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The size-evolution of circumstellar disks in the Trapezium cluster

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Abstract. We compare the observed size distribution of circum stellar disks in the Orion Trapezium cluster with the results of *N*-body simulations in which we incorporated a heuristic prescription for the evolution of these disks. In our simulations, the sizes of stellar disks are affected by close encounters with other stars (with disks). In the second series of simulations, we also take the viscous evolution of the disks into account. We find that the observed distribution of disk sizes in the Orion Trapezium cluster is satisfactorily reproduced by truncation due to dynamical encounters alone. Although in that case, the number of disks in the observed range is only about 10% of all the stars. If we take the viscous evolution of the disks into account, this fraction grows to about 80%, but the age range in which a satisfactory match is realized shifts from 0.2—0.5 Myr to about $\lesssim$ 0.2 Myr. Based on our simulations we argue that when the viscous evolution of the circum stellar disks is important, the arrive at a best comparison with the observations of a cluster of about 1500 to 2500 stars in virial equilibrium that are distributed in a scale-free fashion with a fractal dimension of 1.5 to 1.9.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Planets form around stars and stars form in clusters, and clusters form from giant molecular clouds. This is the standard picture for star and cluster formation as put forward in the book Stahler & Palla (2005). But this model does not tell us much about the kinematics of young star clusters or on the spatial distribution of the individual stars. Observing such embedded star clusters have always been a major problem in astronomy due to the lack of penetrating power of optical telescopes. This has now, in part, been addressed effectively with the ALMA telescope.

From a theoretical perspective, the same problem is addressed by means of simulations. Those simulations are complicated by the intricate coupling between gas dynamics, stellar evolution and formation, gravitational dynamics, and radiative transfer. In the last several years we have introduced the Astronomical Multipurpose Software Environment (AMUSE for short, Portegies Zwart, 2011; Portegies Zwart et al., 2013; Pelupessy et al., 2013), which enables the interfacing and co-operation of a large number of production quality simulation codes to address this multi-scale and multi-physics problems in star- and cluster formation. The hope is that with a coordinated approach of observations and large scale model simulations we will arrive at a more consistent understanding of the formation and evolution of stars in clusters.

In a modest attempt to address the kinematics and dynamics of the earliest embedded stellar conglomerates we focus young star clusters that just emerged from their parental molecular cloud. The Trapezium cluster forms an ideal candidate. It is part of the Orion nebula (Huygens 1656, 1899) (later named M 42, NGC 1976) is one of the closest 412 pc (Reid et al., 2009) young ~ 0.3 Myr (85% of the stars $\lesssim 1$ Myr Prosser et al. (1994), (but see also Hillenbrand, 1997; Hillenbrand & Hartmann, 1998) star forming regions, composed of about 10^3 stars within a radius of ~ 3 pc (de Zeeuw et al., 1999). Even though the cluster is nearby and about to emerge from its parental molecular cloud (López-Sepulcre et al., 2013), its age, the number of members and the origin of its spatial and kinematic structure remains uncertain. Being one of the closest relatively massive young stellar systems it forms a key to understanding cluster formation and early evolution.

The close proximity of the Trapezium cluster allows detailed observations of circumstellar disk sizes using HST/WFPC2 (Vicente & Alves, 2005). This size distribution is well characterized by a power-law (Vicente & Alves, 2005), but the origin of this distribution remains uncertain. Dynamical interactions in young clusters have been demonstrated to be important for the sizes of circum stellar disks (Vincke et al., 2015), and the majority of protoplanetary disks are likely to be truncated by close stellar encounters. On the other hand, the viscous growth of a circumstellar disk should probably not be ignored. It is, however, not clear whether in the Trapezium this process can still be recognized in the observed distribution of circum stellar disks. Vicente & Alves (2005) argue that: *albeit the young age of the Trapezium, and given that disk destruction is well underway, it is perhaps too late to tell if the present day disk size distribution is primordial or if it is a consequence of the massive star formation environment.*

2. Model simulations

We simulated the Trapezium cluster by direct Hermite predictor corrector N-body methods (Makino & Aarseth, 1992) using the `Huayno` package (Jänes et al., 2014) in AMUSE. Each star, upon determining its initial mass, position and velocity was provided with a circumstellar disk with a mass of 10% of the mass of the host star. We adopt two models for the evolution of these disks. In one set of simulations in which each disk is initialized with the same size of 400 AU but without taking the internal evolution of the disk into account. We perform a second series of simulations in which we also account for the viscous evolution of the circumstellar disks using the prescription by Concha Ramírez et. al (in preparation).

