How Do Disks and Planetary Systems in High-mass Open Clusters Differ from Those around Field Stars?

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Abstract

Only star clusters that are sufficiently compact and massive survive largely unharmed beyond 10 Myr. However, their compactness means a high stellar density, which can lead to strong gravitational interactions between the stars. As young stars are often initially surrounded by protoplanetary disks and later on potentially by planetary systems, the question arises to what degree these strong gravitational interactions influence planet formation and the properties of planetary systems. Here, we perform simulations of the evolution of compact high-mass clusters like Trumpler 14 and Westerlund 2 from the embedded to the gas-free phase and study the influence of stellar interactions. We concentrate on the development of the mean disk size in these environments. Our simulations show that in high-mass open clusters 80%–90% of all disks/planetary systems should be smaller than 50 au just as a result of the strong stellar interactions in these environments. Already in the initial phases, three to four close flybys lead to typical disk sizes within the range of 18–27 au. Afterward, the disk sizes are altered only to a small extent. Our findings agree with the recent observation that the disk sizes in the once dense environment of the Upper Scorpio OB association, NGC 2362, and h/β Persei are at least three times smaller in size than, for example, in Taurus. We conclude that the observed planetary systems in high-mass open clusters should also be on average smaller than those found around field stars; in particular, planets on wide orbits are expected to be extremely rare in such environments.

Key words: open clusters and associations: general – planets and satellites: dynamical evolution and stability – protoplanetary disks

1. Introduction

Unlike most clusters/associations in the solar neighborhood, which often dissolve within 10 Myr (Lada & Lada 2003; Porras et al. 2003), some clusters can remain intact for hundreds of megayears and more. These clusters are characterized to be compact (1–3 pc) and relatively massive—properties they have inherited from their formation phase when they were likely even more compact (0.1–0.5 pc). Clusters like NGC 3603, Arches, Trumpler 14, and Westerlund 2 (~2 Myr) are thought to be younger counterparts.1

Given their small sizes and large masses ($M_c > 10^4\ M_\odot$; Figer 2008), the stellar density in such clusters is very high, for example, up to $\sim 2 \times 10^6\ M_\odot\ pc^{-3}$ (Espinoza et al. 2009) in the central areas of Arches. Initially, the stars are mostly surrounded by disks from which planetary systems may form. However, the high stellar density means that protoplanetary disks in such dense environments can be influenced by external processes like external photoevaporation (Johnstone et al. 1998; Störzer & Hollenbach 1999; Scally & Clarke 2002; Matsuyama et al. 2003; Johnstone et al. 2004; Adams et al. 2006; Alexander et al. 2006; Ercolano et al. 2008; Drake et al. 2009; Gorti & Hollenbach 2009; Clarke & Owen 2015; Haworth et al. 2016b) or gravitational interactions (e.g., Clarke & Pringle 1993; Hall 1997; Scally & Clarke 2001). The latter can also alter already-formed planetary systems (see, e.g., de La Fuente Marcos & de La Fuente Marcos 1997; Laughlin & Adams 1998; Spurzem et al. 2009; Shara et al. 2016). In extreme cases these two processes can lead to disk destruction, decreasing the disk lifetime in such clusters. However, more frequently the disk is truncated, leading to a smaller disk size. Here, we concentrate on the effect of flybys on the disk size in compact clusters that develop into long-lived clusters, because this effect is present throughout all the cluster stages and it affects protoplanetary disks, as well as already-formed planetary systems. Taking Trumpler 14 and NGC 3603 as templates means that we look at the high-mass end of clusters ($M_c \geq 10^4\ M_\odot$), which are sometimes referred to as starburst clusters. Many open clusters have somewhat lower masses. A comparison to lower-mass compact clusters will be given in Section 4.3.

There are only a few surveys providing disk sizes in compact young massive clusters, because determining the disk sizes in these environments is challenging. One reason is that most of these high-mass compact clusters are located at relatively large distances, for example, Trumpler 14 is 2.7 kpc away. In addition, the compactness and high mass of these clusters mean that crowding is a major issue. A further problem is that, owing to their high mass, these clusters contain many massive stars that dominate the radiation. However, disk frequencies are better constrained by observations than the disk sizes. For example, in the young compact clusters Arches (2.5 ± 0.5 Myr) and the Quintuplet (4 ± 1 Myr) disk frequencies of 6% ± 2% and 4.0% ± 0.7%, respectively, have been observed (Stolte et al. 2010, 2015). These are considerably smaller than the ones found in less dense environments such as the Orion nebula cluster, with approximately 70% (Hillenbrand et al. 1998), as shown in Figure 1. Therefore, it can be concluded that a dense environment has a strong effect on the disks. Whether the lower disk fraction in compact clusters is mainly due to the effect of flybys or external photoevaporation is an open question, as will be discussed in Section 4.3. Here, we concentrate on the effect of...
flybys on the disk size, but future investigations should also consider the effects of external photoevaporation, which have been neglected here.

As protoplanetary disks are the prerequisite for planet formation, there have been speculations whether planets could form at all in such harsh environments. Early surveys of exoplanets in long-lived open and globular clusters could only give upper limits for the portion of stars having a Jupiter-like companion (see, e.g., Paulson et al. 2004; Mochejska et al. 2006; Pepper et al. 2008; Hartman et al. 2009; van Saders & Gaudi 2011). So far about 20 planets around main-sequence stars have been found in seven different open clusters (see Table 1), among them even planetary systems containing at least two planets. In addition, some planetary candidates have been found (Brucalassi et al. 2017). Apart from the planets listed in Table 1, there is also indirect evidence for the presence of so-far-undetected planets through external metal pollution of white dwarfs, for example, in the Hyades (Farihi et al. 2013; Zuckerman et al. 2013). However, most of these clusters have a lower mass than the ones studied here. In addition, let us consider the system PSR B1620-26, which consists of a millisecond pulsar–white dwarf binary surrounded by a Jupiter-mass planet in a 40 yr orbit (Thorstens et al. 1993) in the globular cluster NGC 6121 (M4). Its formation has been related to dynamical interactions that occurred in the cluster (Sigurdsson et al. 2003). In summary, at least some planetary systems are able to survive in such dense stellar environments for many gigayears. Given the low number of known planets in clusters, it is still unclear whether planets are as frequent in clusters as in the field (van Saders & Gaudi 2011; Meibom et al. 2013).

As mentioned above, we concentrate here on the typical disk and planetary system (DPS) size in dense clusters as a result of flybys. More specifically, we address the question whether the sizes of the DPS in open clusters differ from those found around field stars and, if so, how to quantify these differences in size.

