1. INTRODUCTION

The origin of brown dwarfs (BDs), to which we also include very low mass stars (<0.1 \( M_\odot \)) as well as the formation of massive exoplanets is contentious. The most common idea is that BDs form like stars, and planets form by accretion onto a core formed from dust conglomerate within a circumstellar disk. However, there is increasing evidence that an alternative formation scenario for BDs and, possibly, some of the most massive exoplanets is required. BDs differ from low-mass stars in several ways. First, there is the “BD desert”—a lack of BD companions to stars, especially at separations below about 30 AU within which companion planets and stars are common. In addition, the properties of BD–BD binaries are very different from star–star binaries, showing a significant lack of systems wider than \( \approx 20 \) AU beyond which most stellar binaries are found. Furthermore, while typically every second star is a binary system only every fifth BD is a binary. Clearly, we must ask ourselves why stars and BDs are so different if they form by the same mechanism. Indeed, in order to numerically set up a realistic stellar and BD population, stars and BDs need to be according to different algorithmic pairing rules (Kroupa et al. 2003). In other words, they follow different formation channels.

The fragmentation of extended circumstellar disks is one of the most promising alternatives to the standard scenario of star-like formation for BDs (Goodwin & Whitworth 2007). Research on circumstellar disk evolution has made great progress in recent years, but there are still many unanswered questions (Papaloizou & Terquem 2006; Henning 2008; Hillenbrand 2008). One issue that has gained surprisingly little attention in the past is the role of gravitational interactions between the disk and passing stars within the young host stellar cluster. Since stars are generally born in clusters (Forgan & Rice 2009), rather than as isolated objects, star–disk and disk–disk interactions (Boffin et al. 1998; Watkins et al. 1998a; Pfalzner et al. 2005; Thies et al. 2005) probably play an important role for the dynamical evolution of such disks and thus for massive planet and BD formation through fragmentation of the disks.

For a typical open star cluster hosting about 1000 stars within a half-mass radius of 0.5 pc, encounters closer than 500 AU will happen approximately every 10 Myr (Thies et al. 2005). They are even more frequent in denser clusters in which they are thought to form at least half of the stars in the Galaxy. Encounters in star clusters are therefore expected to play a significant role in the evolution of extended disks of several 100 AU radii.

The formation of planets through core accretion is typically expected to happen within the innermost 100 AU of a circumstellar disk (Hillenbrand 2008), although there are many unanswered questions especially concerning the very first stages of core accretion (Henning 2008). Fragmentation has been proposed as an alternative way to form the most massive gas giant planets by Mayer et al. (2002) and Boss (1997, 2004, 2006). In recent years, however, there has been a growing consensus that disk fragmentation cannot produce gas giant planets in the inner regions of disks for two reasons: (1) heating from the central star stabilizes the innermost regions and thus inhibits fragmentation and (2) these regions cannot cool fast enough to allow temporary gas clumps to collapse (Stamatellos & Whitworth 2008; Lodato et al. 2007; Cai et al. 2010). This picture changes greatly beyond about 100 AU where cooling becomes sufficiently efficient for gravitational collapse to occur. Consequently, disk fragmentation has been proposed as an alternative mechanism for the formation of BDs (Whitworth...
and the average number, \( n_{\text{enc}} \), of encounter parameters below \( b \), for a given number of stars, \( N \),

\[
n_{\text{enc}}(<b) = \frac{N}{b^2} \frac{b^2}{r_{\text{grav}}^2} .
\]  

\( t_{\text{enc}} \) is approximately given by

\[
t_{\text{enc}} = \frac{2.4 \times 10^{13}}{N} \left( \frac{M_{\text{tot}}}{M_\odot} \right)^{-1/2} \left( \frac{r_{1/2}}{\text{pc}} \right)^{7/2} \left( \frac{b}{\text{AU}} \right)^{-2} .
\]  

It has to be noted that the actual periastron distance, \( r_{\text{peri}} \), is always (and sometimes significantly) smaller than \( b \) due to gravitational focusing. The relation between \( r_{\text{peri}} \) and \( b \) for a given eccentricity, \( e \), is

\[
r_{\text{peri}} = \sqrt{\frac{e - 1}{e + 1}} b .
\]  

For an ONC-type cluster with \( N = 7500 \), an average star mass \( M_* = 0.5 M_\odot \), a total mass \( M_{\text{tot}} = 10000 M_\odot \) (i.e., 30% of the mass consists of stars and the rest of gas, see Kroupa et al. 2001), and a half-mass radius of \( r_{1/2} = 0.5 \text{ pc} \), we find that encounters below 500 AU occur on average every 11 Myr. If a massive extended disk exists for about 1 Myr, this means that about 9% of all disks of this type will suffer such an encounter. See also Thies et al. (2005).

