Abstract. Most massive stars are in binaries. Binarity can drastically alter their evolution, which can result in the formation of X-ray binaries or binary black hole systems, the dominant sources of gravitational waves. While single star formation is increasingly well understood, the detailed physics of binary/multiple massive star formation has received less attention. In particular, a good understanding of the combined influence of birth environmental conditions such as rotation, turbulence, magnetic fields, on (massive) stellar multiplicity is still lacking. In this proceeding, we summarize recent numerical efforts to clarify these points, using radiation-magneto-hydrodynamical simulations of massive pre-stellar core collapse with the RAMSES code, including the relevant physics to identify several fragmentation processes. We find magnetic fields to limit disk fragmentation in several ways: they remove angular momentum via outflows and magnetic braking, thereby limiting (and/or delaying) disk growth, self-gravitational effects and fragmentation. In binaries linked by a gaseous filament, magnetic pressure impedes gas concentration in the filament, thus suppressing fragmentation via spiral arm-filament, a fragmentation channel ubiquitous in hydrodynamical runs. On the opposite, core rotation and turbulence carry angular momentum, favouring disk growth and fragmentation. Moreover, turbulence reduces magnetic braking and outflows, again favoring disk fragmentation. We conclude that the environmental conditions (rotation, turbulence, magnetic fields) are keys to understand (massive) stellar multiplicity.

Keywords: stars: formation, stars: massive, accretion, magnetohydrodynamics(MHD), methods: numerical, binaries: general

1 Introduction

The majority of stars is in binary or higher-multiple systems. Moreover, the multiplicity fraction (i.e. frequency of multiple systems) and companion fraction (average number of companions) increases with the primary stellar mass, so that at least 90% of Main-Sequence massive stars ($\geq 8\mathrm{M}_\odot$) are in multiple systems, and massive stars have, on averaged, at least 1.6 companion (Offner et al. 2022). Various mechanisms can influence the final multiplicity of a stellar system, at distinct stages of the stellar system formation (see e.g. the reviews by Lee et al. 2020 and Offner et al. 2022). In the final stages, the system's multiplicity can be affected by stellar capture; in the earliest stages, core (or turbulent) fragmentation (e.g. Gingold & Monaghan 1983, Machida et al. 2005) and gravitational fragmentation of accretion disks (e.g. Bonnell & Bate 1994) are at play to form stars and increase the system's multiplicity; in this proceeding, we focus on disk fragmentation.

Several attempts to identify the dominant fragmentation channel in astrophysical environments have been undertaken. For instance, Tobin et al. (2018) searched for rotation signatures in the circum-multiple gas in the Perseus molecular cloud, targeting low-mass stellar systems; the detection of these signatures would suggest that the youngest stars were born out of disk fragmentation. They found that, in their sample, 8 out of 12 stars were consistent with disk fragmentation origin, the remaining 4 being attributed to core fragmentation. Thus, those results suggest at the very least that disk fragmentation is at play, in addition to core fragmentation. Although the extrapolation of these results to high-mass stars is not straightforward, disk fragmentation is not found to be inhibited around massive protostars in numerical simulations (e.g. Krumholz et al. 2009, Mignon-Risse et al. 2020, Oliva & Kuiper 2020).

Disk fragmentation occurs in two stages. First, non-axisymmetric instability in (axisymmetric) disks is triggered when the disk self-gravity becomes sufficiently important; when occuring, the disk grows spiral arms. The associated unstable state of a disk is expressed via the condition $Q > 1$, where Q is the Toomre parameter Q (Toomre 1964). It compares the relative importance of self-gravity, which triggers the instability, and shear and pressure supports (of radiative, magnetic and thermal origin), that prevent it. Under some circumstances, this condition can be re-formulated as $Q \approx M_{\mathrm{disk}} / M_\star > H/R$, where M_{disk} is the primary disk mass, $M_\star$ the primary star mass, and H/R the primary disk aspect ratio (of the order 0.1); thus, disk growth can lead to disk self-gravitational instability. Second, these spiral arms can lead to gravitationally unstable structures (e.g. via collision of spiral arms) that collapse to form a stellar companion.