2.1. Dynamical evolution of circumstellar disks

When taking the dynamical evolution of the cluster into account we keep track of close encounters between stars. The parameters of these close encounters are used to calculate the effect of the stellar fly-by on the circum stellar disks. This process is symmetric in the sense that the disks of both stars in the encounter are affected by the fly-by. We calculate the effect of the encounter on the disk size following the prescription used in Portegies Zwart (2016). This is a simple model in which circumstellar disks of a star with mass m is truncated to a radius of

$$r_{\rm disk} = 0.28q\left(\frac{m}{M}\right)^{0.32}, \qquad (1)$$

upon an encounter with a star of mass M at a closes approach of q.

2.2. Viscous evolution of circumstellar disks

Circum-stellar disks are viscous, in wich case, they evolve asymptotically towards a similarity solution (Lynden-Bell & Pringle, 1974). We adopt the description of the similarity solutions (Hartmann et al., 1998), which depends on the radial viscosity dependence exponent

γ (which we chose to be 1), the characteristic disk-radius $r_{\rm disk}$ (outside of which $1/e \simeq 37\%$ of the disk mass initially resides) and t_v, the viscous timescale at $r_{\rm disk}$.

We can now write the characteristic radius of the disk as a function of time t (Lynden-Bell & Pringle, 1974)

$$r_{\rm disk}(t) = \left(1 + \frac{t}{t_v}\right)^{\frac{1}{2-\gamma}} r_{\rm disk}. \qquad (2)$$

Here t_v is the viscous timescale which depends on the characteristic viscosity of the disk ν_c, and which we calculate using the turbulence parameter $\alpha = 10^{-2}$ (see Concha Ramírez etal for details, in preparation).

3. Results

We perform two series of calculations one in which we only take the dynamical truncation into account, and one series in which we include the viscous evolution of the disk. The former is performed with initial disk sizes of 400 AU, and the latter with initial disk sizes of 30 AU.

3.1. Initial conditions

Simulations are initialized with 1500 stars. Stellar masses are selected randomly from a broken power-law (Kroupa, 2001) between $0.01\,{\rm M}_\odot$, and $100\,{\rm M}_\odot$ (The mean mass of this mass function $\langle m\rangle \simeq 0.396\,{\rm M}_\odot$). The positions of the stars are selected from a fractal distribution (Goodwin & Whitworth, 2004) with a fractal dimension of $F = 1.2$, 1.6 and $F = 2.0$, but additional simulations were performed using the Plummer (1911) distribution. The velocities of the stars ware initially scaled such that the cluster has virial ratio $Q = 0.5$ with an initial characteristic cluster radius of 0.5 pc. In Fig. 1 we present the initial realizations for our calculations. Each of these initial realizations is calculated using the N-body code with and without viscous evolution.

The initial realization in Fig. 1 was used for the calculations in which we only take the dynamical truncation of the circumstellar disks into account (see § 3.2), and for the calculations in which we also take the viscous evolution into account (in § 3.3).

3.2. Dynamical truncation

The disks for the calculations in which we only take the dynamical evolution into account start all with a size of 400 AU. Dynamical truncation will lead to reduced disk sizes. In Fig. 2 we present the projected view of the four simulations at an age of 1.0 Myr.

The disks in the simulation with a low fractal dimension (top left in Fig. 2) are all very small compared to those with a more homogeneous initial distribution of stars (i.e., those with a higher fractal dimension). For the fractal models most disks are truncated to below 100 AU, with a clear trend with fractal dimension in the sense that the models with a higher fractal dimension have a larger number of large disks. In the initial Plummer distribution (bottom right) the stars in the core are particularly strongly affected by dynamical truncation, whereas the stars in the periphery is hardly affected and therefore still have a large disk sizes.

3.3. Viscous evolution

The results of the simulations in which the viscous evolution of the disks was taken into account are presented in Fig. 3.

