

The four known planets in OCs are a gas giant planet around a red giant (TYC 5409-2156-1) in NGC 2423 (Lovis & Mayor 2007), a gas giant planet around a giant star (\( \epsilon \) Tauri) in the Hyades (Sato et al. 2007), and two hot Jupiters Pr0201b and Pr0211b in Praesepe (Quinn et al. 2012). The last two are the first hot Jupiters known in OCs. On the other hand, as compared to bounded planets, several more free-floating planets (hereafter FFPs) are found in OCs. Lucas & Roche (2000) detected a population (~13) of FFPs in Orion. Bihain et al. (2009) found three additional FFPs in \( \sigma \) Orionis, which is a very young OC (VYOC; ~3 Myr).

Both the detection and non-detection of planets in OCs help us to calculate the occurrence of planets in clusters, which includes the formation and stabilities of planetary systems. The formation of a planetary system is assured by the IR observation of a circumstellar disk. In theory, Adams et al. (2006) also show that the photoevaporation of protoplanetary disks is only important beyond 30 AU due to the median FUV flux of other stars. After planetary systems were formed, star interactions (merges, flybys, etc.), galactic tides, stellar evolution, interplanetary interactions, etc., would influence the final orbital architectures of these planetary systems.

Several previous works investigated the stabilities of planetary systems in clusters. Solving restricted problems, Malmberg et al. (2011) and Smith & Bonnell (2001 and references therein) simulated the influences of assumed flybys on planetary systems and concluded that stars passing by with perihelion \( \geq 1000 \) AU may be negligible, while closer flybys may exit the eccentricities of planets. Laughlin & Adams (1998) and Davies & Sigurdsson (2001) studied planets in binary systems that encountered stars or other binaries. This revealed that after the encounter with binary systems, the planetary systems around both single stars or binaries are more easily disrupted than those after an encounter with single stars. To model the real dynamical environment of clusters, Spurzem et al. (2009) used hybrid Monte Carlo and N-body methods to study the evolution of single planetary systems under more realistic flybys from cluster environments. They found that the liberation rate of planets per crossing time is constant. In their cluster models, a uniform stellar mass is assumed with no binary included. Parker & Quanz (2012) developed a sub-structured cluster model and simulated the orbital distributions of single planetary systems in the cluster after 10 Myr. They concluded that during the dynamical evolution of YOCs, the planetary systems experienced a relatively violent evolution during the first few megayears, and the fates of these planets depended strongly on their initial locations, i.e., planets.
far from the host star can be disrupted easily. Considering the variation of inclinations in binary systems, Parker & Goodwin (2009) indicated that about 10% of the planets in clusters may be affected by the Kozai mechanism.

As mentioned above, most previous works used restricted problems to study the influences of a single flyby event on the planetary architectures. However, in a real cluster environment, flybys may continuously influence the planetary system. Also, the influence of planetary interactions was ignored due to their single-planet models. As we know, the pumping of eccentricities in closely packed multi-planetary systems usually leads to dynamical instabilities (Terquem & Papaloizou 2002; Zhou et al. 2007). Planet–planet scattering as well as secular resonances also influence the orbits of the planets (Nagasawa & Ida 2011; Wu & Lithwick 2011). The Kozai mechanism can pump the eccentricities of planets in binary systems, and therefore planetary systems may become unstable due to strong planet–planet interactions (Malmberg et al. 2007a).

In this paper, we adopt the multi-planetary system models in VYOCs to investigate their different fates as well as the final orbital architectures of bounded planets. Different from previous works, we use strict N-body simulations to include both the dynamical evolution of clusters and mutual planetary interactions. We focus on VYOCs with ages less than 10 Myr so that the dynamical evolution in the cluster is more important than galactic tides or stellar evolution (see also Section 2.1). Multiple flybys are considered in our simulations. We use a more strict model of OCS here than previous works that contains a mass spectrum and a fraction of binary stars and sets planets located around each star to reveal their stability and orbital architectures both in binary systems and around single stars. Note that here we first consider the multi-planetary systems in reasonable cluster environments. Using this model, we intend to investigate how the OC environments mainly influence the architecture of bounded planets at different locations in the clusters. We will also obtain the fraction of FFPs and their spatial distribution in OCS.

The structure of this paper is as follows. We introduce our cluster and planetary models in Section 2. In Section 3, we first represent the dynamical evolution of clusters. After that, Section 4 shows the statistical results of both stars and planets in clusters. We study the fates of planets in binaries (Section 5). FFPs in the host cluster and ejected objects are included in Section 6. Finally, we summarize the main results in Section 7 and discuss some assumptions adopted here.

2. THE CLUSTER MODEL AND THE INITIAL SETUP

In this section, we represent our VYOC model and the initial setups of planetary systems in clusters.

2.1. Very Young Open Cluster Model

The evolution of a general cluster is not only influenced by its internal gravity. Galactic tides and stellar evolutions after the main-sequence phase are still important for the evolution of clusters. The galactic tidal disruption timescale can be evaluated as \( t_{\text{diss}} = 0.077 N^{0.65} \omega / \omega \) (Gieles & Baumgardt 2008), where \( N \) is the number of stars in the cluster and \( \omega \) is the angular velocity around the galaxy center. For a typical cluster with typical \( N \sim 1000 \) near our solar system, \( t_{\text{diss}} \approx 0.3 \) Gyr. Therefore in our model, galactic tides can be ignored in a much shorter timescale of \( \sim 10 \) Myr for VYOCs.