In this proceeding, we address the influence of the birth environmental conditions (rotation, turbulence, magnetic fields) of stars on disk fragmentation and on the subsequent stellar multiplicity, in the context of massive star formation. Since accretion disks around massive young stars are found to be supported by thermal pressure rather than radiative (Mignon-Risse et al. 2020) or magnetic (Mignon-Risse et al. 2021, Commerçon et al. 2022) pressure, we will be mainly interested in how these environmental conditions influence the self-gravitational instabilities triggering via the disk growth. For this, we will be following the collapse of a massive pre-stellar core using the `RAMSES` (Teyssier 2002) to solve the equations of radiation-magneto-hydrodynamics (Fromang et al. 2006, Masson et al. 2012, Mignon-Risse et al. 2020).

2 First experiment: impact of magnetic fields on multiplicity

In this first experiment, we compare two sets of calculations: one set without magnetic fields (referred to as "hydrodynamical" runs) and one set with magnetic fields, including ambipolar diffusion. We use an axisymmetric numerical setup identical to Mignon-Risse et al. (2023b). It consists of a core of $200\,\mathrm{M}_\odot$, radius $= 0.1$ pc, density profile $\rho(r) \propto r^{-3/2}$, rotation profile defined by the angular frequency $\Omega(R) \propto R^{-3/4}$, with R the cylindrical radius, with a rotational-to-gravitational energy ratio of 5% in the core midplane. The dust-to-gas ratio 1%, with a dust sublimation model at high (> 1000 K) temperature. In the magnetized runs, the mass-to-flux to critical-mass-to-flux ratio is $\mu = 2$ at the core border. Finest resolution is varied between 10 AU and 1.25 AU. When a gas parcel is gravitationally-bound and Jeans-unstable, it is replaced by a sink particle that mimics a star (Bleuler & Teyssier 2014).

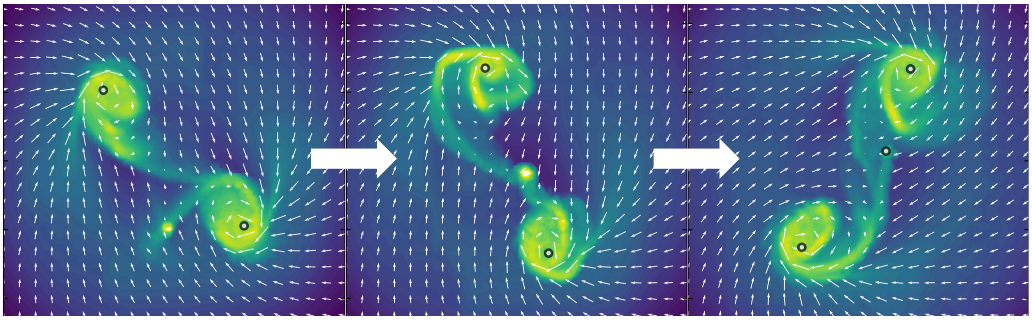

Fig. 1. Time sequence of density slices with sink particles overplotted, illustrating the arm-filament collision mode of fragmentation, in one of the hydrodynamical runs. The slices cover 1000 AU ×1000 AU. This mode of fragmentation, ubiquitous in the hydrodynamical runs, is absent in the magnetized runs.

