Origins: From the Protosun to the First Steps of Life
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Constraints from zoom-in simulations on the protostellar accretion process

Michael Kuffmeier†

Institute for Theoretical Astrophysics (ITA), Zentrum für Astronomie (ZAH), University of Heidelberg,
Albert-Ueberle-Straße 2, DE-69120, Heidelberg, Germany
email: ru151@uni-heidelberg.de

Abstract. Stars are embedded in different environments of Giant Molecular Clouds during their formation phase. Despite this fact, it is common practice to assume an isolated spherical core as the initial condition for models of individual star formation. To avoid the uncertainties of initial and boundary conditions, we use an alternative approach of zoom-in simulations to account for the environment in which protostars form. Our models show that injections of ^{26}Al from a close-by supernova into the young solar system were highly unlikely. Moreover, we find that the accretion process of protostars is heterogeneous and environment-dependent.

Keywords. stars: formation, (magnetohydrodynamics:) MHD, accretion, accretion disks, solar system: formation, ISM: clouds, (stars:) binaries: general

1. Introduction

Over the last few decades, a picture of isolated star formation has been established: an individual star forms due to the gravitational collapse of a prestellar core (Shu *et al.* 1987). The core is typically assumed to be an isolated entity, approximately spherically in shape often referred to as 'spherical cow' approach. Starting with the assumption of a non-rotating, unmagnetized sphere, over the years models have become increasingly sophisticated by accounting for additional effects such as e.g. rotation, magnetic fields, and turbulence (e.g. Machida *et al.* 2007, Seifried *et al.* 2013, Tomida *et al.* 2015, Vaytet *et al.* 2018).

Regardless of these advances, the fundamental limitations of the spherical cow approach still apply, namely idealized initial and boundary conditions. In fact, already in his pioneering work on protostellar collapse, Richard Larson pointed out: 'For the boundary condition [...] we have in most cases adopted the simplest assumption' and 'For the initial conditions we have again adopted the simplest assumptions' (Larson 1969). 50 years later, it is widely accepted that stars form in different environments of Giant Molecular Clouds (GMCs) and the morphology of prestellar cores deviates from spherical symmetry owing to the connection to the underlying filamentary structure in the interstellar medium (ISM) (Andre *et al.* 2010, Federrath 2016, Rivera-Ingraham *et al.* 2017).

Therefore, models accounting for the protostellar environment provided by the GMC are required, such as has been done in recent 'zoom-in' simulations. In these simulations, the starting point is a turbulent GMC, in which prestellar cores form consistently and where the formation process of stars and disks is studied by applying sufficient adaptive mesh refinement (AMR) around individual protostars. (For a similar approach

† International Postdoctoral Fellow of Independent Research Fund Denmark (IRDF)

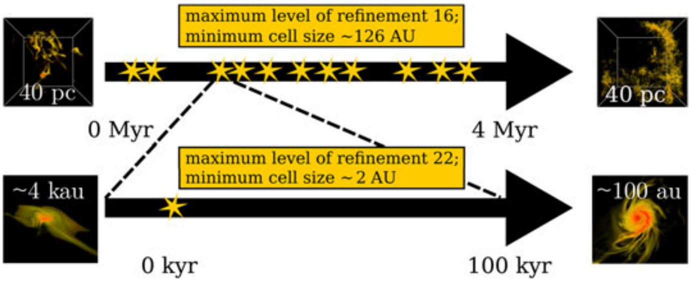

Figure 1. Sketch of the zoom-in technique adopted from Kuffmeier *et al.* (2017). In the first step, the turbulent GMC evolves for about 4 Myr using a minimum cell size of 126 au. Afterwards, sink particles are selected for zoom-ins using a minimum cell size of typically 2 au in the vicinity of the sinks.

using smoothed-particle hydrodynamics (SPH) and without considering magnetic fields see Bate 2018.) In this proceeding, we briefly summarize some major results that were obtained with the zoom-in method. In particular, we used this approach to constrain

- the abundance of short-lived radionuclides such as ^{26}Al,
- the accretion process of stars, and
- the formation process of protostellar disks in different environments.