The stellar evolution after the main-sequence phase is also important for the orbital evolution of planetary systems, e.g., the red giant phase (Villaver & Livio 2007, 2009). As we know, the lifetime of stars in the main sequence can be evaluated as a power law by their mass, \( t_{\text{MS}} \approx 10^{10} \text{yr} \left( M/M_\odot \right)^{-2.5} \) (Bressan et al. 1993), and stars more massive than 16 \( M_\odot \) would have a lifetime of less than 10 Myr. In the IMF of our cluster model represented next, there are less than four stars with a mass larger than 16 \( M_\odot \). Due to their large masses, their gravities are important for the cluster but the evolution of these stars is omitted. We do not consider the residual gas in the cluster due to its limited mass and unknown spatial distribution. The IMF of our cluster model is taken as two parts (Kroupa 2002):

\[
N(M) \propto \begin{cases} \left( M / M_\odot \right)^{-1.3}, & 0.1 < M / M_\odot < 0.5, \\ \left( M / M_\odot \right)^{-2.3}, & 0.5 < M / M_\odot < 50. \end{cases}
\]

We truncate the stellar mass \( > 50 M_\odot \) due to the rarity of these stars in the cluster. For example, the most massive star in Orion is \( < 50 M_\odot \) (\( \theta \) Ori C; Kraus et al. 2007, 2009). Small stars less than 0.1 \( M_\odot \) are also ignored in our model due to their limited gravity and the very low occurrence of planets around these stars. The IMF of our cluster model is shown in Figure 1(a) with a total mass of 800–900 \( M_\odot \).

To make our cluster model more reasonable, we take a fraction of binary systems into account. The fraction of binary systems \( f_b \) is related to the mass of the primary star. Here, we adopted four different fractions of binary systems according to different ranges of the primary stellar masses1:

\[
f_b = \begin{cases} 0.42, & 0.08 < M / M_\odot \leq 0.47, \ (\text{FM92}) \\ 0.45, & 0.47 < M / M_\odot \leq 0.84, \ (\text{Mayor92}) \\ 0.57, & 0.84 < M / M_\odot \leq 2.50, \ (\text{DM91}) \\ 1.00, & 2.50 < M / M_\odot, \ (\text{Mason09}) \end{cases}
\]

The separations and eccentricities of the binary systems are set as follows. According to Duquennoy & Mayor (1991) and Raghavan et al. (2010), the periods \( P \) (in days) of the binaries follow a logarithmic Gaussian distribution,

\[
f(\log_{10} P) \propto \exp\left( -\frac{(\log_{10} P - \mu)^2}{2\sigma^2} \right),
\]

where \( \mu = 4.8, \sigma = 2.3 \). The eccentricities obey a thermal distribution: \( f(e) = 2e \) (Kroupa 2008). Here we only consider “S” type planets (planets around each star) in binaries. We constrain the periastrons of binary orbits \( \geq 30 \) AU, because in these binary systems the planets (in orbits \( \leq 10 \) AU) are stable in the restricted three-body problem (Holman & Wiegert 1999). Meanwhile, 1000 AU is adopted as the upper limit of the binary semimajor axes. Inclinations are set as zero for all binaries so their initial orbital planes are all parallel, while three other orbital elements are chosen randomly. The mass ratio of binary stars is selected as a uniform distribution according to Duquennoy & Mayor (1991).

In our non-rotating cluster model, each cluster contains 1000 stars in total, located initially in 1 pc3. According to the density profiles of some YOCs (e.g., NGC 2244, 2239, Bonatto & Bica 2009; NGC 6611, Bonatto et al. 2006), the location of these stars
can be described by the two-parameter King model (King 1966) with the form 
\[ \rho(r) = \frac{\rho_0}{1 + (r/r_c)^2} \]
where \(r_c = 0.38\) pc in this paper. This is consistent with the King model after integration in the direction of our sight. The velocities of these stars are set to obey a Gaussian distribution with a mean value of \(v = 1\) km s\(^{-1}\) and a dispersion of \(\sigma = 1\) km s\(^{-1}\). The direction of their velocities is isotropic; therefore, we truncate the distribution where \(v < 0\), as seen in Figure 1(b). The distribution of stellar location and velocities, as well as the IMF of stars in our model, corresponds with the normal assumption that all the planets initially formed in circumstellar disks and their angular momentums are always in the same direction approximately. Here we set the inclination \(i = 1^\circ\) and eccentricity \(e = 0\) for all the planets.

2.2. Setups of Planetary Systems

As mentioned in Section 1, here we focus on OCs with an age less than 10 Myr. These VYOCs are able to give us insight into the properties of planetary systems around young stars. A large amount of the circumstellar disk fraction is found in the VYOCs by \(K\)-excess observations: i.e., 30\%–35\% of the T-Tauri stars have a disk in the \(\sigma\) Ori cluster with an age of \(\sim 3\) Myr (Hernández et al. 2007). Using the Chandra X-Ray Observatory, Wang et al. (2011) found a \(K\)-excess disk frequency of 3.8\% \(\pm\) 0.7\% in the 5–10 Myr old cluster Trumpler 15. The fraction of circumstellar disks limits the formation rate of planets. Combined with the stable rate of planetary systems during subsequent evolution, we can evaluate the planetary system occurrence in these VYOCs.

Due to the large fraction of disks in VYOCs, here we consider planetary systems with two planets around each cluster member. Considering perturbations from other planets or flyby stars, their orbital parameters can be changed significantly. We use the normal assumption that all the planets initially formed in circumstellar disks and their angular momentums are always in the same direction approximately. Here we set the inclination \(i = 1^\circ\) and eccentricity \(e = 0\) for all the planets. The other three angles of orbital elements are set randomly. We calculate four different initial masses and locations of planets to model different configurations of planetary systems, as shown in Table 1. Planetary systems with two Jupiters represent those with two gas giants in clusters, called the 2J model. The one Jupiter and one Earth models with different locations represent more general systems. Note that all initial planetary systems are stable if they did not experience any close encounter with another star. Hereafter, a planetary system is unstable when the system loses at least one planet because of close encounters in clusters.