### 2.2. Disk Model

The initial conditions for the disk are taken from Stamatellos & Whitworth (2008, 2009a). The disk model has a power law profile for temperature, \( T \), and surface density, \( \Sigma \), from Stamatellos & Whitworth (2008), both as a function of the distance, \( R \), from the central star,

\[
\Sigma(R) = \Sigma_0 \left( \frac{R}{\text{AU}} \right)^{-q_\Sigma} ,
\]  

\[
T(R) = \left[ T_\odot^2 \left( \frac{R}{\text{AU}} \right)^{-2q_T} + T_\infty^2 \right]^{1/2} .
\]
where \( q_\Sigma = 1.75 \), \( q_r = 0.5 \), and \( T_0 = 300 \) K. \( \Sigma_0 \) is chosen corresponding to a disk mass of 0.48 and 0.50 \( M_\odot \) (see Table 1), i.e., \( \Sigma_0 = 8.67 \times 10^4 \) g cm\(^{-2} \) and \( \Sigma_0 = 9.03 \times 10^4 \) g cm\(^{-2} \), respectively. \( T_\infty = 10 \) K is a background temperature to account for the background radiation from other stars within the host cluster. This configuration leads to an initial Toomre stability parameter, \( Q \) (Toomre 1964) between 1.3 and 1.4 between about 100 and 400 AU, leading to weak spiral density patterns but not to fragmentation. \( Q \) is given by

\[
Q = \frac{c_s \kappa}{\pi G \Sigma},
\]

with \( c_s \) being the sound speed and \( \kappa \) being the epicyclic frequency which can be, at least roughly, approximated by the Keplerian orbital frequency. The radiation of the perturber is included in the same way as that of the central star, assuming a mass-to-luminosity relation of \( L \propto M^4 \) for low-mass stars. However, as long as the perturber is no more than about 0.5 \( M_\odot \), corresponding to an early M-type or late K-type main-sequence star, its influence on disk evolution is very small.

The disk is initially populated by SPH particles between 40 and 400 AU. Before starting the actual encounter computation, the disk is allowed to "settle" for about 20,000 years (i.e., about two orbits at the outer rim) to avoid artifacts from the initial distribution function. During this settling, the disk smears out at the inner and the outer border extending its radial range from a few AU up to \( \geq 500 \) AU, eventually stabilizing. The \( Q \) value is slightly increased beyond 200 AU relative to the initial setting while remaining largely unchanged below this radius, as can be seen in Figure 1. The actual surface density after the settling is therefore slightly smaller and thus the disk slightly more stable than in the initial setup. Any self-fragmentation of the unperturbed disk would have happened during the settling time when the Toomre parameter is lowest.

### Table 1

| Model  | \( N/1000 \) | \( M_\ast (M_\odot) \) | \( M_D (M_\odot) \) | \( M_{\text{pert}} (M_\odot) \) | \( r_{\text{pert}} (\text{AU}) \) | \( e \) | \( \iota \) (deg) | \( m_{\text{envpert}} (M_\odot) \) | \( N_{\text{formed}} \) | \( N_{\text{ejected}} \) | Binaries |
|--------|-------------|-----------------|-----------------|-----------------|-----------------|-----|-------------|-----------------|-----------------|-----------------|---------|
| E002   | 100         | 1.00            | 0.50            | 0.50            | 500             | 1.1 | 10          | 11.7             | 4               | 1               | ...     |
| X002   | 250         | 1.00            | 0.50            | 0.50            | 500             | 1.1 | 10          | 12.0             | 5               | 2               | 1 \( \approx 4 \text{ AU} \) |
| Y002   | 250         | 1.00            | 0.50            | 0.50            | 500             | 1.1 | 10          | 10.2             | 3               | ...             |         |
| E003   | 100         | 0.75            | 0.48            | 0.50            | 500             | 1.1 | 10          | 16.1             | 3               | 2               | 1 \( \approx 2 \text{ AU} \) |
| X003   | 250         | 0.75            | 0.48            | 0.50            | 500             | 1.1 | 10          | 12.6             | 4               | 1               | ...     |
| E004   | 100         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 10          | 5.6              | 2               | ...             |         |
| X004   | 100         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 10          | 11.0             | 3               | ...             |         |
| E006   | 100         | 0.75            | 0.48            | 0.50            | 500             | 2.0 | 10          | 4.8              | 2               | ...             |         |
| X006   | 250         | 0.75            | 0.48            | 0.50            | 500             | 2.0 | 10          | 4.4              | 3               | 1 \( \approx 4 \text{ AU} \) |         |
| E007   | 100         | 0.75            | 0.48            | 0.50            | 500             | 3.0 | 10          | 2.1              | 0               | ...             |         |
| E008   | 100         | 0.75            | 0.48            | 0.50            | 600             | 1.5 | 10          | 2.8              | 0               | ...             |         |
| F008   | 100         | 0.75            | 0.48            | 0.50            | 600             | 1.1 | 10          | 6.5              | 0               | ...             |         |
| E009   | 100         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 30          | 3.0              | 3               | ...             |         |
| X009   | 250         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 30          | 7.6              | 4               | ...             | 1       |
| E010   | 100         | 0.75            | 0.48            | 0.50            | 550             | 1.5 | 10          | 4.1              | 3               | ...             |         |
| X010   | 250         | 0.75            | 0.48            | 0.50            | 550             | 1.5 | 10          | 8.8              | 4               | ...             |         |
| E011   | 100         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 45          | 7.6              | 6               | ...             | ...     |
| F011   | 100         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 45          | 4.2              | 2               | ...             | ...     |
| X011   | 250         | 0.75            | 0.48            | 0.50            | 500             | 1.5 | 45          | 6.1              | 2               | ...             | ...     |
| E015   | 100         | 0.75            | 0.48            | 0.40            | 400             | 1.5 | 45          | 7.9              | 3               | ...             | ...     |
| E016   | 100         | 0.75            | 0.48            | 0.40            | 400             | 1.5 | 45          | 10.4             | 2               | ...             | ...     |

