COLLAPSE OF MASSIVE MAGNETIZED DENSE CORES USING RADIATION MAGNETOHYDRODYNAMICS: EARLY FragmentATION INHIBITION

Benoît Commerçon1, Patrick Hennebelle2, and Thomas Henning1

1 Max Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany; benoit@mpia-hd.mpg.de
2 Laboratoire de radioastronomie, UMR 8112 du CNRS, École normale supérieure et Observatoire de Paris, 24 rue L’homond, 75231 Paris Cedex 05, France

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ABSTRACT

We report the results of radiation-magnetohydrodynamics calculations in the context of high-mass star formation, using for the first time a self-consistent model for photon emission (i.e., via thermal emission and in radiative shocks) and with the high resolution necessary to properly resolve magnetic braking effects and radiative shocks on scales \(<100\) AU. We investigate the combined effects of magnetic field, turbulence, and radiative transfer on the early phases of the collapse and the fragmentation of massive dense cores. We identify a new mechanism that inhibits initial fragmentation of massive dense cores where magnetic field and radiative transfer interplay. We show that this interplay becomes stronger as the magnetic field strength increases. Magnetic braking is transporting angular momentum outward and is lowering the rotational support and is thus increasing the infall velocity. This enhances the radiative feedback owing to the accretion shock on the first core. We speculate that highly magnetized massive dense cores are good candidates for isolated massive star formation while moderately magnetized massive dense cores are more appropriate forming OB associations or small star clusters.

Key words: magnetohydrodynamics (MHD) – methods: numerical – radiative transfer – stars: formation – stars: massive – stars: kinematics and dynamics

1. INTRODUCTION

Massive star formation ($M_\star > 8M_\odot$) is one of the most challenging astrophysical problems. It is established that most massive stars form from massive prestellar cores and occur in high-order multiple systems (e.g., Zinnecker & Yorke 2007). Nevertheless, all theoretical numerical models to date show high-order multiple systems (e.g., Zinnecker & Yorke 2007). Bontemps et al. (2010) and Longmore et al. (2011) suggests that collapsing massive dense cores are less fragmented than what numerical calculations produce although the limited observational resolution available precludes a definitive answer. For instance, isothermal simulations (e.g., Bonnell et al. 2001; Bonnell & Bate 2006) and radiative calculations (Krumholz et al. 2007, 2009), magnetized ones (Wang et al. 2010; Hennebelle et al. 2011; Peters et al. 2011; Seifried et al. 2011) and even calculations including radiative ionization (Peters et al. 2010), all tend to form several fragments. Indeed, both radiation and magnetic fields tend to reduce the number of fragments (e.g., a factor of about two for highly magnetized cores) without suppressing the fragmentation. To balance this fragmentation issue, Krumholz & McKee (2008) proposed a column density threshold for massive star formation. However, this model only applies to massive star formation under certain conditions, and in particular to massive stars, whose formation has been possible thanks to the radiative feedback of low-mass protostars.

In this Letter, we perform full radiation-magnetohydrodynamics (RMHD) calculations of massive, turbulent, and magnetized dense cores. This work is an extension toward higher masses of the study by Commerçon et al. (2010), who investigated low-mass star formation.

The Letter is organized as follows. In Section 1, we discuss our numerical method and initial conditions. Our results are presented in Section 2. In Section 3 we discuss a new scenario for massive star formation and Section 4 concludes the paper.

2. MODEL

2.1. Initial Conditions

Our initial setup is identical to the one used in Hennebelle et al. (2011), except that we do not use a barotropic equation of state (EOS). We consider 100 $M_\odot$ spherical dense cores, which are threaded by a magnetic field parallel to the x-direction. The initial radius of the sphere is 0.617 pc and the total box length is 2.76 pc. The density profile is given by $\rho(r) = \rho_c / (1 + (r/r_0)^2)$, where $\rho_c = 1.4 \times 10^{-20}$ g cm$^{-3}$ is the central density, and $r_0 \approx 0.22$ pc is the extent of the central plateau. We impose a density contrast of 10 between the central density and the edge density. The initial temperature of the core is uniform and equals 10 K. Outside the cloud, the matter is also set to 10 K. The adiabatic index is set to $\gamma = 7/5$. We use the Rosseland $\kappa_R$ and Planck $\kappa_P$ mean opacities derived in Semenov et al. (2003). At temperature >1000 K, we impose $\kappa_P = \kappa_R = 0.01$ cm$^2$ g$^{-1}$ in order to limit the grain evaporation effect and to account for an inertia of the evaporation. We impose an initial subsonic turbulent velocity dispersion which follows a Kolmogorov power spectrum $P(k) \propto k^{-5/3}$, where the phases are randomly sorted in the Fourier space. Only one realization is explored in this study. The turbulence is not artificially sustained but does not really decay as the gravitational time is typically shorter than the crossing time. The kinetic energy power spectrum peak roughly corresponds to the box size. The ratio of the turbulent to gravitational energies is given by $\alpha_{\text{turb}}$. We do not explicitly include rotation but the turbulent field contains angular momentum (both local and global). Note that our initial conditions exhibit a relatively flat density profile, which should favor fragmentation (Girichidis et al. 2011).