We adopt the MERCURY package for \(N\)-body simulations (Chambers 1999). We include the gravities of each star and each planet during integrations and let the clusters evolve for 10 Myr. During our simulations, we truncate the clusters at 10 pc, i.e., stars and planets >10 pc away from the cluster center are removed as ejected objects. A binary system is thought to be

![Figure 1](image-url)
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Figure 2. (a) The stellar densities in the 2J model at \( t = 0, 1, 3, 5, 10 \) Myr. The stellar density sharply decreases with time. After 10 Myr, the density is at least one order smaller than the initial values. (b) The variations of virial parameter \( Q \) (red line) and half-mass radius \( r_h \) (black line) with time. \( Q \) can keep 0.5 after 3 Myr, which means the virial equilibrium is nearly satisfied. As \( r_h \) increases, the cluster expands quickly and \( r_h \approx 1.5 \) pc after 10 Myr, about three times larger than the initial value. (c) The fraction of stars in clusters decreases with time in different models. In the initial 3 Myr, the fraction decreases slowly (\( \sim 3\% \)), and after that the fraction decreases to 80\%–85%.

disrupted into two single stars when its semimajor axis is greater than 1000 AU. To judge if the planets are ejected from their host planetary systems, we use a critical semimajor axis of 100 AU, but do not remove the ejected planets. These planets can become FFPs and cruise in the clusters unless they leave the clusters.

3. DYNAMICAL EVOLUTION OF CLUSTERS

Before investigating the architectures of planetary systems in the VYOCs, we study the evolution of clusters in this section. Figure 2 shows the variations of the density profiles \( \rho \), half-mass radius \( r_h \), virial parameter \( Q \), and the percentage of the star number \( N_S/N_{Stot} \) with time. Panel (a) gives the densities of stars at 0, 1, 3, 5, and 10 Myr in the 2J model. Due to the expansion of the clusters, the density decays with time, which will significantly influence the close encounter rate between planetary systems, and thus results in different dissolution timescales of planetary systems, as shown in the next paragraph. In panel (b), the half-mass radius \( r_h \) (dashed line) increases to 1.5 pc, about three times its initial value. Although the cluster extends to a much larger region in space, the virial parameter \( Q \) (solid line) is still at the virial equilibrium \( (Q \sim 0.5) \) at the end of our simulation. Panel (c) shows that about 3\% of the cluster members are ejected out of the cluster in the first 3 Myr in all models. In our models, the velocity dispersion \( \sigma = 1 \) km s\(^{-1}\) (1 km s\(^{-1}\) \( \approx 1 \) pc Myr\(^{-1}\)) and about \( \sim 97\% \) of stars have a velocity dispersion \( < 2\sigma = 2 \) km s\(^{-1}\). Adding to the mean velocity 1 km s\(^{-1}\), it will take at least \( \sim 3 \) Myr for a star in 1 pc to arrive at the boundary of the cluster (10 pc as we set in Section 2). Between 3–10 Myr, because of the dissolution of the cluster, 12\%–17\% of the stars escape from the host cluster and only 80\%–85\% of the stars still stay in these clusters after 10 Myr.

To obtain the analytic dissolution timescale, we use the half-mass relaxation timescale (Spitzer 1987, p. 40):

\[
\tau_{rh} = 0.138 \left( \frac{N}{\ln N} \right) \left( \frac{GM_{cl}}{r_h^3} \right)^{-1/2}. \tag{5}
\]

Using the following typical values, \( N = 1000, M_{cl} \sim 800M_\odot \), and \( r_h = 0.9 \) pc at \( t = 3 \) Myr in Figure 2(b), we obtain \( \tau_{rh} \approx 12 \) Myr. For isolated clusters here (without the galactic tide), the escape velocity of the cluster \( v_{esp} = 2(\sigma^2/v)^{1/2} = 2 \) km s\(^{-1}\) in the initial Gaussian distribution of velocities, and \( \sim 18.86\% \) of the stars have initial velocities \( v \geq v_{esp} \); therefore, the dissolution timescale of the cluster is

\[
\tau_{diss} \approx \tau_{rh}/0.1886 \approx 64 \text{ Myr}. \tag{6}
\]

According to this analytic dissolution timescale, we can estimate that the cluster will lose 7 Myr/\( \tau_{diss} \sim 11\% \) of the stars between 3–10 Myr, which is consistent with our simulation results.

The mass segregation timescale for a star with mass \( M \) is also important for the next discussion; here, we use a typical expression by Spitzer (1987, p. 74),

\[
\tau_{seg} = \left( \frac{M_{\ast}}{\bar{M}} \right) \left( \frac{N}{\ln N} \right) \left( \frac{r_h}{\sigma} \right), \tag{7}
\]

where \( M_{\ast} \) is the mean mass of stars in the cluster. For the typical value used above, we obtain \( \tau_{seg} \leq 10 \) Myr for an \( M \geq 2 M_\odot \) star due to energy equipartition in our models.
Besides the retention of planetary systems, a number of planets have been disrupted from their host stars and obtained a large velocity. Finally, these planets escape from the cluster and become FFPs. There are at least 10% more planets that were disrupted by two lines: eccentricity $e > 0.9$ and inclination $i > 90^\circ$ primarily because of close flybys as near as $<100$ AU. Due to the ejection of planets, only 2.7%–5% of the planets are still cruising in the cluster and become FFPs, while at least 12%–21% became FFPs outside the host clusters. $N_F$ and $N_S$ represent the number of surviving planets and stars in the cluster. $N_{0ps}$, $N_{0pi}$, and $N_{0ps}$ represent the number of systems with two original planets, only one original planet, only one recaptured planet, and no planet, respectively. $N_{FFP}$ is the number of FFPs staying in clusters, while $N_{FFPo}$ is FFPs ejected outside, and $N_S$ is the number of binary pairs. The number of single stars with no planets or stellar companions is $N_s$. The bounded energy $E_b$ is the total initial energy of two planets around the host star.

