Massive Stars Near and Far
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The origin of massive stellar systems via disk fragmentation

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Abstract. In this contribution, we explore the question on the formation of multiple massive stellar systems via disk fragmentation with the help of the highest-resolution simulations to date of a fragmenting disk in the context of massive star formation. The simulations start from a collapsing cloud of 200 solar masses, followed by the formation of an accretion disk that develops spiral arms and fragments. Due to the high resolution of our grid, we are able to self-consistently form the fragments without the need for a subgrid module such as sink particles. We track the formed fragments into the first stages of companion formation, which allows us to give an estimate of the multiplicity of the final system due to disk fragmentation. We find in total around ~ 6 fragments, some at orbits of ~ 1000 au, and some close (possibly spectroscopic) companions.

Keywords. stars: massive – stars: formation – accretion, accretion disks – stars: binaries: close – methods: numerical

1. Introduction

Massive stars are observed in clusters with high multiplicity (Zinnecker & Yorke 2007). With recent increasing evidence that massive stars form in accretion disks like their low-mass siblings (see, e.g., Ilee et al. 2018; Beuther et al. 2017; Johnston et al. 2020; Maud et al. 2019), we explore the question of whether massive multiple stellar systems can be formed via disk fragmentation during the star formation process.

We base this contribution in the findings reported in Oliva & Kuiper (2020). In that study, we performed high-resolution simulations of the formation of a massive star surrounded by a fragmenting accretion disk. An overview of the evolution of the system can be summarized in the following way: after an initial epoch dominated by gravitational collapse, lasting around 4.5 kyr, a Keplerian-like accretion disk is formed. It becomes Toomre-unstable, forms spiral arms and fragments. There is a fragmentation-dominated epoch lasting around 11 kyr, where fragments form, interact and get destroyed or have the potential to evolve further into companions. Beyond the fragmentation epoch, we observe a quiescent epoch characterized by the stabilization of the inner disk.

2. Methods

We performed a set of five simulations with increasing spatial resolution of the formation of a massive star from the collapse of a slowly-rotating cloud core of 0.1 pc in

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radius and $200\,\mathrm{M}_\odot$ in mass. The gas hydrodynamics is solved using the `Pluto` code (Mignone et al. 2007), with additional modules for self-gravity (Kuiper et al. 2011) and radiation transport. Specifically, we used `Makemake` (Kuiper et al. 2020) to model frequency-dependent irradiation of the (proto)star, and the thermal (re-)emission from the gas and dust with the gray flux-limited diffusion approximation. Stellar evolution is accounted for with the evolutionary tracks of Hosokawa & Omukai (2009). For the dust opacities, we use the tabulated values from Laor & Draine (1993), and we calculate the local evaporation of the dust grains by means of the formula of Isella & Natta (2005).

The mass of the cloud core is initially distributed with a density profile $\rho \propto r^{-1.5}$ (with r being the spherical radius). The initial radial velocity is zero, and the initial angular velocity is distributed such that $\Omega \propto R^{-0.75}$ (R being the cylindrical radius), with a normalization constant determined by the ratio of kinetic energy to gravitational potential energy, which is set to 5%. The exponent of the density profile power law and the ratio of kinetic to gravitational energy are within the expected values measured in star-forming cloud cores (see, e.g., Gieser et al. 2022; Beuther et al. 2002; Goodman et al. 1993). The choice for the exponent of the initial angular velocity profile keeps the initial ratio of kinetic to gravitational energy independent of radius, and allows for the formation of a more massive (and thus more fragmentation-prone) accretion disk earlier in time.

The simulations were run in a time-independent three-dimensional grid in spherical coordinates, where the radial position increases logarithmically, and the polar angle is spaced with the cosine function in such a way that the maximum resolution is achieved in the equatorial plane. The azimuthal angle is discretized uniformly. Our simulation domain has an inner boundary of 30 au, which we call the *sink cell*, and inside it, we model the formation of the central massive protostar. On purpose, we do not use any sub-grid sink particle model for the disk fragments. Thanks to the high resolution of the grid, the disk fragments are self-consistently described within the methods of hydrodynamics. In this contribution we focus on the highest-resolution simulation of the set, that corresponds to a grid of $536 \times 161 \times 512$ cells, of which ~ 26 million are used to model the disk physics.

3. From disk fragments to companion stars

When the accretion disk becomes Toomre-unstable at around $t = 4.5$ kyr, two initial spiral arms form which in turn quickly give rise to fragments. The data reveal that fragments always form in association to a spiral arm, for example due to growing overdensities in the spiral structure or because of collisions between spiral arms. The fragments continuously interact among themselves and with the disk and spiral arms: they merge, migrate and get sheared. Fragments are observed to develop secondary accretion disks of their own, with their own spiral arms that give rise to further fragments in a process that supports the hierarchical fragmentation scenario. An example of the disk fragmentation dynamics is captured in Fig. 1.