The magnetic intensity is set by the parameter $\mu = (M/\Phi)/(M/\Phi_{\text{crit}})$, which represents the value of mass-to-flux over critical mass-to-flux ratio (Mouschovias & Spitzer 1976; Hennebelle et al. 2011). In this Letter, we explore three magnetization degrees: $\mu = 130$ corresponding to a weak initial magnetic field, and $\mu = 5$ and $\mu = 2$ which are close to the

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Table 1

| Model  | $\alpha_{\text{turb}}$ | $\Delta x_{\text{min}}$ (AU) | Coarse Grid | $t_0$ (Myr) |
|--------|------------------------|-----------------------------|-------------|--------------|
| SPHYDRO | $\infty$ | $\sim 10^{-5}$ | 2.16 | 128 | 0.4786 |
| MU130  | $\sim 136$ | $\sim 0.2$ | 2.16 | 256 | 0.4935 |
| MU5    | $\sim 5.3$ | $\sim 0.2$ | 2.16 | 256 | 0.5397 |
| MU2    | $\sim 2.3$ | $\sim 0.2$ | 2.16 | 256 | 0.5982 |

We also investigate an almost spherical case with no magnetic field and no turbulence (model SPHYDRO) to serve as simple reference with respect to which the other simulations can be compared. All the simulation parameters are summarized in Table 1. Future work will imply further investigations on the effects of turbulence or rotation, but this goes beyond the scope of this Letter.

2.2. Numerical Method

We use the adaptive mesh refinement code RAMSES (Teyssier 2002), which integrates the self-consistent equations of RMHD using ideal MHD (Fromang et al. 2006; Teyssier 2006), and flux-limited diffusion for radiation (Commerçon et al. 2011b).

We impose a refinement criterion $N_J = 10$, which ensures that the local Jeans length is resolved by at least 10 cells. The initial grid contains $256^3$ cells and we use 10 levels of refinement for an effective resolution of $262144^3$ and a minimum grid size of $\sim 2.16$ AU. We apply periodic boundary conditions for hydrodynamics and gravity, and we impose a temperature of 10 K for the radiation at the edge of the box.

3. RESULTS

3.1. Qualitative Description

In this section, we qualitatively describe the results of the four calculations. Calculations are synchronized at the time $t_0$ when the maximum level of refinement is reached (see Table 1). The subsequent evolution after $t_0$ strongly depends on the physical conditions (rotation, outflows, etc.). At $t_0$, the first hydrostatic core (FHSC; Larson 1969) is forming. As expected, we note that the stronger the magnetic field is, the later the collapse occurs because magnetic fields “dilute” gravity. In Figure 1, column density and local Jeans length maps of the four calculations are shown in the $xz$-plane. The boxes are centered at the maximum density of the total computational domain. In the SPHYDRO model, only one central fragment is formed and the collapse is nearly spherical. The mass of the fragment, i.e., where $\rho > 10^{11}$ cm$^{-3}$, at time $\sim t_0 + 2.6$ kyr is $\sim 0.2 M_\odot$. The integrated mass of the envelope from the fragment which is stable against fragmentation, i.e., $M_{\text{int}}/M_f > 1$, is $\sim 30 M_\odot$ and the accretion rate is $\sim 10^{-4} M_\odot$ yr$^{-1}$.

In the MU130 model, the additional turbulent support clearly favors fragmentation (six fragments are formed at that time) over a region of 2000–4000 AU. The mean separation between the fragments is about 1000 AU and they are distributed at this early time along a filamentary structure. This separation corresponds to the typical Jeans length associated with the region surrounding each fragment. The overall accretion rate on the fragments is relatively low, $\sim 10^{-5} M_\odot$ yr$^{-1}$, and consistent with the ones obtained in the low-mass star formation framework. The mean mass of the fragments is about $0.2 M_\odot$ ($\sim 1.2 M_\odot$ in total) and corresponds to the local Jeans mass.

In the MU5 model, the core has fragmented into two main objects, one being formed by the merger of secondary fragments. The fragmentation zone has the same filamentary morphology.

Figure 1. Top: column density maps integrated in the $y$-direction for the four models: SPHYDRO at time $\sim t_0 + 2.6$ kyr, MU130 at time $\sim t_0 + 25.4$ kyr, MU5 at time $\sim t_0 + 7.5$ kyr, and MU2 at time $\sim t_0 + 7.3$ kyr. Bottom: local Jeans length and velocity field cut in the $xz$-plane for the same calculations and at the same time as in the upper row.
Figure 2. Low-resolution runs for the MU130 and MU2 models.