### 4. PLANETARY SYSTEMS AROUND CLUSTER MEMBERS

#### 4.1. General Statistical Results

The general results of the four models are analyzed in detail in this section. Table 2 represents the number of survival objects in the clusters in different models. Although 80%–85% of the stars are still in clusters, only 66%–74% of the planets stay in the clusters. There are at least 10% more planets that were disrupted from their host stars and obtained a large velocity. Finally, these planets escape from the cluster and become FFPs more easily than more massive stars. In these YOCs, we divide the survival planetary systems into the following three classes.

1. **2pisi systems.** Stable planetary systems maintaining two original planets. 55%–68% of the initial systems are in this class.

2. **1pisi systems.** Planetary systems lost one planet and have only one original planet that survived. Only 6%–18% of the stars ejected one planet.

3. **pisj systems.** Recaptured planetary systems, which is very rare. In our model, they are less than 1%.

Hereafter, these systems are represented as 2pisi, 1pisi, and pisj systems. Besides the retention of planetary systems, a fraction of stars (~6%–13%) lost both planets ($N_{0ps}$) primarily because of close flybys as near as $<100$ AU. Due to the ejection of planets, only 2.7%–5% of the planets are still cruising in the cluster and become FFPs ($N_{FFP}$), while at least 12%–21% of the planets become FFPs outside the host cluster ($N_{FFPo}$). In our model, ~47% of the stars are initially in binary, and after a 10 Myr evolution in the cluster ~64% of the binary systems are preserved. After the evolution of the cluster, we also find a few "naked" stars, $N_s$, without any planetary or stellar companions.

In Table 2, we see some rough correlation with the bounded energy of planets ($E_b$). $N_P$, $N_{FFP}$, $N_{FFPo}$, and $N_{ss}$ have negative correlations with $E_b$, while $N_{2pisi}$ is the opposite. The results are reasonable because larger energy is needed to disrupt planetary systems with higher $E_b$. The JSE2 model with a larger $E_b$ has 10% more survival planets than model J10E4 (see also Figure 6(a)). As Spurzem et al. (2009) detailed the influences on single planetary systems with different semimajor axes, we do not survey the influences of $E_b$ in detail here due to our limited four models. More details about binary systems and FFPs will be discussed in Sections 5.2 and 6. Here we focus on the architecture of survival bounded planetary systems and other properties.

### 4.2. Architectures of Planetary Systems

Figure 3 shows the orbital architectures of planetary systems in different models. In each $a$–$e$ plane, planetary systems are divided into three classes: 2pisi (green triangles), 1pisi (black circles), and pisj (red squares) systems. The filled symbols represent Earth-like planets while the open symbols represent Jupiter-like planets. Most planets still stay near their initial locations. The outer Jupiter-like planets can more easily change their angular momentum than inner planets during flybys, and therefore change their locations or eccentricities more probably. In panels (b)–(d), Earth-like planets are difficult to eject; therefore, most 1pisi systems retain their filled circles.

The distributions of eccentricities and inclinations of these three classes of planetary systems are shown in Figure 4. Obviously, the 2pisi systems have only a negligible fraction to change their initial eccentricities ($\sim 3% > 0.1$) or inclinations ($\sim 6% > 10^\circ$). Meanwhile, a large part of the 1pisi systems changed their eccentricities larger than 0.1 ($\sim 50%$) or inclinations larger than 10$^\circ$ ($\sim 30%)$. Ejected planets become FFPs, which can be recaptured by some other stars randomly. Hence, the pisj systems tend to have much wider and flatter distributions of both inclinations and eccentricities.

Here we note that for these 1pisi systems, 282 inner planets survived compared with 223 outer ones. The ratio is 1.3:1 on average. To reveal the different properties of these systems retaining inner or outer planets, we plot Figure 5, adding pisj systems as blue triangles. The black squares mean 1pisi systems with outer planets that survived, while red circles represent systems where inner planets survived. In Figure 5(a), we give the final locations of all the systems in the inclination–eccentricity plane, which is divided into four regions by two lines: eccentricity $= 0.1$ and inclination $= 10^\circ$. The red line is inclination $= 90^\circ$. Planets above this red line move in retrograde orbits. Figure 5(b) gives the fraction of systems in the four regions. Nearly all the pisj systems have an eccentricity $>0.1$, and none of them have a small eccentricity ($< 0.1$) and inclination ($< 10^\circ$). In the 1pisi systems where the outer planet is ejected, about 45% of the surviving inner planets have small eccentricities and inclinations. However, if the inner one is ejected, then only about 25% of the surviving outer planets have small eccentricities and inclinations, while more than 70% of the planetary systems have obviously changed their eccentricities ($> 0.1$) or inclinations ($> 10^\circ$).

The spin-orbit misalignment can be estimated by the Rossiter–McLaughlin effect (see Winn et al. 2010); thus, the
Figure 3. Configurations of survival planetary systems for four different models. Three classes of systems are represented here: 2pisi (green triangles), 1pisi (black circles), and pisj (red squares) systems. The filled symbols represent Earth-like planets while the open symbols represent Jupiter-like planets. Earth-like planets are hard to eject, therefore most 1pisi systems are shown as filled circles.