We developed an algorithm for the identification and tracking of fragments within the three-dimensional density and temperature data of the disk. Thanks to this tool, we were able to follow the evolution of individual fragments in their journey to become companions, up to the first stages of star formation. In the innermost ~ 150 au of the disk, the grid has cells of a sufficiently small size to resolve the size of a first Larson core according to the calculations by Bhandare et al. (2018) (a few astronomical units). Thus we are able to observe the formation of first Larson cores, that is, the first gravitational collapse of a disk fragment which is halted by thermal pressure. In the data, they are distinguished as a maximum in density and temperature, such that the enclosed mass within a region of the order of 1 au is of the order of $10^{-2}\,\mathrm{M}_\odot$, consistent with the calculations by Bhandare et al. (2018). However, the total available mass around the fragments (including their secondary accretion disks and surrounding material up to a

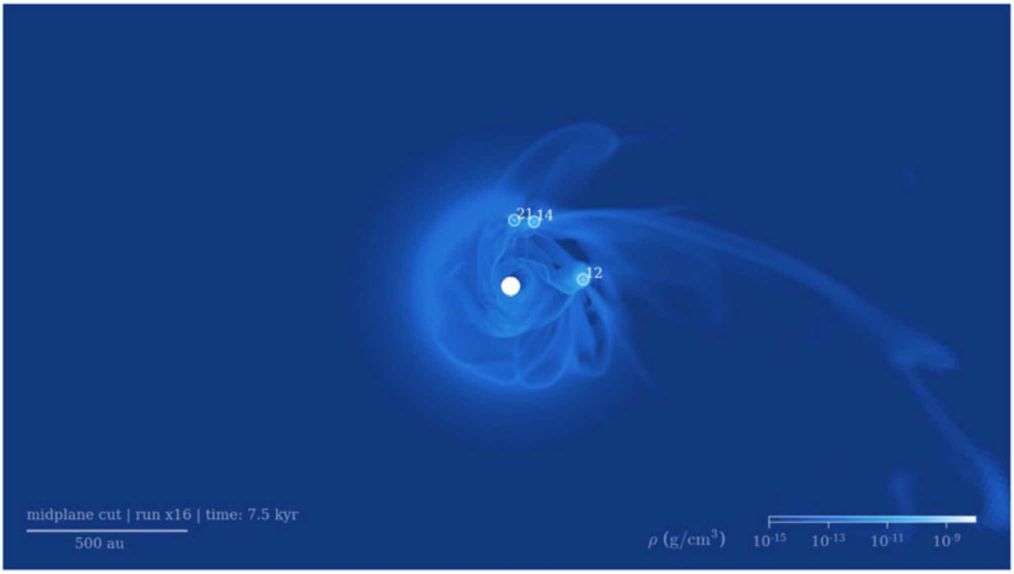

Figure 1. Midplane cut through the density field of the fragmenting accretion disk. Fragments labeled as 21 and 14 are interacting gravitationally. Fragment 12 is surrounded by a secondary accretion disk, and is also featured in Fig. 2. The numbers are only identification tags generated by the fragment-tracking algorithm and do not necessarily give information on the total number of fragments produced.

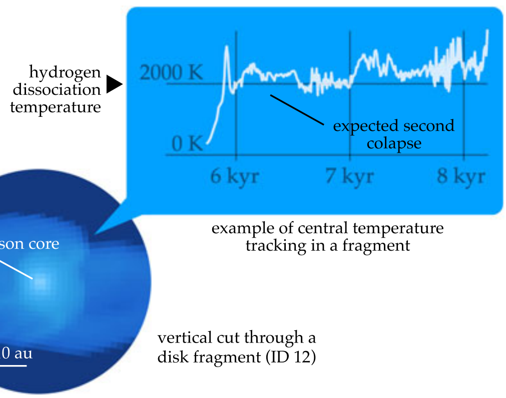

Figure 2. Evolution of a disk fragment into the first stages of stellar evolution.

radius of 40 au) is of the order of a few solar masses. Fragments formed later in time tend to be more massive.

During this stage, the orbits of the fragments are eccentric and chaotic because of their interactions. We observe that the orbits of some fragments become too close to the central massive protostar and get accreted by it. In the process, gravitational energy is converted into radiation energy in the form of an accretion burst.