The spatial distribution of the stars in Fig. 2 is somewhat difference than in Fig. 3. This is caused by deviations in disk size and therefore in the moment that an encounter it triggered in the simulation. These triggers cause the N-body integrator to reinitialize and which introduces a round off in the last decimal place of the calculation. This gives rise to small changes in the last decimal place of the stellar positions and velocities, and these changes propagate exponentially to more significant digits. the chaotic nature of the N-body problem then causes the positions and velocities of the stars to be different (see Boekholt & Portegies Zwart (2015) for a discussion on this).

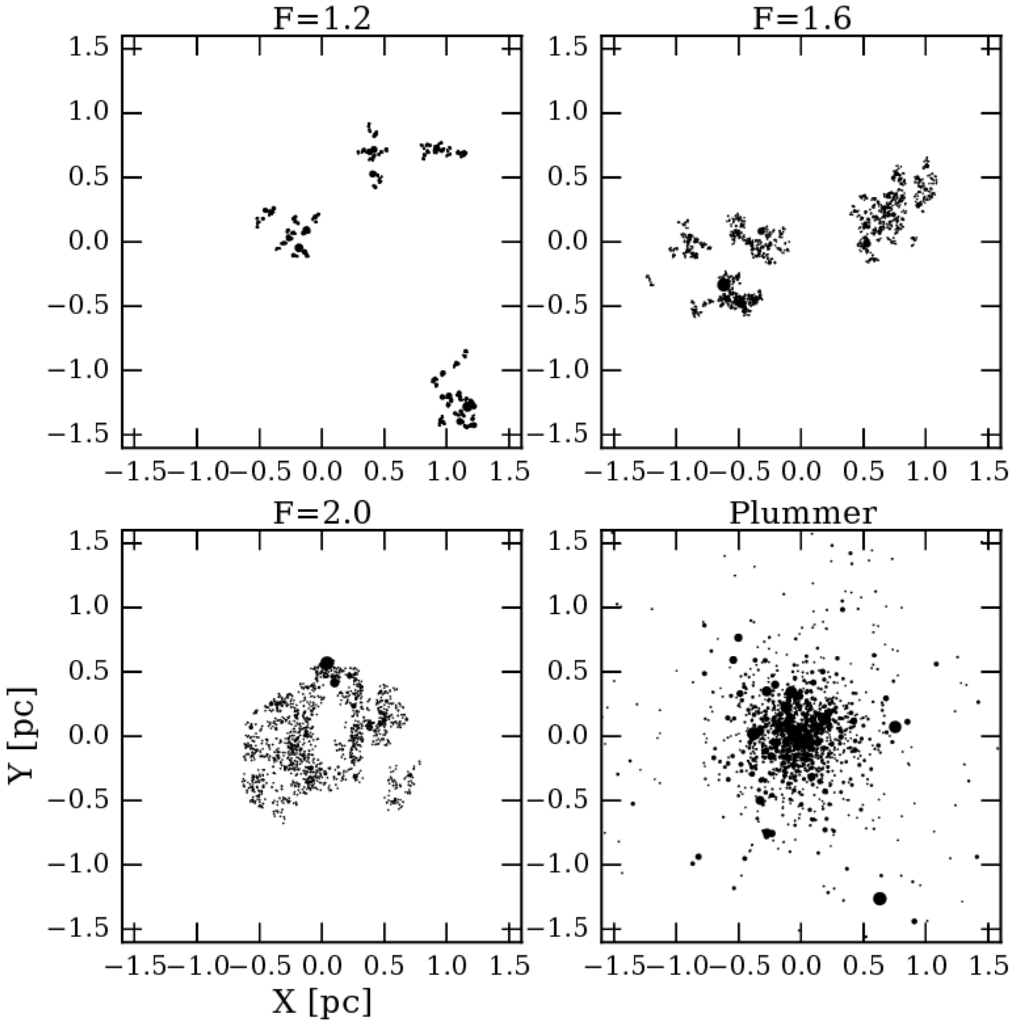

Fig. 1. Initial realization for 4 clusters, each composed of $N = 1500$ stars initially in virial equilibrium (Q=0.5) and distributed with a characteristic radius of 0.5 pc. From the top left to the bottom right give a fractal distribution with F=1.2, F=1.6 (top right), F=2.0 (bottom left) and a Plummer sphere (bottom right).

The disk-size distribution in the fractal models as well as in the Plummer model shows many disks with a size of 100 to 400 AU. This fraction is considerably larger than in the simulations without viscous evolution. Only in the Plummer, some disks are able to grow beyond 400 AU.