Figure 4. Distributions of (a) inclinations and (b) eccentricities of 2pisi, 1pisi, and pisj systems. Most 2pisi systems have little change in their eccentricities and inclinations, while most 1pisi systems have eccentric or inclined planets. Recaptured planets tend to stay in very eccentric and inclined orbits.

inclination study in our simulations is also interesting. Assuming all stars spin in the same direction invariably for simplicity, we have many planets in misaligned orbits (>10°) in clusters. More than 25% of the 1pisi systems that have their outer planets ejected have the surviving planets in misaligned orbits. The same misaligned fraction is also obtained in 1pisi systems that have inner planets ejected. We also find 21 planets (~4%) in retrograde orbits that have surviving single planetary systems. These fractions are quite low except in pisj systems, as shown in the smaller panel in Figure 5(b). However, it is still higher than the occurrence in 2pisi systems, which contain only 14 (<0.6%) planets in retrograde orbits. Based on the results here and considering all the planetary systems in the clusters, we calculate the lowest fraction of planetary systems in VYOCs with a misalignment of at least ~6%. Only 1% have planets in retrograde orbits.
4.3. $r$-correlations and Mass-correlations

As pointed out by Binney & Tremaine (1987), the frequency of close encounters is sensitive to the stellar density, which decreases with both evolution time and the distance from the cluster center $r$ (the same hereafter). As shown in Figure 6(a), the fractions of surviving planets are very different from that of stars (Figure 2(c)) due to the fast decay of stellar density $\rho$ in the center of the clusters. In all four models, the fraction of surviving planets decreases in the first 1 Myr. After that, $\rho$ decays quickly and the decreasing rate becomes smaller and smaller.

Similar to the previous time dependence, the stabilities of planets change with different locations in OCs. In the center of the clusters, the density can be much larger than in the outer region, which leads to a higher frequency of close encounters (see Equation (11)). Planetary systems near the center of OCs can be disrupted quickly. This is obvious as shown...
tems with cluster locations (dist) for in Figure 6(b). The number of surviving planets is denoted by Variations of total angular momentum $\Delta L$ for planets at different cluster locations (dist) for $N_p = 2, 1, 0$ from top to bottom. The unit of $\Delta L$ is $M_p \cdot \sqrt{GM_\odot} \cdot \text{AU}$. We can find the correlation between $\Delta L$ and $r$, shown by dotted lines: $|\Delta L| = a(10 - r) + b$. The constants $a, b$ depend on $N_p$. Much denser environments make the angular momentum exchange more frequently and lead to a larger $\Delta L$.

in Figure 6(b). The number of surviving planets is denoted by $N_p$. The distribution of unstable planetary systems with $N_p = 0$ peaks at 0.958 pc sharply, while a flatter distribution of systems with $N_p = 1$ peaks around 1 pc. The peak for stable systems with $N_p = 2$ is located at 1.29 pc, i.e., these stable systems stay in the outer region compared with the other two unstable systems. This is consistent with the fact that planetary systems in the inner region of OCs are probably unstable. In the inner 1 pc, about 40%, 30%, and 20% of the planetary systems have $N_p = 0, 1,$ and 2, respectively. About 80% (the horizontal dotted line) of the systems with $N_p = 0, 1, 2$ are concentrated in 2, 3, 4 pc approximately. We call this correlation the $r$-correlation.

The variations of angular momentum $\Delta L$ for planets in these three systems are also plotted in Figure 7. We can find an obvious correlation between the maximum $\Delta L$ (with a unit $M_p \cdot \sqrt{GM_\odot} \cdot \text{AU}$) and $r$. In the center of the clusters, more close encounters take more angular momentum away. In Figure 7, we show linear estimations of the upper limit for

$$|\Delta L| = a(10 - r) + b,$$

where the constants $a, b$ for different $N_p = 2, 1, 0$ are listed in Figure 7. $\Delta L$ for the three different planetary systems at different locations must be less than this limit in our VYOC models.

As shown in Equation (7), the mass segregation timescale can be less than 10 Myr for stars $> 2 M_\odot$. The mass segregation leads to a spatial distribution of stars that correlate to the stellar mass. Massive stars sink into the inner region while small stars cruise in the outer region. It is similar to the $r$-correlation. However, another influence of stellar mass on planetary stability has the opposite effect. Large mass stars may hold planets around them more tightly, and thus they need more energy to release these planets. The stellar mass correlation (called mass-correlations) combines these two competing effects.

In Figure 8(a), we give the fraction distribution of planetary systems ($f$) for $N_p = 0, 1, 2$. No planets survived around stars more massive than $16 M_\odot$ because these stars have sunk deep into the center of the cluster in a very short timescale, $\tau_{\text{seg}} < 1.2$ Myr, and planetary systems in the center of the cluster are much less stable as pointed out above. The black dashed line columns show the observational data (the same label as in Figure 6(b)). In order to compare with the initial IMF $f_0$ of host stars, we represent a normalized fraction (divided by $f_0$) in Figure 8(b) to highlight the fraction variation. Systems with $N_p = 2$ remain stable for stars with $M < 2.5 M_\odot$. A sharp decrease in the fraction for $N_p = 2$ and large enhancements for $N_p = 1, 0$ exist at $M = 2.5 M_\odot$. This critical mass indicates a boundary of about $2.5 M_\odot$ for the two competing effects. For those more massive stars, most planets around them can still be disrupted due to the heavy density ($\rho$) in the inner region of the cluster, although they are bounded more tightly. Less massive stars cruise in an environment with a much lower $\rho$ and can hardly release any planets. From an observational aspect, three of the four planetary systems in OCs are found around stars with masses $< 2.5 M_\odot$. The left one, $\epsilon$ Tauri, has a stellar mass

Figure 7. Variations of total angular momentum $\Delta L$ for planets at different cluster locations (dist) for $N_p = 2, 1, 0$ from top to bottom. The unit of $\Delta L$ is $M_p \cdot \sqrt{GM_\odot} \cdot \text{AU}$. We can find the correlation between $\Delta L$ and $r$, shown by dotted lines: $|\Delta L| = a(10 - r) + b$. The constants $a, b$ depend on $N_p$. Much denser environments make the angular momentum exchange more frequently and lead to a larger $\Delta L$.