We tackle these questions by performing numerical simulations of young compact clusters and following their evolution over the first 10 Myr of their existence. Afterward, we have analyzed the data to study the influence of the cluster environment on protoplanetary disks. There have been numerous studies investigating the effect of the gravitational interactions on protoplanetary disks and planetary systems in cluster environments. However, many of them concentrated on the flyby rate or disk frequency (Olczak et al. 2006, 2010; Pfalzner et al. 2006; Craig & Krumholz 2013; Steinhausen & Pfalzner 2014). In addition, they mostly focus on the less dense clusters typical for the solar neighborhood (Rosotti et al. 2014; Vincke et al. 2015; Portegies Zwart 2016; Vincke & Pfalzner 2016). A recent study investigates the environmental effects during the interesting star formation phase (Bate 2018); however, here again a less dense environment is considered and only the first 0.5 Myr have been modeled. Studies that investigate the effect on disk sizes or planetary system sizes including dense clusters were recently carried out by Portegies Zwart & Jilkova (2015) and Winter et al. (2018b). However, Portegies Zwart & Jilkova (2015) only gives a rough analytical estimate of an unaffected zone, and Winter et al. (2018b) look at the current density in the considered clusters but do not take into account the temporal development of the clusters.

However, dense clusters evolve along well-defined radius–age and mass–age tracks, changing their stellar density by orders of magnitude during the first 10 Myr (Pfalzner 2009; Pfalzner & Kaczmarek 2013b). In stark contrast to their less dense counterparts like the Taurus or even the Orion Nebula Cluster (ONC), in dense clusters only a few stars become unbound owing to gas expulsion at the end of the star formation process. Actually, stellar encounters are the main driving force of cluster expansion (Pfalzner & Kaczmarek 2013b), so stellar density in these clusters steadily declines with age. The effect of cluster expansion on disk sizes has so far not been modeled for dense clusters. Only the effect of a more or less fixed density environment was modeled in the above-mentioned studies. However, expansion naturally occurs during the development of such clusters, which might influence crucially the effect on DPS.

Ideally one would like to model the cluster dynamics and resolve at the same time the evolution of the disk that initially surrounds each star. There have been first attempts in such a direct method (Rosotti et al. 2014) at a fixed density. However, these simulations are limited to a low number (100) of stars that have equal mass and are in a lower-density environment. Therefore, much fewer interactions happen, and only the first ~0.5 Myr can be modeled owing to computational limitations. By contrast, modeling the compact cluster progenitors requires us to treat at least 1000 stars with an approximately 1000 times higher stellar density, and it is essential that the stellar masses are chosen according to the initial mass function (IMF), as the effect of gravitational focusing is very important in this context (Pfalzner et al. 2006). Therefore, we perform here a two-step approach, where we first model the cluster dynamics while recording all the flybys and then post-process the data to determine the effect of the close flybys on the DPS.

In addition, the model adopted here has as its main advantage that it can be used equally for the disk and the planetary system stage, referred to here as DPS. Thus, we do not need to know how fast planet formation actually happens, which is still a major point of discussion. For disks the simulation particles are representative of the mass distribution of the dust, whereas for planetary systems they represent the parameter space where planets potentially move on circular orbits before the flyby.

An additional difference to previous studies is that most of them considered all encounters to be prograde and coplanar.

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2 DPS sizes refer here and in the following to the disk radius rather than the DPS diameter.
These types of flybys are the most destructive ones, and the determined losses can be interpreted as the upper limit of the effect of flybys on DPS in general (Clarke & Pringle 1993; Heller 1995; Hall 1997; Bhandare et al. 2016). Here we will investigate the more realistic situation of randomly oriented flybys. In summary, the study presented here differs from previous work as it (i) models all phases of the cluster development (embedded, expansion, and semi-equilibrium), (ii) treats dense clusters that will likely develop into long-lived open clusters, and (iii) includes flybys of arbitrary orientation.

In Section 2 we will describe the cluster simulations and the disk size determination in detail. Afterward, we present our results on the effect of the dense cluster environment on the disk size distributions in Section 3. The assumptions that we have made in our setup will be discussed in Section 4. In Section 5, we will discuss the differences that can be expected when comparing planetary systems in open clusters to those around field stars, and we give a short summary.

### 2. Method

As mentioned in the introduction, we use a two-step approach to determine the effect of flybys on the DPS around stars in dense clusters. First, while simulating the cluster dynamics we simultaneously record the flyby history. This is similar to what has been done in our earlier work described in Vincke & Pfalzner (2016) and Pfalzner et al. (2018a), where more details of the method can be found.

#### 2.1. Cluster Dynamics

The cluster simulations are performed using the code Nbody6++GPU (Aarseth 1973; Spurzem 1999; Aarseth 2003; Wang et al. 2015), which is an optimized version of NBODY6++ with hybrid parallelization methods (MPI, GPU, OpenMP, and AVX/SSE) to accelerate large direct N-body simulations. In contrast to Vincke & Pfalzner (2016), we focus here on very dense—potentially long-lived—clusters representative for the case of Arches or Westerlund 2. As such, they are more massive than the special case of M44 studied in Pfalzner et al. (2018a). We start at that point in time when star formation is completed. This means that the times given are not necessarily equivalent to the cluster age, as the star formation phase is not covered in our simulations. We study two cases: one without an embedded phase (C0) and the other one where we have considered a 1 Myr long embedded phase (C1). For the other properties of the simulated clusters, see Table 2.
simulation campaign,\(^{3}\) Note that the simulations are not supposed to exactly reproduce the Arches cluster, but to represent compact clusters in general.

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### Table 2
Compact Cluster Model Setup and Dynamical Timescales

| Model | Represents | \(N_{\text{stars}}\) | \(N_{\text{gas}}\) | SFE | \(r_{\text{hm}}\) | \(t_{\text{emb}}\) | \(M_{\text{stars}}\) | \(M_{\text{cl}}\) | \(t_{\text{dyn}}\) |
|-------|------------|----------------|---------------|-----|-------------|-------------|----------------|-------------|-------------|
| C0    | Westerlund 1 | 32 000 | 10 | 0.7 | (pc) | 0.2 | (M yr) | 18 839 | 26 913 | 0.01 |
| C1    | Westerlund 1 | 32 000 | 10 | 0.7 | (pc) | 0.2 | (M yr) | 18 824 | 26 891 | 0.01 |
| E52   | NGC 2244   | 32 000 | 9  | 0.3 | (pc) | 1.3 | (M yr) | 18 852 | 62 842 | 0.1  |
| E2    | ONC        | 4 000  | 94 | 0.3 | (pc) | 1.3 | (M yr) | 2 358.1 | 7 860.3 | 0.33 |

Note. Column (1): model name. Column (2): representative cases. Column (3): number of stars in the model, \(N_{\text{stars}}\). Column (4): number of simulations in the simulation campaign, \(N_{\text{sim}}\). Column (5): star formation efficiency, SFE. Column (6): initial half-mass radius of the stellar and the gas component, \(r_{\text{hm}}\). Column (7): duration of the embedded phase, \(t_{\text{emb}}\). Column (8): stellar mass of the cluster, \(M_{\text{stars}}\). Column (9): total cluster mass (stars + gas), \(M_{\text{cl}}\). Column (10): dynamical timescale, \(t_{\text{dyn}}\). See text for calculation.