When the central temperature of a first core increases consistently beyond 2000 K, the gravitational energy is used to dissociate the chemical bonds of molecular hydrogen instead of increasing the thermal pressure, and the gravitational collapse can continue. As a result of this process, a second Larson core of a few solar radii in size is expected

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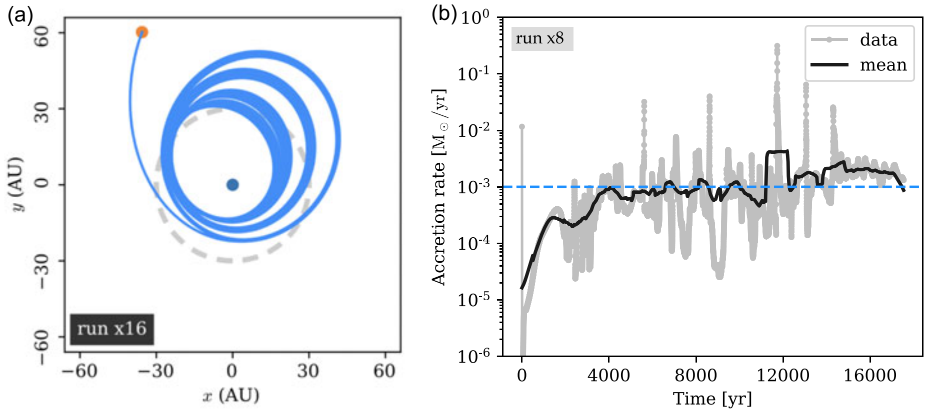

Figure 3. a) Integration of an orbit of a fragment that moves into the sink cell region in the simulation, showing a mechanism for the formation of spectroscopic multiples. b) Accretion rate onto the central massive protostar as a function of time.

to form (Bhandare et al. 2020). Even though our simulation methods did not include hydrogen dissociation, the fragment tracking algorithm enables us to predict when the hydrogen dissociation temperature is reached in the center of the fragment. The high degree of compactness of a second core object leads us to conjecture that the orbits would stabilize: even though second cores would feel the same gravitational interactions as first cores, the pressure gradient force arising from the gas in the disk would decrease. An example of the process first core formation and further evolution into a second core is illustrated with Fig. 2.

4. Multiplicity from disk fragmentation

Because of the interactions experienced by the fragments, only a fraction of them are expected to survive and evolve further into companions. From the analysis in this study, we expect first Larson cores to produce accretion bursts when they go inside of the region belonging to our numerical sink cell. However, second cores have higher probabilities of becoming companion stars, forming close companions if they move to the region close to the central massive protostar and wide companions if they remain in the outer disk.

In the highest resolution simulation of the set, we track 6 mergers and around 5 accretion bursts (very low mass and short-lived fragments are not tracked). At the end of the simulation ($t = 13.5$ kyr), 10 objects are expected to form second cores, 3 of them would become close companions and 3 continue to be located in the disk. The rest of the fragments that should form second cores merge with other fragments (but those mergers must be confirmed with the inclusion of hydrogen dissociation within the methods). Comparing with lower resolution simulations that we were able to run for a longer time, we estimate that the multiplicity produced by disk fragmentation is of the order of six, among close and wide companions. In contrast, previous studies that use sink particles and Cartesian adaptive mesh refinement grids predict numbers of companions that range between none and the order of hundreds (see, e.g., Girichidis et al. 2012; Rosen et al. 2016; Klassen et al. 2016).

From the outcomes of the full simulation set, we estimate that the number of wide orbit companions is of the order of one, with a semi-major axis ~ 1200 au and a mass of $5\,M_{\odot}$. Close companions would have orbits of semi-major axes smaller than 50 au and masses of the order of a few solar masses. However, because of the secondary accretion disks around

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forming companions, we cannot rule out the possibility that the final masses of the close companions might be higher than a few solar masses. Additionally, we integrated as an exercise the orbit of a second core object under the assumption that it is affected by the gravity of the central massive protostar and the average gravity of the disk. The results are displayed in Fig. 3a: we obtained an orbit that reduces over time due to the gain in mass of the central massive protostar. This constitutes a potential mechanism for the formation of spectroscopic multiple systems.

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Discussion

Audience member: What is the role of stellar feedback and magnetic fields on disk fragmentation?

Oliva: Our simulations include stellar irradiation, which stabilizes the innermost regions of the disk at late times. These simulations do not include magnetic fields, although other authors have found that it reduces fragmentation up to a certain degree (see, e.g., Commerçon et al. 2022; Mignon-Risse et al. 2021).

Audience member: How much of the mass of the central massive protostar is gained by accreting fragments?

Oliva: From the curve of accretion rate as a function of time (Fig. 3), we see that the accretion process is not smooth, but rather dominated by discrete accretion events.

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However, the average accretion rate is still well in line with the expected accretion rate assuming smooth accretion.

Ralf Klessen: Are fragments ever ejected from the disk?

Oliva: This is not observed in the highest-resolution simulation presented in this contribution, but in one of the lower resolution runs, a fragment that is in a wide orbit could actually be ejected. This requires further confirmation by running the simulation for a longer time.