Total \( N = 100000 \) (10 of 13 models showing fragmentation): 30 3 1
Total \( N = 250000 \) (8 of 8 modes showing fragmentation): 28 3 3
Grand total (18 of 21 models showing fragmentation): 58 6 4

**Notes.** Overview of our SPH computations. The columns (from left to right) show the computation ID, the number of gas particles in thousands, the mass of the central star, and its disk and the perturbing star. Then follows the periastron distance of the encounter, the eccentricity, and inclination. The four rightmost columns show the amount of gas captured by the perturber in a circumstellar envelope within a radius 40 AU, the number of formed binaries, and the number of bodies that got ejected during the calculation as well as the number of binary systems. In all models, except for E015 and E016 the perturbing star has 0.5 \( M_\odot \) and passes the central star on an initially hyperbolic orbit with initial eccentricity between 1.1 and 3.0 and inclination to the disk plane between 10° and 45°.

3. METHODS

3.1. Smoothed Particle Hydrodynamics (SPH)

All computations were performed by using the well-tested DRAGON SPH code by Goodwin et al. (2004) including the radiative transfer extension by Stamatellos et al. (2007b). Most of the numerical parameter settings have been adopted from Stamatellos et al. (2007a) and Stamatellos & Whitworth (2009a). Gravitationally collapsing clumps are treated by sink particles which form if the volume density exceeds \( 10^{-5} \) g cm\(^{-3} \), and the clump is bound. The sink radius is 1 AU, in accordance with the studies mentioned above and in agreement with the local Jeans criterion. In addition, the central star and the perturbing star are both represented by sink particles.

There are ongoing discussions whether fragmentation can be triggered artificially due to the numerical behavior of SPH and grid-based hydrocodes. Hubber et al. (2006) find that SPH does not suffer from artificial fragmentation. However, Nelson (2006) suggests that SPH may artificially enhance fragmentation due to a pressure-underestimation if the smoothing radius, \( h \), is considerably larger than about one-fourth of a vertical scale.
height of a circumstellar disk. Stamatellos & Whitworth (2009b) show that this criterion is fulfilled for 150,000 or more particles for the types of disk studied in this paper.

Commerçon et al. (2008) have performed calculations of fragmenting protostellar clouds with the adaptive mesh refinement (AMR) code RAMSES and the SPH code DRAGON (which we have been using for this study) and compared the results at different resolutions given by the number $N$ of grid cells and particles, respectively. For about $N = 5 \times 10^5$ cells/particles, fragmentation in both codes appeared nearly equal. With $N = 2 \times 10^5$, the results were very similar to the high-resolution AMR computations while being still acceptable for many purposes at $N = 1 \times 10^5$. Stamatellos & Whitworth (2009b) briefly review the resolution criteria with respect to their models using 150,000 in that paper and 250,000 to 400,000 particles earlier (Stamatellos & Whitworth 2009a).