In order to study to what extent the planetary systems in compact/open clusters resemble or differ from those found around field stars and those formed in less dense clusters, we compare our results to our earlier work, where we modeled less dense clusters typical for the solar neighborhood. The parameters of this cluster (model E52) are also given in Table 2. Most importantly, E52 has the same initial mass as C0 and C1, but the half-mass radius is larger (1.3 pc) and the star formation efficiency (SFE), which is the fraction of gas in the cluster that is turned into stars, is smaller (30% compared to 70%). In this case the embedded phase, \(t_{\text{emb}}\), was assumed to last 2 Myr.

#### 2.1.1. Cluster Initial Conditions

The starting point of our simulations, \(t_{0} = 0\), corresponds to a fully formed cluster. In NBody6++, the gas is not modeled explicitly but just as a background potential. The clusters are set up with an initial half-mass radius of 0.2 pc that is typical for compact clusters at the start of the expansion phase (Pfalzner & Kaczmarek 2013b). The SFE is assumed to be 70%. There are two reasons why it is necessary to assume such a high SFE value: (i) observations hint at much higher SFEs for compact clusters (Rochau et al. 2010; Cottaar et al. 2012; Hénault-Brunet et al. 2012) than for those in the solar neighborhood, and (ii) if one interprets the size–age relation in compact clusters as a temporal sequence, because this demands also such a high SFE (Pfalzner & Kaczmarek 2013b).

Usually, the stellar density distribution is modeled either as a King or a Plummer profile (see Bastian & Goodwin 2006; Rosotti et al. 2014; Banerjee & Kroupa 2015; Wang et al. 2015). Here we choose a modified King profile for the stars and a corresponding Plummer profile for the gas that reflects the situation in observed clusters (Espinoza et al. 2009; Steinhausen 2013).\(^{3}\) The total cluster mass is given by \(M_{\text{cl}} = M_{\text{stars}} + M_{\text{gas}}\), with \(M_{\text{stars}}\) being the stellar component of the cluster and \(M_{\text{gas}}\) the gas mass. It follows that

\[
M_{\text{gas}} = \frac{M_{\text{stars}}(1 - \text{SFE})}{\text{SFE}}. \tag{1}
\]

The stellar masses were sampled from an IMF (Kroupa 2002) with a lower limit of 0.08 \(M_{\odot}\) and an upper limit of 150 \(M_{\odot}\), and the velocities were sampled from a Maxwellian distribution.

\(^{3}\) Note that the simulations are not supposed to exactly reproduce the Arches cluster, but to represent compact clusters in general.

#### 2.1.2. Flyby Frequency

In all cases we assume the clusters to be initially in virial equilibrium. The gas expulsion is modeled as being instantaneous, as \(t_{\text{gas}} < t_{\text{emb}} < 1\) Myr. It is not clear how long the embedded phase of compact clusters lasts. None of the compact clusters younger than 3 Myr, such as the Arches cluster, show signs of considerable amounts of gas (see Pfalzner 2009). Thus, to date, no unambiguous embedded precursor cluster has been identified. From the absence of embedded massive compact cluster precursors and the observed gas-free clusters (\(t_{\text{age}} = 1–2\) Myr), it can be assumed that the embedded phase is short, probably lasting <1 Myr.

Given the absence of observed timescales for the embedded phase, we modeled two cases: \(t_{\text{emb}} = 1\) Myr (C1) and \(t_{\text{emb}} = 0\) Myr (C0) (see also Table 2), the latter being representative for a cluster with a very short embedded phase \(t_{\text{emb}} \ll 1\) Myr. The consequences of these choices will be analyzed in Section 4. Table 1 also gives the simulation parameters of two of the extended clusters modeled in Vincke & Pfalzner (2016), for comparison.

The gas expulsion process brings the cluster out of equilibrium, leading to members becoming unbound. However, as the SFE is quite high, this gas expulsion is only a secondary cause for cluster expansion for models C0 and C1. The main reason why the clusters expand by a factor of 10–20 is the ejection of stars from the densest cluster regions (Pfalzner & Kaczmarek 2013b).

During the simulations, we record for each flyby the relevant parameters (time, duration, periastron, distance of primary to cluster center, mass ratio of encounter partners). This information is then used to post-process the data to obtain the effect of such a flyby on the DPS. For each model, simulations of only the first 3 Myr were performed.

#### 2.2. Modeling the Effect of a Flyby on the DPS Size

We assume that initially each star was surrounded by a protoplanetary disk, equivalent to a 100% initial disk frequency. Observationally it is quite difficult to determine the initial disk frequency, especially in such dense environments. The highest disk frequency observed for a compact cluster is approximately 30% for NGC 3603 (Stolte et al. 2015). However, as disk destruction could be very rapid in such environments, a 100% initial disk frequency may be still a good assumption. Even if the initial disk frequency would be considerably less, this would not be a problem for the results presented here, as we are predominantly interested in the
disk sizes. In this case, our results would still hold for the stars that had initially disks.

Similarly, it is not straightforward what value one should assume for the primordial disk size. Here we make one major assumption that currently is not testable by observations because there exist no observations of disk sizes in young massive compact clusters. This assumption is that disks around stars in compact clusters have initially the same properties concerning their size, mass, etc., as those around nearby young stars that are part of a sparse cluster or associations. One has to keep in mind that those disks might differ in their properties because they normally form in an environment of higher gas and dust density and the embedded phase in compact clusters is much shorter. Consequences might be more massive compact disks, but there are equally strong arguments for less massive, more extended disks. Without observations, that is so far just speculation. Therefore, we assume a low-mass disk as characteristic for young stars in compact clusters.

In Taurus, a very sparse association, the disk size distribution peaks at 200 au, and disks of up to 700 au are found (Andrews & Williams 2007). Observations show disk sizes of 27–500 au in the ONC (McCaughrean & O’dell 1996; Vicente & Alves 2005; Bally et al. 2015); however, the ONC is denser than Taurus, and at an age of at least 1 Myr it is questionable whether the measured disk sizes correspond to primordial ones. It is more likely that the disk size has already been altered owing to photoevaporation or stellar flybys.

Disk size values found, for example, in Taurus should correspond to those unaffected by the environment. Therefore, we assume 200 au as the initial disk size for all stars in our simulations. We will see in the following that almost all disks in the compact clusters are stripped to sizes well below 100 au, so the result is completely independent of this initial choice. With this, we can separate processed from nonprocessed disks easily.

The question is whether and to what degree the DPS sizes can increase again after they have been reduced in size by a flyby. There are various processes that could lead to DPS size growth, which in an extreme case could result in the disks becoming as large as or even larger than they were initially. This is discussed in Section 4.2.

2.2.1. DPS Size Determination after Flybys

For post-processing the flyby data we make use of the computational results from extensive numerical parameter studies, which determine DPS size as a function of the mass ratio $m_{12} = m_2/m_1$, the periasteron distance $r_{\text{peri}}$ (Breslau et al. 2014), and the inclination (Bhandare et al. 2016) during the flyby. A detailed description of the different treatment of coplanar and inclined flybys is given in Appendix A.