In both magnetized and hydrodynamical runs, a binary system is formed after a few kyr. Figure 1 shows a time sequence in one of the hydrodynamical runs at the time when the third star forms. It can be seen that, initially, each star is surrounded by an accretion disk, and the two systems are linked by a filament (left panel of Fig. 1). The disks exhibit large spiral arms. The collision of one disk's arm with the filamentary structure linking the binary leads to the formation of the third star, as illustrated on Fig. 1. This mode of fragmentation is reported in all the hydrodynamical runs and is absent in the magnetized runs. Indeed, the impact of magnetic fields on this fragmentation mode is twofold. First, before fragmentation, disks are about twice larger in hydrodynamical (≈150 AU) than in magnetic runs, in which case their disk size is consistent with magnetic regulation. Indeed, magnetic braking removes angular momentum and thereby limits disk growth and therefore self-gravitational effects such as spiral arm formation. In the hydrodynamical case, only disk fragmentation can limit disk growth. Second, the filament is much more diffuse in the magnetized case. This is visible in Fig. 2, which shows the column density map at the end of the same hydrodynamical run as Fig. 1 and in the resolution-equivalent magnetized run. Indeed, the filament is located in a region where magnetic pressure dominates over thermal and radiative pressures and certainly limits mass concentration.

To sum up, magnetic fields limit massive stellar multiplicity by reducing disk fragmentation because they limit disk growth (provided by the angular momentum of the infalling gas) – while only disk fragmentation can limit disk growth otherwise –, and in binaries, they lead to more diffuse inter-binary filamentary structures (as observed by e.g. Sadavoy et al. 2018). More details can be found in Mignon-Risse et al. (2023a).

3 Second experiment: relative influence of magnetic fields and turbulence on multiplicity

In this second experiment, we only consider magnetized runs (with ambipolar diffusion) and address the relative impact of magnetic fields and turbulence in setting massive stellar multiplicity. The setup (see Commerçon et al. 2022) is similar to the previous one except for the following: the core has a mass $100\,\mathrm{M}_\odot$, radius 0.2 pc, a density profile $\rho(r) \propto 1/(1 + (r/r_\mathrm{c})^2)$ with a central plateau of radius $r_\mathrm{c} = 0.02$ pc, in solid-body rotation with rotation-to-gravitational energy ratio 1% at the core border. On top of this, an initial velocity distribution is set so as to mimic turbulence (in turbulent runs), set by the Mach number $\mathcal{M}$, and we vary the level of magnetization. The relative importance of turbulence with respect to magnetic fields is, thus, set by the Alfvénic Mach number

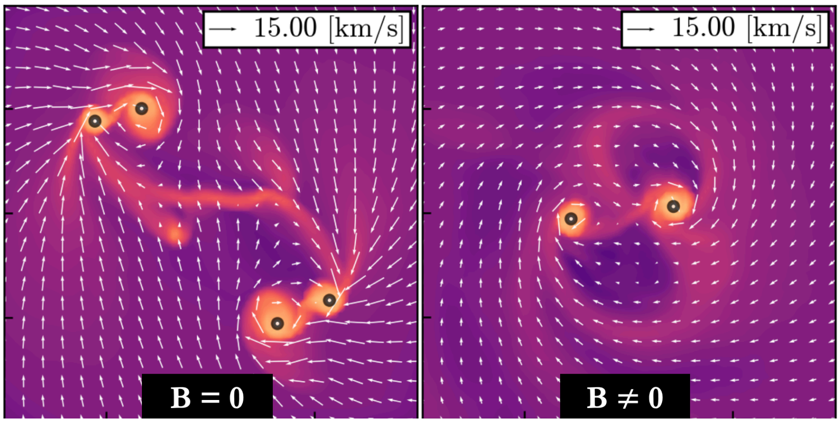

Fig. 2. Column density maps at the end of one of the hydrodynamical runs (left panel) and magnetized runs (right panel). Sink particles are indicated by white dots. The maps cover 2000 AU ×2000 AU. The stellar system is a quadruple in the hydrodynamical run while it is a binary in the magnetized run.

$\mathcal{M}_\mathrm{A}$ ($\mathcal{M}_\mathrm{A} > 1$ means turbulence dominating over magnetic fields). The magnetization level is varied between $\mu = 2$ and $\mu = 5$ at the core border. The finest numerical resolution is set to be 5 AU.