The three most important resolution criteria are the resolution of the local Jeans mass, $M_J$, (and thus the Jeans length), the local Toomre mass, and the vertical scale height of the disk. In particular, the local Jeans mass,

$$M_J = \frac{4\pi^{5/2} \varepsilon^3}{24 \sqrt{G^3 \rho}},$$

must be resolved by at least a factor of $2 \times N_{\text{neigh}} = 100$, corresponding to 0.5 $M_J$ for the 100,000 particle disks and 0.2 $M_J$ for the 250,000 particle disks. Since the global disk setup as well as the evolution after the perturbation (Section 4) is quite similar to that used by Stamatellos & Whitworth (2009b), a similar range of Jeans masses of the forming clumps, i.e., $\sim 2$–20 $M_J$, can be reasonably assumed for our models and has actually been tested for the models E/X002 and E/X009 for all forming objects. The minimum $M_J$ during the clump formation is typically between 4 and 6 $M_J$ and is never below about 2 $M_J$. Therefore, $M_J$ is resolved by a safe factor of at least 4 in the low-resolution case and 10 in the high-resolution case. Accordingly, the minimum Toomre mass of 2.5 $M_J$ as well as the vertical scale height (by at least a few smoothing lengths) is adequately resolved.

### 3.2. Radiative Transfer Model

In Thies et al. (2005), the possibility of fragmentation has been estimated via the Toomre criterion for both isothermal and adiabatic equations of state, both resulting in perturbed regions with highly unstable conditions ($Q < 1$). However, Toomre instability does not necessarily lead to actual fragmentation.

In realistic models of radiative transfer, such as the ones used here, the thermal response of the gas to density changes is between near-isothermal in regions with efficient cooling (outside about 100–200 AU) and near-adiabatic in regions with long cooling times (the inner parts of the disk). Shen et al. (2010) have shown that direct disk–disk collisions may lead to fragmentation of massive extended disks at some 400 AU even for a “thick disk approximation,” i.e., the near-adiabatic case.

The Stamatellos et al. (2007b) method uses the density and the gravitational potential of each SPH particle to estimate an optical depth for each particle through which the particle cools and heats. The method takes into account compressional heating, viscous heating, radiative heating by the background, and radiative cooling. It performs well, in both the optically thin and optically thick regimes, and has been extensively tested by Stamatellos et al. (2007b). In particular, it reproduces the detailed three-dimensional results of Masunaga & Inutsuka (2000), Boss & Bodenheimer (1979), Boss & Myhill (1992), and Whitehouse & Bate (2006), as well as the analytic results of Spiegel (1957). Additionally, the code has been tested and performs well in disk configurations as it reproduces the analytic results of Hubeny (1990).

The gas is assumed to be a mixture of hydrogen and helium. We use an equation of state by Black & Bodenheimer (1975), Masunaga et al. (1998), and Boley et al. (2007) that accounts (1) for the rotational and vibrational degrees of freedom of molecular hydrogen and (2) for the different chemical states of hydrogen and helium. We assume that ortho- and para-hydrogen are in equilibrium.

For the dust and gas opacity, we use the parameterization by Bell & Lin (1994), $\kappa(\rho, T) = \kappa_0 \rho^n T^b$, where $\kappa_0$, $a$, and $b$ are constants that depend on the species and the physical processes contributing to the opacity at each $\rho$ and $T$. The opacity changes due to ice mantle melting, the sublimation of dust, molecular, and H− contributions are all taken into account.

### 3.3. Overview of Calculations

We have conducted 13 SPH calculations using 100,000 and 8 using 250,000 SPH particles (i.e., 21 models in total) corresponding to about nine CPU months in total on 16 core machines. The model identifiers that begin with an “E” or an “F” refer to the low-resolution models while the models with “X” or “Y” are the high-resolution ones. Subsequent letters with identical numbers correspond to follow-up calculations (beginning at the moment of the closest encounter) with identical model settings. Due to the dynamical interaction of the parallel computing CPUs, a slight random perturbation is imposed to the subsequent evolution such that the outcome differs within the statistical noise. The high-resolution calculations are set up with parameters of preceding lower-resolution models that showed fragmentation. Therefore, the fact that all high-resolution computations show fragmentation is due to the parameter selection. The low-resolution calculations are used as a parameter survey while the high-resolution ones are follow-ups to selected low-resolution ones. Please note that not all non-fragmenting models are listed here but only those that represent the borders of the parameter space between fragmentation and no fragmentation.