In contrast to previous studies (see, e.g., Clarke & Pringle 1993; Heller 1995; Hall 1997; Portegies Zwart & Jilkova 2015; Vincke et al. 2015), Bhandare et al. (2016) implicitly took into account randomly orientated DPS, which is a realistic situation for stellar clusters. They find that non-coplanar encounters have a still considerable effect on the DPS size. A database of the computational results can be found at http://www3.mpifr-bonn.mpg.de/encounter-properties/. Averaged over all inclinations, including the coplanar prograde and coplanar retrograde case, they find the following approximate dependence:

$$r_{\text{disk}} = 1.6 \cdot r_{\text{peri}}^{0.72} \cdot m_{12}^{-0.2},$$  (2)

where $r_{\text{disk}}$ is smaller than or equal to the DPS size before the encounter $r_{\text{previous}}$ (all sizes and distances are in au).

Equation (2) holds for mass ratios in the range of 0.3–50; however, it is unfortunately not straightforwardly applicable to our study. The reason is that their fit formula focuses on very close to penetrating ($r_{\text{peri}} \leq r_{\text{previous}}$) encounters, with the largest periasteron distances included being $5 \times r_{\text{ini}}$. In stellar clusters, even in the most compact ones, flybys with even larger periasteron distances are the most common (see also Scally & Clarke 2001; Olczak et al. 2006). For this reason, we set up additional simulations analogous to the ones by Bhandare et al. (2016) with a focus on distant flybys. We obtained a slightly different fit formula for the DPS size after a flyby with ($m_{12}$, $r_{\text{peri}}$) averaged over all inclinations, which gives a better fit for distant flybys:

$$r_{\text{disk}} = \begin{cases} 
(1.6 \cdot m_{12}^{-0.2} - 1.26 \cdot m_{12}^{-0.182}) \cdot r_{\text{peri}} & \text{for } r_{\text{disk}} < r_{\text{previous}}, \\
 r_{\text{previous}} & \text{for } r_{\text{disk}} \geq r_{\text{previous}}
\end{cases}$$

A detailed description of the simulations, the data, and the fit are given in Appendix B. Equation (3) enables us to indirectly study randomly orientated flybys without having to simulate DPS and clusters simultaneously (as done by Rosotti et al. 2014), which would not be possible for groups of 32,000 stars over timescales of 3 Myr.

Previous simulations treated all flybys as coplanar and could only give upper limits for the effect of flybys; as such, they overestimated it. However, Figure 2 shows that there is a difference between coplanar and inclined flyby, but it is relatively small. For example, a 200 au sized disk would be truncated to 84 au by a flyby at a periasteron distance of 300 au, whereas the disk size after a randomly orientated encounter would be 102 au, which is about 20% larger. This is also reflected in the overall median DPS size in each cluster type (see Appendix B). In the following, unless stated otherwise, we will present the outcome of our simulations assuming randomly orientated flybys. Here we only take into account events that lead to a DPS-size reduction of at least 5% ($r_{\text{disk}}/r_{\text{previous}} \leq 0.95$).

Comparing theoretical and observational disk sizes poses many difficulties. On the one hand, there are different definitions of disk sizes in the theoretical treatment, as well as in observations. This issue is discussed in detail in Breslau et al. (2014), and we use their definition of steepest gradient at the outside of the disk, owing to its similarity to most observational methods. On the other hand, observational disk sizes depend on the wavelength range of the observations, whether one looks at the size of the gas or dust disk, the development stage of the disk, and many other parameters (Balog et al. 2016; van der Marel et al. 2018). Given the scarcity of disk size measurements in compact clusters, we just take the given data as their face value. However, when more data will be available in the future, this will require finer specification.

We neglect effects other than flybys that could potentially lead to DPS size changes, for example, viscous spreading or mass transport between disks, meaning that we assume that the disk size remains constant throughout our simulations unless altered by a consecutive flyby (see Rosotti et al. 2014). For a
detailed discussion of potential DPS size changing processes other than flybys, see Section 4.

3. Results

The dynamical evolution of the compact clusters, which might develop into long-lived open clusters, differs considerably from that of the short-lived extended clusters/association that dominate the solar neighborhood. It has been long expected that in such environments interactions are strong and very frequent and as such have a significant influence on the DPS. In the following we quantify the effect on the DPS sizes.

3.1. Cluster Evolution

First, we want to look at the cluster evolution over the first 3 Myr. As mentioned in the introduction, in contrast to associations, compact clusters have a 70% SFE, so the gas loss on its own only leads to a slight increase in the clusters size, but it is rather the ejection of stars in the dense cluster center that is responsible for the strong increase in cluster size (Pfalzner & Kaczmarek 2013b). In Figure 3 the stellar density development of the clusters within a sphere of their half-mass radius (0.2 pc) as a function of time is depicted for our compact models C0 and C1 (light-red circles and dark-red circles, respectively). Note that here the total system mass is taken into account, meaning the gas plus stellar mass. The gas expulsion at \( t = 0 \) for C0 and \( t = 1 \) Myr for C1 results therefore in a drop in mass density by 30%. In addition, the loss of stars due to close flybys leads to a steady decrease in stellar density. As the stellar density decreases, stellar ejections become less common, leading to a gradual slowing down of the expansion process.

3.2. Cluster Density

The cluster density determines the degree of influence of the environment on the protoplanetary disks surrounding its members. Naturally, the number of flybys potentially changing the disk size in the compact clusters is high, about three to four flybys per star during a period of 3 Myr. This is not much more than for an extended cluster of the same mass, which has one to two such flybys per star despite having a lower initial density of roughly 150,000 \( M_\odot \) pc\(^{-3} \) within 0.2 pc.

The reason is the qualitative difference between these encounters: whereas in extended clusters the DPS size is reduced step by step, in compact clusters most disks experience very close flybys already within the first 0.1 Myr; see Figure 4. These very close flybys lead to such DPS disk sizes that the cross section for a follow-up flyby becomes small. As a consequence, the number of flybys that are actually necessary to produce such small DPS sizes is relatively small.

3.3. Median DPS Size

Next, we study the DPS size development in the different cluster environments. As expected, the high density in the compact clusters leads to small protoplanetary disks (see, e.g., Bonnell et al. 2001; Vincke et al. 2015). Most of the change occurs in the early phases of the cluster development. At 3 Myr the mean DPS size is 21 au for model C0 and 11 au in the case of model C1. For model C1 most of the DPS changes happen during the embedded phase, at the end of which the mean DPS size is already 12 au.

As mentioned above, an embedded phase of such compact clusters is probably shorter than 1 Myr, such that the real mean DPS size can be expected to be in the range of 12 au to 21 au by 3 Myr. Figure 5(a) shows that the mean disk size within the half-mass radius is even smaller, approximately 10 and 8 au for C0 and C1, respectively. The interaction dynamics can vary considerably between different realizations (Parker & Goodwin 2012); this is reflected in the relatively large error bars in Figure 5(a), which correspond to the standard deviation of the values.