Figure 8. (a) The fraction of planetary systems ($N_p = 0, 1, 2$) correlates with stellar masses. Observational data with labels $S_1, S_2, S_1, S_4$ are the same as those in Figure 6(b), and 3(75%) of them are less than 2.5 $M_\odot$ (the dotted line). (b) The normalized fraction correlates with stellar masses. As shown in panel (b), if the host star has a mass $< 2.5 M_\odot$, then the normalized fraction is around unit, i.e., it is nearly the same fraction as the IMF. However, a star more massive than 2.5 $M_\odot$ tends to lose at least one planet; therefore, the normalized fractions of $1p_{isi}$ and $p_{isj}$ systems are obviously enhanced.
estimate the final number of binary systems were disrupted in the clusters due to close encounters. We decay of the binary number can be calculated as where Age means the age of the cluster. The timescale for the dissolution factor $\exp(-\tau_{\text{diss}})$ is shown in Equation (6). To estimate $\tau_{\text{diss}}$, we use the encounter timescale obtained by Binney & Tremaine (1987):

$$\tau_{\text{enc}} \approx 33 \text{ Myr} \times \left(\frac{100 \text{ pc}^{-3}}{\rho}\right) \left(\frac{v}{1 \text{ km s}^{-1}}\right) \times \left(\frac{10^3 \text{ AU}}{r_{\text{peri}}}/\frac{M_{\odot}}{m_t}\right).$$

If the average separation of binary stars is $\bar{a}$, assuming the closest distance encountered is $r_{\text{peri}} \approx 2\bar{a}$, then the perturbation of encounters will be the same degree as the binary companion. These encounters will probably disrupt the binaries. Considering a binary can encounter another single star or binary, we use 3.5 times the mean mass of star $M_{\odot}$ as the total mass of stars during the encounter $m_t = 3.5 M_{\odot}$. Taking a typical stellar velocity $v = 1 \text{ km s}^{-1}$, we finally obtain the binary disrupted timescale from Equation (11):

$$\tau_{\text{disrupt}} \approx 33 \text{ Myr} \times \left(\frac{100 \text{ pc}^{-3}}{\rho}\right) \left(\frac{500 \text{ AU}}{\bar{a}}\right) \left(\frac{M_{\odot}}{3.5 M_{\odot}}\right).$$

In our model $\bar{a} = 185 \text{ AU}$, $\bar{M} = 0.8 M_{\odot}$. The stellar density decayed so quickly that here we chose the $\rho \sim 60 \text{ pc}^{-3}$ (the value at 1 pc in the cluster with a moderate age of 3 Myr). Substituting these typical values into Equation (12), $\tau_{\text{disrupt}} \approx 53$ Myr. Thus, about 17% of the binaries are disrupted after 10 Myr, which is consistent with the fraction of the disrupted binary in our simulations. Based on the observations of YOCs, the binary fraction $f_b$ can be estimated by

$$f_b = f_{b0} \times \exp(-\text{Age}/\tau_{\text{disrupt}}).$$

Taking $\tau_{\text{disrupt}} = 53$ Myr and the initial binary fraction $f_{b0} = 47\%$ in our model, we calculate the binary fraction $f_b = 39\%$ after 10 Myr according to Equation (13), which is similar to $f_b = 36\%$ in our simulations. The distributions of semimajor axes $a_b$ and eccentricities $\epsilon_b$ of survival binary systems are shown in Figure 9. The red bars show
the distribution of the initial fraction \( f_0 \), while the green bars show the distribution after 10 Myr \( f_0 \). The upper panel gives the relative fraction \( f_0/f_0 \). The dynamical evolution in clusters can disrupt wider binary systems more easily due to the lower bounded energy, and the eccentricities of binary systems can also be pumped. Therefore, compared with the initial distribution, the fraction of binary systems with small \( e_b(<0.4) \) or large \( a_b(>200\,\text{AU}) \) decreases after 10 Myr. Meanwhile, more binary systems with \( a_b < 100\,\text{AU} \) (>45%) or moderate \( e_b(0.4–0.8) \) (>55%) are left.

Very few new binary systems formed during the evolution of the clusters. In our four models, only 15 new binaries formed in total, with mean eccentricity \( = 0.68 \) and inclination \( = 1.66 \) rad. Their \( a_b \) are not regular at all from 60–1000 AU. The contribution to \( f_0 \) of these binaries is quite small and can be omitted.

5.2. Planets around Binary Stars

During the disruption of binary systems, the planets around each star have different fates. Some collide with host stars, some are ejected out of the systems, and some still orbit around their host stars. In our models, there are a total of 304 disrupted binary stars that still stay in clusters after 10 Myr, while others are ejected out of the cluster. Sixty four of them lose all their planets, 59 stars have only one planet, and the other 181 stars have two bounded planets. We are also concerned with the inclinations of these planets. For the systems with 1 planet, 5 in 59 planets are in retrograde orbits. For those with two planetary systems, five systems have at least one planet in retrograde orbits. In systems containing two planets, planets with mutual inclination \( >l_{\text{Kozai}} \sim 42^\circ \) experience the Kozai effect (Kozai 1962). There are only six such systems around disrupted stars. Around the original single stars, only five systems have a mutual inclination of \( >l_{\text{Kozai}} \). We conclude that due to perturbation during the disruption of binary systems, the mutual inclinations of planets around these disrupted single stars are large and have more of a chance of experiencing the Kozai effect in their long evolution hereafter.