Moreover, we briefly investigate formation of stellar multiples as well as we discuss the implications of young forming disks for planet formation.

2. Zoom-in method

A detailed presentation of the zoom-in method and the sink prescriptions used for stars is beyond the scope of this contribution, and we refer the reader to Kuffmeier *et al.* (2016) and Kuffmeier *et al.* (2017) for a comprehensive description of the method. Using a modified version (Haugbølle *et al.* 2018) of the adaptive mesh-refinement code RAMSES (Teyssier 2002, Fromang *et al.* 2006), we model a turbulent magnetized Giant Molecular Cloud (GMC) as a (40 pc)^3 cubic box with periodic boundary conditions. As illustrated in Figure 1, we evolve the GMC for about 4 Myr with a minimum cell size of 126 au. The mass of the GMC is $\approx 10^5$ M$_\odot$ and stars more massive than 8 M$_\odot$ explode as supernovae after a mass-dependent lifetime driving turbulence as well as enriching the GMC with short-lived radionuclides ^{26}Al and ^{60}Fe. To gain better insight of the properties during the accretion phase, we then select a number of stars typically in the mass range of 1 to 2 M$_\odot$ and rerun the simulation with a minimum cell size of ≈ 2 au in the vicinity of the stars for time scales of ~ 100 kyr. We applied yet another step of zooming-in to resolve the properties of one disk with a minimum cell size of 0.06 au for ~ 1000 yr at $t \approx 50$ kyr after sink formation.

3. Results

3.1. *Constraints on the ^{26}Al abundance in the early solar system*

Calcium-Aluminum rich Inclusions (CAIs) are the oldest known components of the solar system, probably forming within the first 10^4 yr of its existence (Larsen *et al.* 2011, Haugbølle *et al.* 2017). However, in the young solar system the abundance of the short-lived radionuclide ^{26}Al, produced during the process of supernova explosions, is puzzling to explain. Cosmochemical measurements reveal a discrepancy in relative abundance of ^{26}Al (radioactive) compared to ^{27}Al (stable) in ordinary CAIs with a canonical value of ^{26}Al / ^{27}Al $\sim 5 \times 10^{-5}$ (MacPherson *et al.* 1995) and in ^{26}Al-poor FUN CAIs with

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values of ^{26}Al / ^{27}Al $< 1 \times 10^{-6}$) (Kööp *et al.* 2018). A popular scenario to explain the difference suggests an injection of ^{26}Al from a close-by supernova during the early phase of solar system formation. We analysed the abundance of ^{26}Al around different protostars in our zoom-in models to test, whether we can find signs of ^{26}Al injections leading to increases in ^{26}Al / ^{27}Al abundance by more than a factor of 10. In short, the answer is no and variations are only minor for young protostellar systems. We draw the conclusion that a scenario of an early supernova injection within the first $t < 10^5$ yr of the solar system is highly unlikely. Instead, we suggest a model of thermal processing of dust grains (Kuffmeier *et al.* 2016).

3.2. *Heterogeneous accretion and disk formation*

To study the effect of the protostellar environment on the accretion process of different sinks, we analyse the accretion profiles of nine sinks for about 10 to 100 kyr. In contrast to the self-similar collapse of a singular isothermal sphere (Shu 1977), the accretion rate is neither spatially homogeneous nor constant in time. Sinks typically have high accretion rates of more than 10^{-5} $\mathrm{M_{\odot} yr^{-1}}$ in the early collapse phase followed by a decrease in accretion rate. The decrease in accretion rate, however, may differ from object to object. Sinks forming from rather isolated cores show more significant decreases in accretion rates during their evolution than sinks in more perturbed environments, where additional mass infall can raise the accretion profile (for late infall accretion see Padoan *et al.* 2014). For the more embedded sinks, we generally find flatter accretion profiles (Kuffmeier *et al.* 2017). Moreover, we find that the presence of a massive disks can cause increases onto the central sink due to disk instabilities (Kuffmeier *et al.* 2019).