The DPS sizes are relatively small, as, for example, our own solar system with a Neptune semimajor axis of \( \sim 30 \) au could not have formed from such a small disk. On average, the DPS sizes in compact clusters are considerably smaller than extended clusters. For our model E52 a factor of four larger values are obtained, and for the ONC (see Figure 4(q), blue), we obtain a typical value of 160 au for the mean disk size within the half-mass radius, which would be characteristic of the dense clusters in the solar neighborhood.
As the density contrast between the cluster center and its outskirts is very high, one expects that more encounters take place in the cluster core than in the outskirts. This is reflected in the median DPS size as a function of the distance to the cluster center shown in Figure 5(b). For models C0 and C1 (red) the median DPS size is smaller than 10 au close to the cluster center. For model C0 the median DPS size in the cluster core (<0.3 pc) is 8 au, and for model C1 it is 5 au at 0.3 pc. On the other hand, the DPS sizes are only larger than 10 au at distances larger than 0.5 pc for C0 and 0.8 pc for model C1. Again, the scatter in the obtained values is relatively large, but the general trend is always the same, with smaller values closer to the cluster center. As will be discussed in Section 4, it is an open question whether planets can form in such small disks at all. In comparison, for model E52 the median disk size even in the most central area is at least 20 au (Vincke & Pfalzner 2016). For model C0 even the stars at the outskirts of the cluster (>10 pc), which mostly become unbound and leave the clusters, still have a median disk size of 46 au. This means that any star that has been part of a compact cluster, even just for a short time, bears its marks by its small DPS size.

Next, we discuss the question whether stars of different mass are affected to a different degree. Figure 6 shows that the final DPS size depends only slightly on the stellar mass. From low-mass stars to B stars there is only a slight increase in final mean DPS. However, O stars are much more affected by flybys than B stars, as it is very conspicuous in model C0, where the average disk size of O stars is 8 au, compared to 34 au for the B stars. The reason for the slight increase for M to B stars, as well as the decrease for O stars, is the flyby statistics. M stars are most common and are therefore involved in most flybys, whereas the very massive (>20 $M_\odot$) stars act as gravitational foci, therefore undergoing many strong flybys. A similar effect for the disk frequency has been noticed before, e.g., by Pfalzner & Olczak (2007). However, for very large masses the statistics is less good, as there are relatively few very high mass stars.

We assumed that initially all stars had the same disk size independent of the stellar mass, although theoretical (see, e.g., Vorobyov 2011) and observational reasons support a slight dependence of the disk size on the stellar mass. It is often assumed that the disk size increases with stellar mass, ranging from roughly 100 au for stars with 0.08 $M_\odot$ up to nearly 1000 au for solar-like stars (see, e.g., Vorobyov 2011). Such an initial dependence would not alter the results presented here because all final mean DPS sizes are much smaller than 100 au.

### 3.4. Disk Size Distributions in Different Environments

How does the disk size distribution look like in such compact clusters? Figure 7 shows the size distributions for the two compact cluster models. Here we try to mimic observations and consider only stars within 3 pc—the typical field of view (FOV) in observation at 200–400 pc distance, for example, with the Spitzer telescope. Outside this radius, member determination is very difficult owing to the usually high stellar back-/foreground densities.

Surprisingly, disk sizes smaller than 10 au are the most common (35% and 47%, respectively) in such compact clusters; see Figure 7(a). If the disks are cut down to such a small size before planet formation took place, it is unlikely that there is enough material left for gas giants to form by accretion afterward, because the remaining mass in the disk is relatively small. However, if one of the formation channels is hierarchical fragmentation, gas giants might still form in such hostile environments. In some cases there might be sufficient material to form terrestrial planets by accretion, but this requires further investigation.

Large disks are quite rare: only as much as 23%, or even 14% for model C1, of disks are larger than 100 au, and they are mostly located at the outskirts of the clusters. In the extended cluster only about 37% of all stars are smaller than 100 au after 10 Myr. Even though the simulation time was much longer, the majority of disks remain large and only very few are destroyed (6%).

### 4. Discussion

In our cluster simulations we have made a number of assumptions and simplifications, namely, we (1) assumed instantaneous gas expulsion, (2) did not include mass segregation, and (3) did not include primordial binaries. We will discuss the potential influence of each of these in the following section.

#### 4.1. Cluster Dynamical Evolution

##### 4.1.1. Cluster Dynamics

We investigated the effect of the duration of the embedded phase by comparing models $t_{\text{emb}} = 0$ (C0) and $t_{\text{emb}} = 1$ Myr (C1). Model C0 can be used to set constraints to disk size distributions of clusters that are embedded for less than 1 Myr (C1). The duration of the embedded phase does make a difference for the resulting disks and possibly forming planetary systems: the fraction of small disks (≤20 au) is much larger in the embedded model, and the median disk sizes differ by up to a factor of two; see Figures 7 and 5(b).

We assumed the gas expulsion itself to happen instantaneously. This is, at least for the investigated very massive and dense clusters, a justified approximation. In reality, the gas expulsion is thought to last a few dynamical timescales, which are of the order of 0.01 Myr for the compact clusters and 0.1 Myr for the extended model E52, so modeling the gas
expulsion instantaneously is reasonable. If the gas expulsion were to last longer, the clusters would have enough time to adjust to the gas mass loss, so fewer stars would become unbound. Additionally, the mass density would stay higher for a longer time span, leading to a higher encounter frequency and thus smaller disks.

4.1.2. Mass Segregation

In our study, the masses and positions of stars in the clusters were picked out randomly from the respective distributions disregarding initial mass segregation. Although a lot of clusters seem to be mass segregated, it is still under debate whether this is an initial property or a consequence of dynamical evolution. If the number density would remain the same but with the more massive stars concentrated in the center, the encounter rate in the cluster core would increase because of the larger gravitational focusing by the massive stars. Hence, the disks around the most massive stars would be smaller or could even be destroyed.

4.1.3. Binaries

In our simulations all stars were initially single and binaries were not included in the setup. The reason why we neglected binaries is that the data for the effect on the disk of binaries are only available for single cases, but no systematic parameter studies like the ones required here do exist. However, observations show that a large portion of stars are binaries (Köhler et al. 2006; Duchêne & Kraus 2013). This means that the fraction of stars surrounded by disks presented here is an upper limit, as more disks would be destroyed when—or not even form—as part of a binary. The periodic interactions between a disk and its binary star would have to be investigated in more detail to make further predictions about its size and structure.

The inclusion of binaries would also affect the cluster evolution: Kaczmarek (2012) demonstrated that binaries lead to an accelerated cluster expansion on timescales of a few megayears, but as most flybys that lead to disk-size truncation occur during the first megayear, this should not alter the results presented here about the disk sizes. In addition, observations and simulations show that the most massive stars are most probably part of binary systems. This increases gravitational focusing, which in turn might result in even smaller disk sizes.

In our simulations some captures of stars into binaries do occur; however, these are relatively rare processes. They are resolved in the cluster simulation. However, in the effect on the disk size they are treated like that of a flyby at the resulting binary separation. Like in the above case of primordial binaries, this leads to underestimating the effect and would require further investigation in the future.