Since lots of the binary systems survived, we next study the planetary systems in these binaries. As we set two planets around each star, there are a total of four planets in one binary system initially. Figure 10 shows the left number of planets in binaries \( N_p \) in the \( a_b-r \) and \( e_b-a_b \) planes. \( a_b, e_b \) are the semimajor axis and eccentricity of a binary system, and \( r \) is the distance from the barycenter to the center of the cluster. The pink crosses, blue inverted triangles, green triangles, red circles, and black squares represent \( N_p = 4, 3, 2, 1, 0 \), respectively. As shown in panels (a) and (b), the binary systems with larger angular momentum (larger \( a_b \) and smaller \( e_b \)) and smaller stellar density (larger \( r \)) can probably hold on to more planets.

Figure 10. Number of surviving planets in binary systems \( N_p \) in the (a) \( a_b-r \) and (b) \( e_b-a_b \) planes. \( a_b, e_b \) are the semimajor axis and eccentricity of a binary system, and \( r \) is the distance from the barycenter to the center of the cluster. The pink crosses, blue inverted triangles, green triangles, red circles, and black squares represent \( N_p = 4, 3, 2, 1, 0 \), respectively. As shown in panels (a) and (b), the binary systems with larger angular momentum (larger \( a_b \) and smaller \( e_b \)) and smaller stellar density (larger \( r \)) can probably hold on to more planets.

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Figure 11 shows \( N_p \) in different \( X-Y \) planes. We obtain a rough criterion: binary systems with \( a_b(1-e_b^2) > 100\,\text{AU} \) seem to restore all four planets, while others more or less lost planets around them. There is still a small fraction for close binaries that have a small \( e_b \) and can preserve all the planets very well. As seen in Figure 10(a), the distance from the center of cluster \( r \) has less influence than that in single stars.

Statistically, only 1411 planets (58% of the initial planets) stay in 604 binary systems after 10 Myr, i.e., each binary star contains 1.17 planets on average. In these 15 newly formed binaries, a total of 22 planes survived; therefore, we obtain a much smaller mean planet number of 0.7 around each star in these newly formed systems. Compared with single stars, which have \( \sim 1.8 \) planets around each star on average, multi-planetary systems in binary are much less stable than those around single stars.

6. FFPs AND EJECTED OBJECTS

Besides planets bounded around stars, there are fruitful FFPs in our universe (Sumi et al. 2011). In our model, there are a few FFPs left in the cluster; however, there is an abundance of FFPs ejected outside the cluster. This is due to the much larger mean velocities of FFPs compared with the velocities of stars in the cluster; therefore, these FFPs are much easier to be ejected. In this section, we will reveal the distribution of FFPs and other properties of ejected objects.

As the outside Jupiters are much easier to eject out of planetary systems as seen in Figure 3, there are much more Jupiter-like FFPs (about 2.5 times) than Earth-like FFPs. However, their spatial distributions are similar, as shown in Figure 12, i.e., the cumulative distribution functions (CDFs) of these planets with different sizes are nearly the same. Nearly half of the FFPs are concentrated in 2 pc, while 80% of the FFPs are concentrated...
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Figure 11. (a) The number of surviving planets \( N_p \) in binary systems in the \( X-r \) plane \( (X = a_b(1-e_b^2)) \), \( r \) is the distance from the center of the star cluster; (b) \( N_p \) in the \( a_b-e_b \) plane. There is an obvious boundary: planets in binary systems with \( a_b(1-e_b^2) > 100 \) AU are hardly disrupted during the evolution of the cluster.

Figure 12. (a) The spatial distributions of Jupiter-like (red open circle) and Earth-like (blue filled circle) FFPs; (b) the CDFs of Jupiter-like (red solid line) and Earth-like (blue dash line) FFPs. There are no differences between their CDFs. There are about 2.5 times more Jupiter-like FFPs than Earth-like planets.

in 4 pc. As shown in Figure 13(a), the fraction of FFPs is relative to their location \( r \); we show a fitting curve to model the distribution:

\[
    f_{\text{FFPs}} = 0.003 + \frac{0.07}{(r - 1.14)^2 + 0.97}. \tag{14}
\]

The maximum fraction peaks at 1.14 pc.

Besides these FFPs cruising in clusters, there are still a large number of objects (\( N = 2868 \) in sum) that were ejected out of the clusters. The fraction of components of ejected objects is shown in Figure 13(b). 48.2% of these objects are FFPs (\( N = 1381 \)), while the two-planet systems also have a quite large fraction of 40.6% (\( N = 1164 \)). The very rare one-planet systems are only 2% (\( N = 58 \)). The remaining 9.2% (\( N = 265 \)) are single stars with no planetary or stellar companion around them. Most FFPs are ejected out of the host clusters, as seen in Table 2, \( N_{\text{FFPo}} \) has a negative correlation to the bounded energy. In all these FFPs, \( \sim 70\% \) are contributed by planets in binaries, i.e., planets in binary systems seem to be much less stable.

Based on the above results, the FFPs are likely to be found in the inner region of YOCs, and Jupiter-like FFPs are common. Most FFPs are ejected outside their host clusters and cruise in the deep universe. For these planetary systems ejected out of host clusters, more than 80% keep the same initial number of planets. Few planets (\(<10\%\)) in these systems have their orbits changed much. Based on this conclusion, our solar system, which is thought to be formed in a cluster environment, is most likely to form as a similar current configuration before the ejection from its host cluster.

7. DISCUSSIONS AND CONCLUSIONS

In VYOCs, we choose an isolated, isotropic, and non-rotating cluster model and repel the galactic tidal force and stellar evolution in this paper. We investigated the configurations of
both multiple and single planetary systems as well as FFPs in VYOCs without residual gas. In these clusters, a modified King model is adopted to produce the spatial distribution of stars, and virial equilibrium is satisfied as an assumption. Different from previous works, we add a large binary fraction as well as the IMF of stars in the cluster model, which is much more realistic than previously adopted models.

Our major conclusions in this paper are listed as follows.