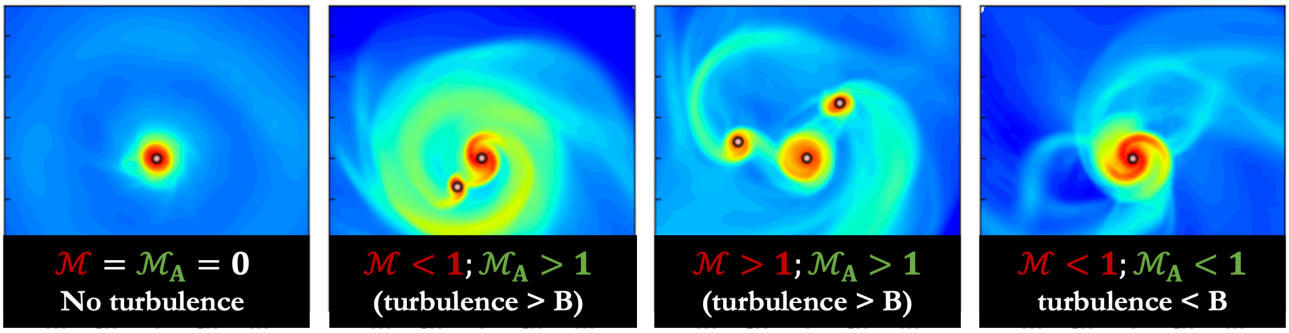

Fig. 3. Column density maps at the same time in the four runs. Sink particles are overplotted as white circles. The maps cover 1500 AU ×1500 AU. Magnetic-dominated runs ($\mathcal{M}_\mathrm{A} < 1$) lead to single star formation; turbulence-dominated runs ($\mathcal{M}_\mathrm{A} > 1$) lead to multiple systems.

Figure 3 shows the column density and multiplicity outcome of this set of simulations at $t = 50$ kyr. Magnetic-dominated (i.e. "sub-Alfvénic" turbulence) runs lead to single stars; turbulence-dominated (i.e. "super-Alfvénic" turbulence) runs lead to multiple systems – binaries at the end of the run, when accounting for sink mergers. On top of the core/turbulent initial fragmentation found to occur in turbulence-dominated runs, we report disk fragmentation in these same runs. These events occur after a 'spike' in disk size is reported, thus a spiral arm forming. In one of these two runs, we observe disk growth followed by spiral arm formation, and spiral arms collision to produce the fragment that will eventually become gravitationally-unstable and lead to sink particle creation. For a given $\mathcal{M}$ value, the run with higher magnetization exhibits a delayed disk growth, spiral arm formation and collision, and the formed fragment falls down onto the disk, which we attribute to angular momentum removal by magnetic fields. Angular momentum transport is found to be dominated by magnetic braking. Magnetic braking weakens as turbulence increases, which we attribute to the turbulence deorganizing the magnetic fields topology.

To sum up, environmental turbulence carries angular momentum and therefore contributes to disk growth, while magnetic fields remove it and limit disk fragmentation (more details in Mignon-Risse et al. 2021).

4 Conclusions

We have studied various ways in which the environmental conditions (rotation, turbulence, magnetic fields) could influence the multiplicity of a young massive stellar system via disk fragmentation, using non-ideal radiationmagnetohydrodynamical calculations. Rotation and turbulence, because they carry angular momentum, contribute to disk growth, self-gravitational instability and subsequent fragmentation. Magnetic fields seem to play an opposite role: they remove angular momentum (via outflows and magnetic braking; whose amplitude is reduced by turbulence), thereby limiting disk fragmentation. In binaries, which are linked by a gas filament, they also add an extra pressure support, thereby suppressing arm-filament collision as another fragmentation channel. In their absence, and in the case of a disk embedded in a reservoir of rotating gas, disk growth would be theoretically unlimited: fragmentation appears as the natural mechanism to limit it. Finally, the aforementioned mechanisms are not only valid for massive stars and could also matter for low-mass star formation. Environmental conditions are, therefore, important in setting (massive) stellar multiplicity.

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