4.1.4. Parabolic Encounters

All flybys were assumed to be parabolic, that is, the eccentricities are \( e = 1 \). The encounter eccentricity depends on the cluster density (Olczak et al. 2010, 2012), especially in the case of very dense clusters investigated here where the real eccentricities can be fairly high owing to the dominance of three-body interactions. The topic of the dependence of the disk size on the eccentricity of the flyby has been scarcely investigated in the literature. However, studies of the disk mass loss indicate that hyperbolic flybys might be less...
of 3.0 \( \text{yr} \) (et al. 2010) indicates that this is also true for disk sizes.

4.1.5. Stellar Evolution

We did not include stellar evolution in our simulations, as we think that the influence on the results is limited. The minimum mass for a star to become a supernova during the 3 \( \text{Myr} \) covered here is 70 \( M_\odot \). Thus, some of the realizations could in principle experience a supernova explosion toward the end of the simulation. However, then most of the disk truncation processes have already taken place, so that the influence of the supernova on the cluster dynamics should be very small. To have a considerable influence on the cluster dynamics, it would be required that the supernova explosion would take place within the first megayear, but the required stellar mass would be about 400 \( M_\odot \).

Even if no supernova explosion were to take place, the mass loss of the massive stars, even during their first few megayears, might be important (Vink 2015). We did not include mass loss in our simulations because, first, the number of high-mass stars is very low in comparison to the low-mass stars; thus, their effect on the average disk size is low. Second, in clusters like the ONC the massive stars play a fundamental role in the dynamics, as they act as gravitational foci. In this type of cluster mass loss of the massive stars might possibly play some role. However, for the much denser clusters, which we discuss here, the massive stars lose this role, as interactions with the lower-mass members become much more common (Olczak et al. 2010). Basically, there needs to be sufficient space around the massive stars to become a focus; if that space is filled up, the massive stars lose their special role as foci. Therefore, the resulting average disk size is dominated by the interactions between the low-mass stars. Thus, even if the massive stars would lose considerable amounts of their mass, this would not influence the result in any sizable way. Third, if we take \( 10^{-7} M_\odot \text{yr}^{-1} \) as an example, this would correspond to a 0.3 \( M_\odot \) loss. A 100 \( M_\odot \) star would be reduced to a 99.7 \( M_\odot \) star after 3 \( \text{Myr} \), which makes hardly any difference on the size after a flyby. Even the 3 \( M_\odot \) difference expected with a \( 10^{-6} M_\odot \text{yr}^{-1} \) mass loss would change the disk size value by less than 2 au even in a very close encounter, which is negligible in an averaging computation over 32,000 stars.

A constant mass-loss rate of \( 10^{-5} M_\odot \text{yr}^{-1} \) would be a problem, especially for stars of 30 \( M_\odot \) and smaller, as they would have dispersed completely by then. However, we doubt that high-mass stars continuously have such high mass-loss rates over the entire 3 \( \text{Myr} \) modeled here. It is much more likely that the mass-loss rate varies strongly with time, even showing bursts like those known for accretion. Nevertheless, the role of mass loss in such massive clusters should be considered in future studies.

4.2. Other Influence on DPS Size

The results from the effect of flybys described in Section 2.2.1 can be used under certain conditions to describe the effect on the disk and also on planetary systems. The difference is that for disks the simulation particles are representative of the mass distribution of the dust, whereas for planetary systems they represent the parameter space where planets potentially move on circular orbits before the flyby.

The question is whether and to what degree the DPS sizes can change after they have been reduced in size by a flyby.

There are various processes that could lead to DPS size growth, which in an extreme case could result in the disks becoming as large as or even larger than they were initially. We have to distinguish between the processes that play a role in the disk phase and those that are only relevant in the phase where a planetary system has already formed.

4.2.1. Disk Phase

The main process that can change the disk size in addition to flybys is external photoevaporation (Haworth et al. 2016a). The radiation from the massive stars is strong enough to ionize the material in the disk, and gradually material is removed from the outskirts of the disk. Therefore, the disk size can be reduced by external photoevaporation. Thus, the above results can be considered as upper limits of the disk size, because external photoevaporation could lead to a further decrease in disk size. Unfortunately, the degree and especially the timescale on which external photoevaporation happens are less constrained than the gravitational effect of flybys (Gorti et al. 2016). In addition, comparison between the expected effect of external photoevaporation and observations indicates that the real effect...
is smaller than that predicted by theory (Gorti et al. 2016). Therefore, the average effect of external photoevaporation in clusters is currently unknown. It is also important to note that external photoevaporation is only efficient when the cluster is no longer heavily embedded in gas. This means that one would only expect additional disk reduction by photoevaporation after the embedded phase has ended.

However, there are not only processes that could lead to further disk size reduction but also those that potentially would lead to a size increase. One of them is viscous spreading during the disk phase, which could lead to an increase in disk size before and after the flyby. The disk size growth before the flyby does not influence our results because basically all disks are affected by flybys to such a degree that they become smaller than 100 au independently of their pre-flyby size. Potentially more important is the viscous spreading that might take place after the flyby. However, considerable disk size increase can only happen if (i) the disk is relatively massive, so that the disk has a sufficiently high viscosity, and (ii) the gas stays in disks for a sufficiently long time. As we have no observational information about the disks masses in compact clusters, we have no idea whether they are more or less massive than around nearby stars. Assuming that it is the same as around nearby young stars, this corresponds to a typical disk mass $m_d \approx 0.01 M_\star$. For such low-mass disks considerable viscous spreading ($>20$ au) is noticeable after $\approx5$–$10$ Myr. However, in compact clusters the average lifetime of disks is very short, at most $1$–$2$ Myr, so that disk spreading is $\ll20$ au. This means that the potentially resulting planetary systems are mostly $\ll40$ au.

### 4.2.2. Planetary System Phase

There are basically two processes that could lead to changes in the system size of an already-formed planetary system after the flyby: capture of one or more planets, or excitation of planets onto eccentric orbits by planet–planet scattering.

Generally capturing requires a close flyby, but in this case not only is material captured but at the same time the disk size is reduced. The material captured from another star tends to go onto highly eccentric orbits with the periastron being relatively small. The latter means that in most cases $r_{\text{peri}}(\text{captured}) < r_d$. As soon as there are objects on eccentric orbits, it is no longer straightforward how to define the disk size. If we consider the periastron distance, then only captured matter does not influence the disk size. However, if one considers the outermost periastron as relevant, then an increase in DPS size could in principle happen.