4. Discussion

In Fig. 4 we compare the mean disk size $\langle R\rangle$ with the dispersion in the disk-size distribution ($\langle R^2\rangle^{1/2}$). The curves with bullets give the results of the simulations. The thick curves are from the simulation in which we only take

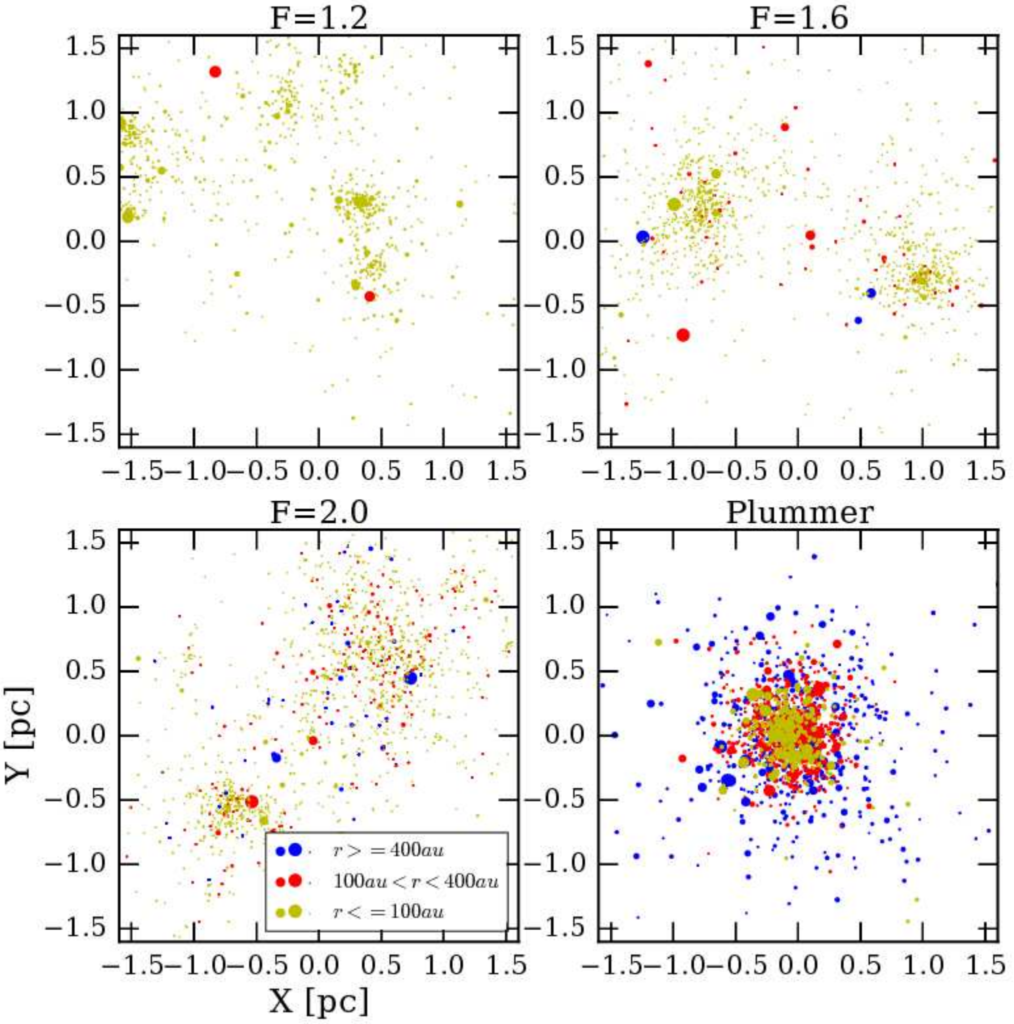

Fig. 2. Presentation of four clusters from the initial conditions which we presented in Fig. 1, evolved to an age of 1.0 Myr. From the top left to the bottom right give a fractal distribution with F=1.2, F=1.6 (top right), F=2.0 (bottom left) and a Plummer sphere (bottom right). The various colors indicate the limiting radii of their disks (see bottom left for the legend). The initial realization is presented in Fig. 1. The sizes of the disks are color coded with yellow for the smallest disks $\lesssim$ 100 AU, blue for disks of $\gtrsim$ 400 AU and red for those in the observed range of 100 to 400 AU.