We chose a 0.5 $M_\odot$ perturbing star as a typical member of a star cluster (Kroupa 2001) for the majority of models, but we also performed calculations with perturbers down to 0.3 $M_\odot$. The encounter orbit is slightly inclined ($i = 10^\circ$ against the initial disk plane) with varying eccentricities from $e = 1.1$ (near-parabolic) to $e = 2$ (hyperbolic), corresponding to a relative velocity of 0.4–2.7 km s$^{-1}$ at infinity. For these parameters, the disk typically fragments to form a few very low mass stars and substellar-mass objects. A calculation with $e = 3$ has been performed but yielded no fragmentation. The same holds true for encounters at 600 AU or more. Depending on the eccentricity, the calculations start 5000–10,000 years before periastron to ensure a sufficiently low initial interaction. The calculations continue for 15,000 years after encounter for the models E/X/Y002 and at least 20,000 for the others. The masses and orbital radii of the objects formed in the calculation are determined at this time. After 15,000 years, the accretion process of the objects has largely finished while dynamical evolution may still lead to major changes of the orbital parameters (and even to ejections of some bodies) if the calculations would have been continued over a longer time interval. For this reason, the orbital separations computed in this study have to be taken as a preliminary state.
It has to be noted that the orbit is altered slightly during the passage due to the transfer of mass and angular momentum. Furthermore, since the encounter dissipates energy, the post-encounter speed is typically lower than the pre-encounter speed and in some cases both stars may be captured in an eccentric binary (which actually happened to the companions 1a and 1b in calculation E003; see Table 1 and Figures 3 and 4). We found, however, that these effects are small.

4. RESULTS

4.1. General Findings

As the unperturbed disk is marginally stable, it does not fragment until the passage of the perturbing star. The first visible effects of a typical fly-by are the appearance of tidal arms and a mass transfer to the passing star (which acquires a small disk). About 2000–3000 years after the periastron passage, parts of the tidal arms become gravitationally unstable and spiral-shaped overdensities begin to form (see the snapshots from model X002 in Figure 2\(^4\)). Some of these continue to contract into a runaway collapse and form bound objects represented by sinks (see Section 3). This typically happens at radii between 100 and 150 AU from the central star with some clumps forming even around 200 AU. Temporary overdensities do also occur within less than 100 AU but, however, dissolve quickly. This is probably due to the heating from the central star and the less effective cooling in these regions as already mentioned in the Introduction and by Whitworth & Stamatellos (2006) and Goodwin & Whitworth (2007). At radii larger than about 200 AU, on the other hand, the gas density is apparently too low for gravitationally bound clumps to form.

Each of the calculations typically produces between two and five (six in one case) low-mass objects with masses between those of very massive planets (0.01 \(M_\odot\)) and very low mass stars (0.13 \(M_\odot\)). Additionally, mass is accreted onto the central star and also mass is transferred to the perturber during the encounter. In the model shown in Figure 2, five objects with masses between 0.013 \(M_\odot\) and 0.10 \(M_\odot\) form: two of them being bound in a binary system. In addition 0.016 \(M_\odot\) of gas accretes onto the central star within 15,000 years, and 0.0028 \(M_\odot\) = 2.8 Jupiter masses (\(M_J\)) of gas transfers to the perturber (into the representing sink particle) while about 0.012 \(M_\odot\) (\(\approx 12 M_J\)) is captured around the perturber as a circumstellar envelope. In our analysis, any gas that is present within a radius of 40 AU but outside the sink radius is counted as circumstellar material of the perturber and shown in the ninth column of Table 1. This mass capture is typical, ranging between 2 and 16 \(M_J\).

In total, 28 bodies between 0.01 and 0.15 \(M_\odot\) formed in eight high-resolution calculations, while the ten 100,000 particle calculations that showed fragmentation yielded 30 bodies between 0.01 and 0.16 \(M_\odot\) (see Tables 1 and 2). Thus, there is no statistically significant relation between the resolution and the number of formed bodies. Similarly, no clear trend toward lower minimum masses of the companions for the high resolution can be derived from the current data. The average mass of the

\(^4\) Supplementary content like movies from our calculations can be downloaded from the AIfA download page.

http://www.astro.uni-bonn.de/~webaiub/german/downloads.php
(a) 8000 yr
(b) 9500 yr
(c) 11000 yr
(d) 11800 yr
(e) 13600 yr

Figure 4. Snapshots of another forming binary at about 12,000 years after the fly-by. The components of the remaining VLMS–BD pair have very unequal masses of 0.09 $M_\odot$ and 0.013 $M_\odot$ (with a mass ratio $q = 0.14$). In contrast to the binary formed in X002 (Figure 2), these bodies became bound due to a frictional encounter of their accretion envelopes.

(A motion and a color version of this figure are available in the online journal.)

The lowest mass member is 0.056 $M_\odot$ for the 100,000 particle models while it is 0.044 $M_\odot$ for the 250,000 ones. Similarly, the average mass of the highest-mass member is 0.097 $M_\odot$ and 0.083 $M_\odot$, respectively. Table 2 also shows the separations of the objects at the end of each calculation. It has to be noted that these can differ largely from the initial separation at the moment of formation. Dynamical interaction between the objects and the disk as well as mutual encounters pushes some bodies at wide and eccentric orbits or even eject them while others migrate closer to the star. The closest separation observed in our calculations is about 10 AU in model E015 after 15,000 years of evolution. The overall outcome is very similar to that of unperturbed self-fragmenting disk as shown in Stamatellos & Whitworth (2009b) except for the lower disk mass. This is quite plausible since the main difference between the two scenarios is the cause for the density patterns which undergo fragmentation.