How common would such a capture event be? Capturing a planet from another star requires a relatively close flyby, and many flybys that lead to DPS truncation are too distant to lead to capturing. In other words, capturing is less common than DPS disk size decrease. This again implies that planet-capturing processes are most common during the early cluster phases and are even rarer than DPS decrease in later phases. Therefore, the question is whether planets that could be potentially captured have already formed during the first $\approx5$ Myr, so that they could lead to a larger DPS size than expected from our results. It is still an open question what is the shortest time span required for planet formation, with estimates ranging from 1 to 10 Myr. The additional difficulty is that the context here implies captured planets that would have been originally orbiting at relatively large distances ($>50$ au) from their previous host star, because only this lightly bound matter can be swapped between stars during a flyby. According to the standard accretion model, planet formation proceeds more slowly in the outer disk regions. Therefore, the only alternative would be that these planets formed early on owing to gravitational instability in a relatively massive disk. In summary, there might be some cases where planet capture can lead to a larger DPS afterward, but these cases are likely quite rare, meaning that they should not significantly alter the results presented above.

The only process that could lead to considerably larger DPS in compact clusters than the ones discussed above is, in our opinion, planet–planet scattering. Here long-term interactions between the planets orbiting a star can lead to the ejection of planets or the excitation of the orbit of one or more members of the system to a larger distance from the host star. How common such a process is depends on the compactness of the original planetary system. Again, it is not known how compact planetary systems around stars and particularly around cluster stars typically are. Even if we assume that compact systems are common and excitation to more distant orbits happens often, this would probably not result in a larger observed DPS size in the near future. The reason is that mostly the least massive planet is excited onto a wider generally eccentric orbit. Unfortunately, in the foreseeable future it will not be possible to detect low-mass planets moving on wide orbits in mostly fairly distant compact clusters.

In summary, the above-presented results should be representative not only for the situation at an age of 10 Myr but also for the long-term appearance of planetary systems in such compact clusters.

### 4.3. Comparison with Other Models

As mentioned in the introduction, most simulations so far concentrated on DPS sizes in less dense clusters. These are more typical in the solar neighborhood, and as such more observational data exist for comparison. Winter et al. (2018a) investigate clusters spanning from low-density clusters to those similar to the ones studied here. They did not take into account the cluster development, meaning that the cluster density stays constant for the entire 3 Myr they model in their Monte Carlo approach. However, they also treat the effect of external photoevaporation. Taking both processes into account, Winter et al. (2018a) obtain a mean disk size of approximately 85 au at a cluster age of 3 Myr for their low-density model (model D). The density in this model is slightly lower than the one by Vincke & Pfalzner (2016); however, both these values for typical disk sizes in low-density clusters are significantly larger than the value of 21 au we obtain for the compact clusters considered here. This means that there is a significant difference between the typical DPS sizes in the typical solar neighborhood clusters and the ones likely to develop into long-lived open clusters.

Pfalzner et al. (2018a) modeled one specific open cluster, namely, M44. This cluster probably had a similar size to the one modeled here but an approximately 10 times lower mass to start with, and therefore an $\sim10$ times lower stellar density. Therefore, it might be considered a prototype for many of the open clusters with lower masses. As the stellar density is lower than in the case modeled here, one can expect that the disk sizes should on average be slightly larger, or that the relative number of very small disks should be slightly smaller. Figure 6 in Pfalzner et al. (2018a) confirms this expectation. There one
can see that 13% of all disks in M44 are smaller than 10 au compared to about 35%–47% in the case studied here.

Winter et al. (2018a) considered also compact clusters similar to the ones we consider here. They find that generally external photoevaporation dominates as a disk truncation process over the effect of flybys. Does this mean that flybys are only a second-order effect for the disk size? Not really; they specifically point out that their model only applies to the situation when the cluster is no longer strongly embedded, as only then external photoevaporation can act to its full extent.

We saw in Section 3 that 80% of the disk-truncating flybys happen during the first 0.2 Myr of cluster development, meaning during the deeply embedded phase, i.e., the phase when external photoevaporation does not act yet. The mean disk size at the end of the embedded phase is well below 30 au. We have to compare that to the value provided by Winter et al. (2018a), who give a mean disk size of 35–38 au for their highest-density cluster (model D). This means that the disk sizes at the end of the embedded phase are already smaller than what one would expect to happen as a result of photoevaporation in the consecutive 3 Myr. In other words, flybys dominate the disk truncation process during the embedded phase. It is not clear what happens afterward, as the results of Winter et al. (2018a) cannot simply be transferred to these smaller disks. A future study is required that includes not only the effect of flybys and external photoevaporation but also the embedded phase and the cluster expansion process.

The clusters investigated here differ from extended clusters not only through their much higher density but also by having a star formation efficiency that is at least 60%. In a recent study, Wijnen et al. (2017) compare the effect of dynamical encounters with that of a special model of face-on accretion and ram pressure stripping. They find that the latter are dominating as long as the total cluster mass in stars is $\lesssim 30\%$ regardless of the cluster mass and radius. In other words, encounters dominate over face-on accretion and ram pressure in the compact clusters that we have investigated here. However, in the early star formation this effect could be important and should be investigated in a dedicated study.

5. Summary and Conclusion

For a long time it was unclear whether planets could form and survive in the dense stellar environment of open clusters. However, during the past few years several protoplanetary disks and about 20 planets have been found in open clusters, showing that planets can indeed withstand such harsh environments. Some open clusters are probably older counterparts of young compact clusters like Arches or Westerlund 2. Here, we have studied the influence of stellar flybys on the size of protoplanetary disks and eventually forming planetary systems by performing simulations of such young, compact clusters. We have considered two models, one with a very short phase (C0) and the other with a 1 Myr long embedded phase (C1). Starting with an initial disk size of 200 au, we find that in both cases stellar flybys are responsible for significant changes in the disk size. After 3 Myr, all disks are reduced in size by flybys, with 77% and 86% being smaller than 100 au in C0 and C1, respectively. However, what is most interesting is that disk sizes $< 10$ au are the most common in such environments; 35% and 47% of all disks are smaller than 10 au in model clusters C0 and C1, respectively. This corresponds to mean disk sizes of 21 au for C0 and 11 au for C1.

Disks that are reduced to sizes smaller than 10 au have a relatively small mass, and their structure is very complex (Breslau et al. 2014). It is not certain that the remaining material would be identified as a disk any more by observations. As their structure differs considerably from a flat Keplerian disk, it is not clear what effect that feature has on the planet formation process. It could either prevent it altogether, because at least in the outer areas the matter is unevenly distributed, or it could actually accelerate dust growth owing to an induced increase in collision frequency. This has to be considered in more detail in future work.

Here we only consider the effect of flybys on the disk size; however, in such dense and massive clusters the strong radiation from the massive stars—external photoevaporation—can lead to additional disk size reduction. However, in contrast to flybys, external photoevaporation works most efficiently at the end of the embedded phase; the relative importance of these two effects should be determined in the future.

The observational statistics of DPS sizes in compact and/or open clusters are still scarce, so comparing our results with observations has to be done with great care. The estimated sizes vary in the range of a few au up to roughly 40 au; see Table 3. We can conclude that the overall median DPS sizes found in our simulations (11 au and 21 au) agree surprisingly well with the sizes of DPS found in open clusters (14–40 au; see Tables 1 and 3).