the dynamical disk-truncation into account, whereas the thin curves are from the calculations in which also the viscous evolution is taken into account. The bullet points along the thick curves indicate time intervals of 0.1 Myr, for the thin curves this is 0.05 Myr. The thick curves start to the right at R = 400 AU with zero dispersion, because all the disks have the same size in these simulations. But the dispersion changes already in the early beginning of the simulation, and the first bullet point (at 0.1 Myr) is located rather far from the initial

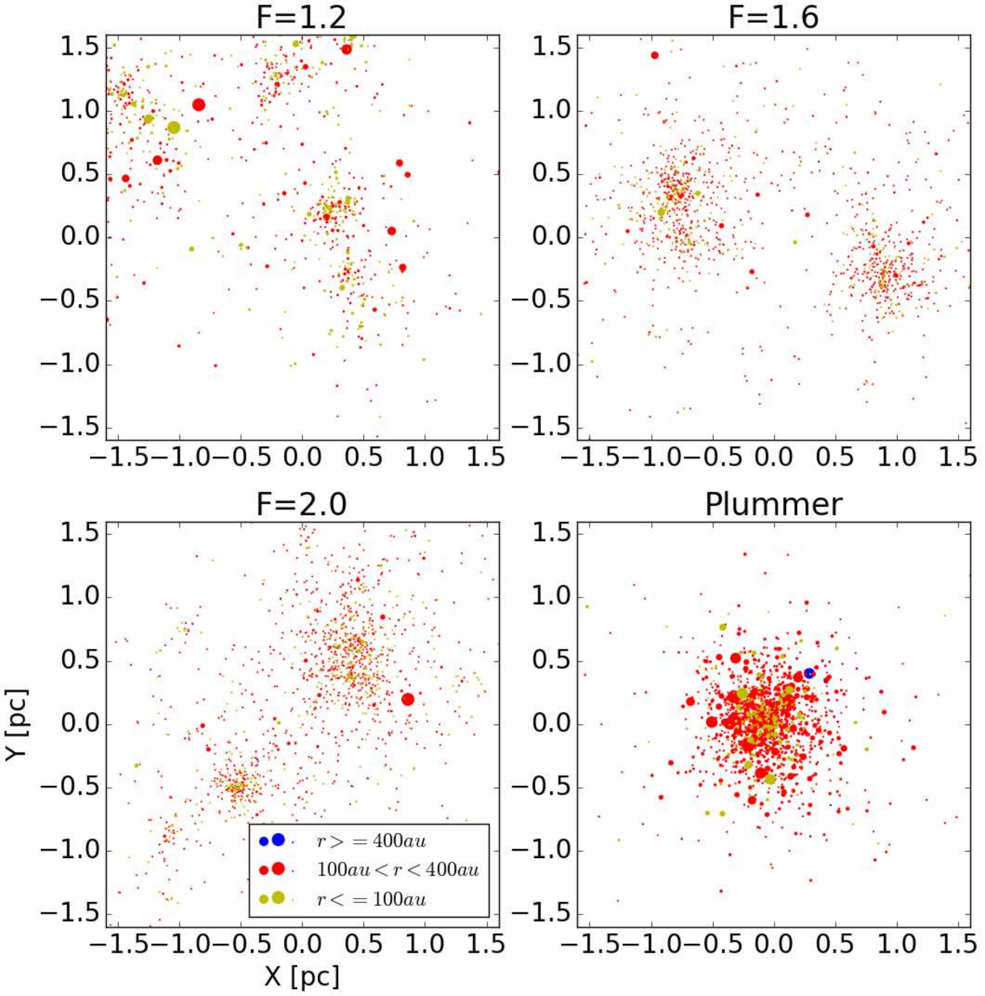

Fig. 3. Presentation of four clusters from the initial conditions which we presented in Fig. 1, but evolved to 0.3 Myr.The various colors indicate the limiting radii of their disks (see bottom left for the legend).

value. This effect is strongest for the model with a low fractal dimension (thick red curve).

The thin curves start at zero dispersion and with a disk size of 30 AU, which is the initial size for all the disks in the simulations where the viscous evolution is taken into account. These latter curves run from the lower left to the upper right.

Dynamical truncation seems to play little role in the evolution of the disk size in the viscous models. This is main caused by the effectiveness of dynamical truncation, which truncates most disks in the first ∼ 0.1 Myr. Once the most active dynamical phase of the cluster is over, the further evolution of the disks is governed by the viscous evolution.