While Toomre density waves are the source of fragmentation in self-fragmenting disks, the gravitationally induced fragmentation occurs in tidal arms. In both cases, a dense bar-like in the disk reaches the density limit for fragmentation and thus the underlying physics is essentially the same.

Figure 5 shows the mass distribution of the $n$ bodies created in all calculations with 100,000 particles (top frame), 250,000 particles (middle frame), and both combined (bottom frame). A power-law mass function $dn/dm = k (m/M_\odot)^{-\alpha}$ can be fitted to this distribution. This has been done in Figure 5 for the substellar regime (dashed line). In the bi-logarithmic scaling, the slope of $d \log n/d \log m$ corresponds to $1 - \alpha$ due to the differentiation of the logarithm (see Thies & Kroupa 2007 for details). The linear fit to the mass function for all combined calculation outputs
appears to have a slope of 0.9$^{+0.3}_{-1.0}$ ($<0.16 \, M_\odot$) corresponding to power-law index of $\alpha = -0.1^{+0.3}_{-1.0}$. If the calculations are separated by resolution, the 100,000 particle models correspond to $\alpha = +0.1^{+0.3}_{-0.2}$ while the 250,000 particle models similarly yield $\alpha = +0.1^{+0.3}_{-0.2}$. The slightly flatter initial mass function (IMF) in the separate mass functions may be interpreted as a weak resolution dependence of the average created mass which gets smeared out in the combined mass function. However, the difference between the slopes of 0.2 is within the 1$\sigma$ uncertainty. The uncertainty, based on the Poisson errors of the log mass bins, is indicated by a shaded region. Above 0.12 $M_\odot$ there is a sharp drop in the mass distribution that can be treated as a truncation. Similar results have been obtained by Stamatellos & Whitworth (2009a) and Shen et al. (2010). Interestingly, this is also in good agreement with both the substellar IMF deduced by Kroupa (2001) as well as the separate substellar IMF deduced in Thies & Kroupa (2007, 2008). However, more calculations are needed to provide statistically robust tests of the IMF. Furthermore, there is no weighting with respect to the different likelihood of the different encounter settings (i.e., inclination, fly-by distance, etc.). Since the outcome of the computations does not show a specific dependency on the orbital parameters (except for whether there is fragmentation) such a weighting might introduce an artificial bias by amplifying the random noise of higher-weighted models.

4.2. Binary Formation

In the same way as in the models of Stamatellos & Whitworth (2009a) of isolated circumstellar disks, very low mass binary systems can also form in gentle three-body encounters between low-mass objects in the disk. Such a triple in-orbit encounter occurred during the X002 computation about 8000 years after the fly-by, as shown in Figure 3 where a 4 AU binary system composed of 0.09 $M_\odot$ and 0.10 $M_\odot$ objects forms through a triple encounter. This binary remains bound to the host star in an orbit of about 100 AU. These separations are consistent with the observations of VLMS binaries according to which the most probable separation is around 3 AU (see, e.g., Figure 10 in Stamatellos & Whitworth 2009a). Another binary-forming mechanism was unveiled during calculation E003 (see Table 2). A 2 AU binary, consisting of a VLMS of 0.09 $M_\odot$ and a BD with 0.013 $M_\odot$, formed through a grazing encounter of circumstellar accretion envelopes, which subsequently evolve into a circumbinary disk. The event is shown in a sequence plot in Figure 4. In two similar events in run X006, two accreting clumps merged to a single one of about 0.03 $M_\odot$ 9600 years after the fly-by, and 6000 years later this body and a third one got captured into a binary of about 5 AU separation, probably involving both triple encounter and grazing collision. The masses at the end of the calculation are 0.03 and 0.04 $M_\odot$.

Binaries formed via these processes may later be separated from their host star in a subsequent encounter with another star as already discussed for single substellar companions (Kroupa 1995; Goodwin & Whitworth 2007) or, possibly, by dynamical interaction with more massive companions in the same system. These models produce 55 systems of BDs and VLMSs, and three binaries giving a binary of $3/55 = 0.05$, whereby the binaries have semimajor axes of 4, 2, and 5 AU. Thus, while the separations are quite consistent with the observed VLMS and BD binaries, the present theoretical binary fraction is somewhat low.