1. After dynamical evolution for 10 Myr, clusters are expanded but still in virial equilibrium. The general statistical results of the four models (see Table 1) are presented in Table 2. More than half of the planetary systems still retain their original planet number. A cluster can lose about 26%–34% of its original born planets. The number of surviving planets ($N_P$), FFPs inside the cluster ($N_{FPi}$), FFPs outside ($r > 10$ pc) the cluster ($N_{FPo}$), and single stars without any companions ($N_{ss}$) depend on the different bounded energy of planets $E_b$.

2. More than 90% of the 2pisi systems change eccentricities less than 0.1 or inclinations less than 10°, while most 1pisi systems have eccentricities or inclinations of planets that obviously changed. Planets in pisj systems have a wide, flat distribution of eccentricities and inclinations. In 1pisi systems, inner planets are preserved preferentially. If an inner planet was ejected, then the remaining planet seems to have more probability of changing eccentricities or inclinations (Section 4.2).

3. Under the assumption that all the stars spin in a fixed direction in our cluster models, at least 6% of the stars have misaligned planetary systems and 1% have retrograde planets. These spin-orbit misalignment systems are likely to be generated in unstable systems (1pisi or pisj).

4. Unstable planetary systems are concentrated in the inner region of the clusters while the stable systems are following a flatter distribution in the outer region, as shown in Figure 6(b). With a sharp peak at $\sim 1$ pc, the fraction of planetary systems with $N_P = 0$ in the inner 2 pc is about 80%. The fraction of systems with $N_P = 1$, 2 in 2 pc is about 60% and 50%, respectively. Our results are consistent with observations: two of the four planetary systems are in 2 pc of OCs.

5. The stellar mass is also a key factor for the stability of bounded planets. We obtained a critical mass of $\sim 2.5 M_\odot$ in Figure 8, above which the planetary systems are probably unstable and most of them lose at least one planet. Planetary systems around stars with $< 2.5 M_\odot$ are likely to maintain all their original planets. According to our results, a large fraction (> 80%) of the bounded planets can be found around stars with $(M = 0.1–1 M_\odot)$ in VYOCs. Massive stars ($> 16 M_\odot$) tend to lose all the planets around them. We also compared our results to observations.

6. In YOCs, binary systems can be ejected or disrupted in the timescale $t_{\text{diss}}$ or $t_{\text{diss}}$. The binary fraction can be estimated by Equation (13) in Section 5.1. In our model, nearly 64% of the binaries still exist in the cluster after 10 Myr. However, their orbits have been changed due to the evolution of the cluster. The number of binary systems with $a_b > 200$ AU decreases by disruption, and binary systems with $ecc < 0.4$ likely have their eccentricities pumped to a moderate value. At the same time, a minority of new binary systems (15 in total) have formed.

7. The planets around disrupted binary stars are more unstable than those around single stars. After the violent perturbations during binary disruptions, more than 30% of the planetary systems lost at least one planet. However, planetary systems around these disrupted binary stars contribute lots of retrograde planets, as pointed out in Section 5.2.

8. The stability of planetary systems in binaries depends on $a_b$, $e_b$, as shown in Section 5.2. We give a rough criterion: planets in binary systems with $a_b(1 - e_b^2) > 100$ AU are hardly disrupted during the cluster evolution. The influence of $r$ on binary systems is less obvious than that in single stars.

9. 15%–25% of the planets are released as FFPs, and only 1/4 of them are still cursing in OCs after 10 Myr. However, they can only stay in the inner domain of the cluster; therefore,
around stars play crucial roles in the formation and evolution of planets in clusters, gas with limited mass can hardly influence the dynamical evolution of the cluster. However, the gas disks around stars play crucial roles in the formation and evolution of planets (Liu et al. 2011). The gravity of the outer gas disk can also lead to secular effects on multi-planet systems and under some conditions with small mutual inclination can also lead to the onset of the Kozai effect (Chen et al. 2013). In clusters, the flybys also influence the structure of the gas disk and consequently change the occurrence of planets (Forgan & Rice 2009).

Second, the isotropic assumption and virial equilibrium in our cluster model are also queried by some authors. Sánchez & Alfaro (2009) and Schmeja (2011) indicated a substructure in young star-forming regions. As mentioned by Parker & Quanz (2012), the number of surviving planets also depends on the initial virial parameter $Q$ of the cluster.

We only choose four models with different planetary systems, therefore it is hard to discuss the influence of bounded energy $E_b$ in detail. In our future work, additional planetary systems are needed to study the correlation between planetary stability and $E_b$. We only set two planets around each star as the first step to consider the multi-planetary systems. The stabilities of a system with more planets might be much more sensitive with close encounters. Different properties of the clusters, i.e., the total mass, core radius, number of stars, etc., lead to different timescales of cluster evolution (Malmberg et al. 2007b). Therefore, the fraction of preserved or ejected planets depends on these parameters too.

The rotation of the cluster will influence the dynamical evolution of the cluster directly. Observations of cluster NGC 4244 show an obvious rotation (Seth et al. 2008). Since we adopted a non-rotating cluster, we can only study a one-dimensional $r$-correlation, as in Section 4.3. Adding a rotating rate to the clusters, the stability of planetary systems at different latitudes with the same distance is varied due to the different mean velocities $v$, which is presented in the expression of $\tau_{\text{enc}}$ (Equation (11)).

As we only study the VYOCs here, the galactic tidal effect and stellar evolution are not important, as pointed out in Section 2.1. However, when studying a longer evolution of the cluster with age $>10$ Myr, the galactic tides and stellar evolution timescales need to be estimated again. Galactic tides tend to evaporate cluster members and change the properties of clusters (Baumgardt & Makino 2003). During stellar evolution, a star will experience giant branch, horizontal branch, asymptotic giant branch, etc., in the H–R diagram. The stability of planets around it must be checked carefully during all these phases (Villaver & Livio 2007).

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