It should be emphasized that the clusters in Table 3 differ considerably from those in clusters in the solar neighborhood, such as the ONC. The Arches cluster at 7 kpc might be a bit far away, but in clusters like NGC 3606 the disk sizes might be possible to determine with ALMA. However, the above results restrict not only the disk sizes in such compact clusters but also the sizes of the planetary systems that can form and survive in such hostile environments. Our simulations predict also that planetary systems in such environments will usually have sizes of $< 10$ au, and it will basically be impossible for systems with sizes of 100 au to form and survive in open clusters.

Observations show disk sizes of 27–500 au in the ONC and $\geq 3–12$ au in the Arches cluster (Eisner et al. 2008; Stolte et al. 2010). A comparison with the solar system puts these sizes in perspective. Neptune orbits at an approximate distance of 30 au from the Sun. However, every fourth protoplanetary disk and/or planetary system in such open cluster progenitors has a size of less than 30 au (model C1). A size of 21 au corresponds roughly to the distance to Uranus, and 11 au is just outside Saturn’s orbit.

### Table 3
Observed Properties of Disks in Open Clusters

| Name       | Cluster Properties | Disk Properties | References |
|------------|--------------------|-----------------|------------|
|            | $t_d$ (Myr) | $M_d$ (10$^3$ $M_\odot$) | No. | $R_{disk}$ (au) |
| NGC 2362   | 4–5     | $>0.5$          | 4   | 6.2–40.9$^a$   | (1), (2) |
| h/γPersei  | 13 ± 1  | $\geq 4/3$      | 10  | 1.0–38.4       | (3), (4) |

Note. Columns (1)–(3): cluster name, its age $t_d$, and its mass $M_d$. Column (4): number of observed disks. Column (5): (dust) disk radius $R_{disk}$. Column (6): references. References: (1) Dahm 2005; (2) Currie et al. 2009 and references therein; (3) Slesnick et al. 2002; (4) Currie et al. 2008.

$^a$ Lower dust radius for 200 K and upper dust radius for 120 K.
Another question is how many of these small disks contain sufficient material to form planets or even planetary systems. As the 23 observed planets in open clusters show, obviously at least some do. Two of those planets even form a planetary system consisting of a hot Jupiter and a very eccentric Jupiter-like planet. However, we expect that these planetary systems differ considerably from those found around field stars. So systems with planets on orbits 100 au wide should be very rare or even nonexistent unless they were captured from another star (Jilková et al. 2015).

In addition, many of the systems should have sharp outer edges like our own solar system (Pfalzner et al. 2018b), and the orbits of the outer planets should often be very eccentric and inclined relative to the inner system. Actually, one planetary system found so far in an open cluster looks just like we would predict from our simulations: the outer planet moves on a highly eccentric orbit with $a_{\text{ol}} \leq 5.5$ au (Pfalzner et al. 2018a). This is exactly the kind of planetary system that we would expect to dominate in such open cluster environments.

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Appendix A

Inclined versus Coplanar, Prograde Flybys

The size of a disk around a star with mass $m_1$ after a flyby with a star of mass $m_2$ at a periastron distance of $r_{\text{peri}}$ has been recently investigated numerically in two large parameter studies. The first, by Breslau et al. (2014), analyzed a thin disk of massless tracer particles around a star after it was perturbed by a second star on a coplanar, prograde orbit with respect to the disk. They found a simple description of the disk size after such a flyby depending on the mass ratio of the two stars ($m_{12} = m_2/m_1$) and the periastron distance:

$$r_{\text{disk}}^{\text{copl}} = \begin{cases} 0.28 \cdot r_{\text{peri}} \cdot m_{12}^{-0.32}, & \text{if } r_{\text{disk}} < r_{\text{previous}} \\ r_{\text{previous}}, & \text{if } r_{\text{disk}} \geq r_{\text{previous}} \end{cases}$$

where $r_{\text{previous}}$ is the disk size previous to the flyby in au.

This parameter study was extended by Bhandare et al. (2016) by including flybys of different inclinations, that is, different angles between the disk plane and the plane of the perturber’s orbit. Averaging over all inclinations for one set of $(m_{12}, r_{\text{peri}})$, they obtained the following fit formula:

$$r_{\text{disk}}^{\text{avg}} = \begin{cases} 1.6 \cdot r_{\text{peri}}^{0.72} \cdot m_{12}^{-0.2}, & \text{if } r_{\text{disk}} < r_{\text{previous}} \\ r_{\text{previous}}, & \text{if } r_{\text{disk}} \geq r_{\text{previous}} \end{cases}$$

This formula describes flybys with mass ratios of 0.3–50.0 and up to periastron distances of five times the initial disk size $r_{\text{init}}$. However, the focus of the fit was disk-penetrating and close flybys (roughly up to two times $r_{\text{peri}}$). In stellar clusters, even in the most compact ones, flybys with larger periastron distances and/or high mass ratios are still the most frequent type of flyby. Despite the distance, these flybys can lead to disk truncation if the mass ratio is large (see also Scally & Clarke 2001; Olczak et al. 2006). To be able to describe such distant flybys more precisely, we have performed additional encounter simulations, analog to the ones by Bhandare et al. (2016): a disk of $10^6$ massless tracer particles was set up around a star, and a second star passed by, removing particles from the disk and reshaping the remnant disk. The disk size after such an encounter was chosen to be the steepest point in the time-averaged density distribution. The initial disk size was set to 200 au, with mass ratios of 0.3–50, and all inclinations ($0^\circ–180^\circ$) were covered. Periastron distances between 400 au and 1000 au were covered in steps of 50 au to obtain a better resolution than before in this parameter range, which is important for our simulations; see Figure 8. In this case the points for closer flybys were excluded from the fit:

$$r_{\text{disk}} = \begin{cases} (1.6 \cdot m_{12}^{-0.2} - 1.26 \cdot m_{12}^{-0.182}) \cdot r_{\text{peri}}, & \text{if } r_{\text{disk}} < r_{\text{previous}} \\ r_{\text{previous}}, & \text{if } r_{\text{disk}} \geq r_{\text{previous}} \end{cases}$$

Note that self-gravity and viscosity within the disk were neglected. More details about the simulation setup, the disk size determination, and the influence of the above-made assumptions are given in Breslau et al. (2014) and Bhandare et al. (2016).
Appendix B

Average Disk Size after Randomly Oriented Flybys

With the fit formula above, we can now quantify the difference in disk size obtained assuming flybys to be coplanar to those where it is assumed that all inclinations are equally likely. Figure 9 depicts the median disk size after 10 Myr, (1) where all flybys were assumed to be prograde and coplanar, using the disk size description by Breslau et al. (2014) (hatched boxes), and (2) taking into account all inclinations using the average disk size as defined by Equation (6) above (filled boxes).

As expected, the median disk size of randomly orientated flybys is larger than for purely coplanar, prograde ones in all cluster models. The absolute difference is actually quite small, especially in the compact clusters. Nevertheless, in relative terms, the median disk size increases by 23% comparing coplanar to randomly orientated flybys, independently of the cluster.

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