4.3. The Role of Eccentricity and Inclination

In a previous study (Thies et al. 2005), we found that the strength of the perturbation increases with decreasing eccentricity and inclination. This agrees with results of an SPH parameter study by Pfalzner et al. (2005). While disk–disk collisions produce most objects due to shock formation (Shen et al. 2010), coplanar encounters increase the effectiveness of the tidal perturbations which cause our disks to fragment. This is a consequence of the low relative velocity between the perturber and the perturber-facing parts of the disk in coplanar encounters and thus a longer tidal exposure time. While drag forces in disk–disk collisions are larger for larger collisional velocities, the tidal force does not depend on the velocity, and therefore the total amount of tidally transferred momentum for a given fly-by distance is larger for slower encounters, i.e., for those with lower eccentricity.

5. DISCUSSION

Our computations show that the tidal perturbations of massive (otherwise stable) disks can form massive planets and BDs. Previous computations had assumed the interaction of two massive disks (Shen et al. 2010), reducing the probability of such an event dramatically. Our scenario only requires a single extended disk. This scenario can produce very low mass companions at large distances from the primary star and may help explain recent direct detections of massive planets orbiting at >100 AU, far beyond where core accretion could have formed them\(^5\), as well as intermediate (Liu et al. 2002) and distant

\(^5\) See also the Extrasolar Planets Encyclopaedia, http://exoplanet.eu/.
(Stamatellos et al. 2007a; Stamatellos & Whitworth 2009a) BD companions to stars. Like Stamatellos & Whitworth (2009a), we are also able to form BD binaries through three-body encounters within the disk and, in addition, through dissipative encounters. But the required disk mass is considerably smaller, by about 30%–40%, since even initially stable disks do form upon perturbation in our calculations. The mass function of companions formed by this process is in good agreement with that of self-fragmentation, and with the separate substellar IMF deduced in Thies & Kroupa (2007). However, the volume of the current results does not allow robust statistical tests of the normalization of this substellar IMF relative to the stellar IMF. Nevertheless, the obtained results are in remarkable agreement both with the form of the substellar IMF and the binary properties in the BD and VLMS regime, although the binary fraction is somewhat low (Section 4.2). More computations will have to be performed at different resolutions (up to a million particles) to enhance quality as well as quality of the data.

5.1. How Often Do Such Encounters Occur?

Furthermore, it has to be noted that triggered fragmentation is probably responsible only for a fraction of disk-fragmentation events while a good fraction may be triggered simply by overfeeding of an accreting disk toward self-fragmentation. Although the borders of the parameter subspace suitable for triggered fragmentation are not yet fully determined, the current findings show that encounters of a higher inclination than 45°, outside 600 AU or with eccentricities above 2, are generally unlikely to trigger fragmentation for the disk type studied here. The same holds true for perturbers of less than 0.3 M⊙.

By combining all these limits of the parameter space, one can estimate the fraction of random encounters with a mutual periastron below 500 AU that are suitable for fragmentation of the analyzed disk type. If a characteristic velocity dispersion of ~2 km s⁻¹ and an upper stellar mass limit of 10 M⊙ within the host cluster are assumed, only about 3% of all encounters below 500 AU lead to fragmentation. However, disks with even only slightly larger mass or lower background temperature may be pushed much easily to fragmentation, probably enlarging the parameter space significantly. Furthermore, other perturbing effects like stellar winds or supernova shock waves, which might influence large volumes within the host cluster at once, are not covered by this study, nor are the effects of dust.

5.2. Consequences for Planet Formation

All objects formed in our calculations have masses above 0.01 M⊙ or 10 M⊕ and are thus above the masses typically assumed for planets. However, we cannot rule out at the moment that also objects below 0.01 M⊙ may form through fragmentation, especially around lower-mass host stars which heat the inner disk region much less than more massive ones. Another critical point may be the resolution limits (although the local Jeans mass is well resolved even in the inner disk region, as discussed in Section 3.1).

It has to be emphasized that planet formation probably typically takes place in the inner disk region through core-accretion (Hillenbrand 2008), which is less influenced by the perturbation unless companions formed through it migrate into these inner regions. There might still be significant impacts on the outcome of planet formation for stellar encounters, though. Even temporary gravitational instabilities that do not collapse into a BD or planet directly may induce the formation of substellar companions down to Kuiper Belt Objects by induced vorticity and subsequent dust trapping (Barge & Sommeria 1995; Klahr & Bodenheimer 2003, 2006). Also the development of baroclinic vortices may be altered under the influence of tidal perturbations, either inhibiting or promoting the formation of dust aggregates. This mechanism may even work in typical protoplanetary disks and is a subject of our ongoing research. According to solar system architecture (Heller 1993; Eggers et al. 1997; Kenyon & Bromley 2004) and radioastral evidence (Takigawa et al. 2008; Sahijpal & Gupta 2009; Gaidos et al. 2009; Gounelle & Meibom 2008, however, disagree), the highly probable origin of our Sun in a large star-forming region further emphasizes the importance of such scenarios.