It is hard to judge which simulation matches best with the observed cluster mean-disk size and the dispersion in this distribution. From Fig. 4 the models with a Plummer sphere

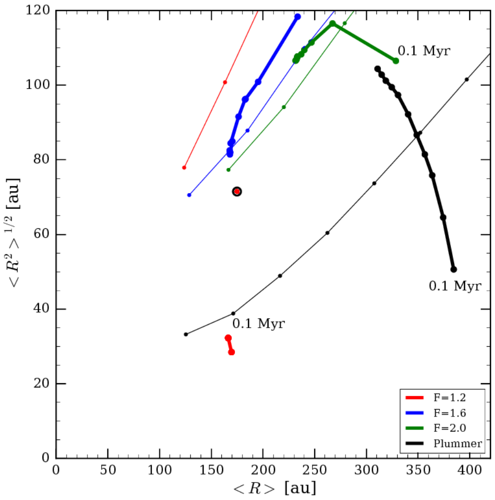

Fig. 4. Evolution of the root-mean-square disk size $\langle R^2\rangle^{1/2}$ as a function of average disk size $\angle R\rangle$. In this analysis, we limit ourselves to disks of at leat 100 AU. The thin lines give the results of the simulations in which we take the viscous evolution into account. Disks in those simulations start at small radius and with a small dispersion (to the lower left of the figure) and grow in time. The thin red curve starts at an age of 0.15 Myr, because before that moment all disks are smaller than 100 AU. The thick curves at an age of 0.05 Myr with bullet points every 0.05 Myr. The thick curves give the results of the simulations with only dynamical truncation. These curves run from the right to the left, because the disks can only decrease in size in these simulations. The bullet points for the thick lines are placed at intervals of 0.1 Myr. The red bullet with a black circle indicates the observations for the disks in the Trapezium cluster by Vicente & Alves (2005).

appear to fail to reproduce the observed distribution, irrespective if the viscous evolution is taken into account. The models with a low fractal dimension ($F = 1.2$) have similar problems in explaining the observed disk characteristics.

The models with a fractal dimension of $F = 1.6$ appear to give the most satisfactory results. If the viscous evolution is taken into account a slightly higher fractal dimension, up to $F \simeq 2.0$ may still give reasonable results. The main difference here is that without viscous evolution the simulated distributions matches the observations at relatively old age of the cluster at $\sim$ 1 Myr, whereas when the viscous evolution is taken into account the clusters may be considerably younger $\lesssim$ 0.2 Myr.

5. Conclusions

We performed simulations of young small star clusters in which the evolution of the circum stellar disks was taken into account via a semi-analytic prescription. The dynamical evolution of the clusters was performed with a direct N-body method. The distribution of disk sizes was compared with the observed disk-size distribution in the Trapezium cluster. The best match is realized with a fractal dimension of $F = 1.6$, but slightly higher values, up to $F \sim 2.0$, cannot be excluded. According to our simulations, an initial Plummer sphere as density distribution does not match with the current disk-size distribution in the observed cluster.

Taking the viscous evolution of the circumstellar disks into account adds an interesting physically motivated aspect to our calculations. If our adopted parameterization of the viscous evolution of the circum stellar disks represent the underlying physics correctly we have to conclude that this process dominates the disk evolution in the first 1 Myr of the dynamical evolution of the cluster. Dynamical truncation in this epoch is then ineffective. Our clusters, however, are highly dynamically active in the first $\sim$ 0.1 Myr, at which time the viscous disc are still very small; they are both with a radius of 30 AU. Dynamical truncation in this initial epoch then has little chance to effectively truncate the disks, simply because they are still too small. At a later time, when the disks have grown the cluster is already expanding after the first dense phase and dynamical interactions again are not effective in truncating the disks.

We, therefore, argue that the relative importance of the viscous growth and dynamical truncation depends on the cluster conditions at birth. If a cluster experiences its densest phase shortly after $\sim$ 0.3 Myr dynamical truncation will be important for determining the distribution of disk sizes. On the other hand, an early dense phase $\lesssim 0.2$ Myr causes the viscous evolution to dominate the later disk sizes. The distribution of disk sizes may then be used as a sensitive measure of the earliest dynamical state of a young star cluster.

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