3.3. *Disk formation*

Spherical collapse simulations, demonstrate that rotation of the collapsing prestellar core leads to the formation of a disk around the protostar owed by the conservation of angular momentum. Models that additionally account for magnetic fields by numerically solving the equations of ideal magnetohydrodynamics (MHD) find that magnetic fields efficiently transport angular momentum outwards, and hence, quench disk formation – at odds with observations of disks around protostars even in the earliest stages. The magnetically induced suppression of disks is commonly referred to as 'magnetic braking catastrophe'. However, catastrophic magnetic braking is circumvented by accounting for non-ideal MHD effects (e.g. Wurster *et al.* 2018) and/or turbulence (e.g. Seifried *et al.* 2013) in more advanced models of spherical collapse. Our models do not account for non-ideal MHD effects, but consistently include the underlying turbulence in the GMC. Out of six runs using a minimum cell size of 2 au, we find three sinks that host rotationally supported disks already after only ~ 10 kyr. In the other three cases, the formation of disks is suppressed or disks only occur intermittently. We find that angular momentum is predominantly transported in radial direction from the disk via Maxwell stresses with turbulence as a counter mechanism preventing disk formation altogether (Kuffmeier *et al.* 2017). Anticipating results with non-ideal MHD effects included, especially ambipolar diffusion (Hennebelle *et al.* 2016, Masson *et al.* 2016), we expect a higher fraction of disks per sink due to further reduction of magnetic braking (Kuffmeier & Nauman 2017). Considering the early presence of disks around young stars with high accretion rates and continuous infall, we emphasize that the mass budget for planet formation may well be larger than in models assuming steady disk masses.

3.4. *Outlook: the origin of stellar multiples*

Initially, we selected sinks that formed from the least perturbed prestellar cores in our simulations to simplify the comparison with models assuming isolated core collapse. However, we have started to look into more perturbed cores that are connected to massive GMC filaments. In particular, we find the formation of a binary companion at a distance of ≈ 1500 au from the primary at $t \approx 36$ kyr after the formation of the primary (Kuffmeier *et al.* 2019). This companion forms inside a filament that is connected to the primary due to compression on time scales of only a few kyr. After its formation, the companion gains more mass and approaches the primary within about 15 kyr to form a binary system of ~ 100 au distance. Based on these findings and against observations of Class 0 protostars of which the separation distribution shows an enhancement at about 100 au (Tobin *et al.* 2018), we suggest the following formation scenario for binary systems: companions form inside filaments at ~ 1000 au distance (Offner *et al.* 2010, Offner *et al.* 2016), move towards the primary due to its gravitational potential on time scales of about $\sim 10^4$ yr, eventually forming a binary system due to conservation of angular momentum with a characteristic separation of ~ 100 au.

4. Summary

We briefly present the major results of studying the accretion process of individual protostars forming in different environments using zoom-in simulations. Regarding the abundance of ^{26}Al in the early solar system, our results demonstrate that an early injection scenario is highly unlikely to be the origin of the discrepancy measured between ordinary CAIs and FUN CAIs. Accounting for the GMC environment additionally shows that the accretion process of protostars is heterogeneous in space, time and differs among protostars. Consistent with these results the properties of disks vary in different environments and young disks can be efficiently replenished with fresh material from the interstellar medium.

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Discussion

Waller: You noted that stars do not form in isolation and went on to describe simulations invoking turbulence and accretion. My question is whether you have considered the effects of UV irradiation by stars that have already formed.

Küffmeier: We account for heating induced by UV irradiation by applying the recipe of Franco and Cox (1986). According to this recipe heating is quenched in the densest gas. We plan to implement a full radiative transfer scheme in the future.

Maury: Are the different disk properties sampled around unequal objects linked to unequal mass-to-flux ratios?

Küffmeier: The prestellar cores in our simulations deviate from the classical scenario of a spherically symmetric core due to the presence of turbulence in the GMC. Therefore, the mass-to-flux ratio is not constant since the amount of enclosed mass and magnetization can change over time. We find that mass-to-flux ratios are in the range of 2-10 with large disks forming in the case of the highest mass-to-flux ratios. However, we also see disks forming at lower values, indicating that disk formation is not only determined by a single mass-to-flux ratio.