Another fact worthy of being discussed is the capture of disk material by the perturbing star. As mentioned in Section 4, about 0.003 M⊙ = 3 Mj are accreted by the perturber in a typical 500 AU encounter-like model E/X002, while the amount of accreted gas can be as large as 10 Mj, as in models E/X003 (see Table 1). An even larger amount can be contained in a circumstellar disk or envelope around the perturber. Although being smaller than typically assumed for the minimum-mass solar nebula (see Crida 2009), this may still be sufficient for the formation of Jupiter- or Saturn-type planets around the perturber. Since the orientation of this encounter-related accretion disk is not correlated to the stellar rotation of the perturber, this scenario may provide an explanation for highly inclined or even retrograde planets which have recently been detected (Narita et al. 2009; Johnson et al. 2009). If the captured gas is accreted onto a pre-existing circumstellar disk of the perturber star, this might even lead to the formation of planetary systems with multiple mutually inclined (or even retrograde) orbital planes.

At this point we have to emphasize that gas capture from a massive extended circumstellar disk is only one of the several possible gas capture scenarios and is being observed in our work as a spin-off besides the main topic of this article. As the more general case, capture of material from any dense gas aggregate in the hosting star-forming region after the formation of the protostar itself may be a possible channel to form non-aligned planets. As the most general formulation, we note that the whole process of planet formation from the pre-stellar cloud in the context of stellar encounters in young star clusters to a fully established planetary system appears to be a discontinuous one in many cases, probably limiting the probability of regularly shaped planetary systems with solar system-like architecture. This issue will be investigated in detail in future work.

One issue not treated by our calculations is the varying protostar and disk mass during the accretion process. According to Machida et al. (2010), the growing disk may become temporarily unstable when the mass of the protostar is still negligibly small (~10⁻³ M⊙). In their nested-grid calculations, the disk fragments in the region of <100 AU and even within 10 AU. However, their simulations do not include a realistic treatment of radiative transfer. It is a subject of future investigations whether accreting disks under perturbation may develop into planetary systems with solar-type architecture.

Furthermore, the influence of magnetic fields is completely ignored in our calculations. Liverts et al. (2010) show that both hydromagnetic and thermomagnetic effects may amplify density waves in the disk into instability and may provide an effective viscosity via turbulence which may assist accretion onto the star.

Observations of tidally perturbed fragmenting disks would surely be the best confirmation of this scenario. Due to the
short duration of the fly-by of only about 10,000 years, the chance of such an event being “caught in the act” is small. It may, however, be possible to identify encounter-triggered fragmentation if observers succeed in detecting the typical tidal arms around the disk-hosting star as well as smaller amounts of non-circular filaments around a close-by star indicating it as a candidate perturber star. Such structures may be detectable with future high-resolution instruments like ALMA in star-forming regions like the ONC. Another possibility is to target FU Orionis stars which are thought to be undergoing enhanced accretion, such enhanced accretion may be caused by the perturbation of disks by a close encounter.

6. SUMMARY AND CONCLUSIONS

In a series of SPH calculations, we have shown that massive (∼0, 5 \( M_\odot \)), extended (≥ 100 AU) circumstellar disks can be stable when isolated, but fragment when perturbed by a moderately close and slightly inclined stellar encounter. Binaries formed in two cases: via triple encounters of companions and via grazing encounters of accreting envelopes. This agrees with binary formation in self-frAGMENTING disks (Stamatellos & Whitworth 2009a). We further found that the mass distribution of companions formed in disks is in agreement with the canonical substellar IMF as a separate population (Kroupa 2001; Kroupa & Bouvier 2003; Thies & Kroupa 2007, 2008). We have to note, however, that direct tidally induced fragmentation is probably only responsible for a fraction of all disk fragmentation events due to the relatively small orbital parameter subset that is suitable for fragmentation of disks of about 0.5 \( M_\odot \). More massive disks are expected to be more prone to fragmentation even due to weak perturbations but are also more likely to reach the limit for self-fragmentation. This study, however, shows that tidal perturbations do not necessarily inhibit fragmentation but are instead capable of inducing fragmentation in disk that otherwise would silently disperse or be accreted by the central star without ever experiencing fragmentation. The perturber star may accrete gas from the target circumstellar disk and may form planets on misaligned or even counter-rotating orbits with respect to the stellar spin. Future work will analyze disks with different masses and more or less massive host stars as well.

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