Figure 3. Radial profiles of density and temperature for the SPHYDRO model at the same time as in Figure 1. The gray vertical lines indicate the radius at which $\tau = 1$.

3.2. Quantitative Analysis of the SPHYDRO Model

In this section, we focus on the thermal behavior observed in the SPHYDRO model, i.e., without turbulence and magnetic field. Figure 3 shows radial profiles of density and temperature at time $\sim t_0 + 2.6$ kyr. The density profile exhibits the classical $R^{-2}$ slope in the envelope (Larson 1969; Penston 1969; Shu 1977). Unlike the low-mass star formation case, for which...
Figure 4. Temperature–density distribution for the four models. The top row corresponds to snapshots just before grain evaporation for the SPHYDRO, MU5, and MU2 models, and to time $t_0 + 6$ kyr for the MU130 model. The bottom row corresponds to the same time as in Figure 1. The color coding indicates the mass in $M_\odot$ per bin of equal density and temperature. The black lines represent iso-Jeans mass curve, ranging from $10^{-4} M_\odot$ (bottom right line) to $10 M_\odot$ (top left dashed line). The yellow curve represents a classical barotropic EOS.

$T \propto R^{-0.5}$ in the optically thin envelope, we find that the temperature profile in the preshock region ahead of the FHSC is steeper. The optically thick region extends up to a radius of $\sim 130$ AU (vertical gray line), much larger than the FHSC radius $R_\text{FHSC} \sim 20$ AU. The radiation is thus trapped in an optically thick bubble where the infalling gas can be efficiently heated and the Jeans length rises efficiently. Compared to the low-mass star case, the accretion rate and thus the post-accretion shock temperature are larger ($\sim 250$ K compared to $\sim 70$ K). Since $\kappa R \propto T^2$ for temperature $<100$ K, this explains the larger optical depth found toward higher masses. The temperature profile is well fitted in the optically thick region with $T \propto R^{-7/8}$ (dotted line). Such a profile is obtained assuming that the rate of change in kinetic energy, $\sim GM \dot{M}/R$, equals the radiative flux, $\sim R^2 c^2/(3k_R \rho)R_T^4/R$ (with $\kappa_R$ constant for temperature ranging from 100 K to 1000 K). At larger radii the optically thin behavior, $T \propto R^{-0.5}$ (dashed line), is recovered after a transition regime until the equilibrium temperature of 10 K is reached.

### 3.3. Comparison with the Other Models

Figure 4 shows the temperature distribution as a function of the density at two times for the four models. To visualize the difference between our work and other studies, we overplot the barotropic law that is used in Hennebelle et al. (2011). With a full RMHD model, we obtain a spread in temperature and Jeans length. As first suggested by Commerçon et al. (2010) in the low-mass star formation framework, we show that there is a strong interplay between magnetic field and radiative transfer which may suppress initial fragmentation. Because of the rotation slowdown owing to the magnetic braking (most efficient at scales $<200$–$300$ AU), the infall velocity on the fragment is

The accretion luminosity on the FHSC, $L_{\text{acc}} = GM\dot{M}/R_c$, is thus about the same. In the MU130 model, the accretion rate is much lower and the contraction of the FHSC slower because of lower temperature. As a consequence, the typical Jeans mass is about two orders of magnitude lower than in the SPHYDRO and MU2 models. As in other models (Krumholz et al. 2009; Peters et al. 2011; Hennebelle et al. 2011), the MU130 model shows fragmentation in several objects even at time $t_0 + 6$ kyr, where three objects formed with a separation of $3000$–$5000$ AU. As the magnetic braking is very small here, the radius at which the collapse is stopped and where fragmentation is taking place is thus much larger than the FHSC radius, and the accretion luminosity negligible. Even with a fragment undergoing second collapse, the radiative feedback would not be efficient at a distance of $d \sim 3000$ AU to suppress fragmentation. For an optically thin envelope, the temperature indeed scales as $T \sim (L/(4\pi\sigma d^2))^{1/4}$, where $L$ is the accretion luminosity on the protostar, $L = GM\dot{M}/R_c$ ($\sim 13$ K at 3000 AU with $M = 1 \times 10^{-5} M_\odot$ yr$^{-1}$, $M_* = 0.2 M_\odot$, and $R_* \sim 5 R_\odot$). Finally, the MU5 model shows an intermediate behavior. Although the heating owing to the accretion shock on the central fragment is already large, external regions have time to cool and to continue collapsing to form a secondary fragment.

### 4. Toward Massive Star Formation?

### 4.1. Discussion

As first suggested by Commerçon et al. (2010) in the low-mass star formation framework, we show that there is a strong interplay between magnetic field and radiative transfer which may suppress initial fragmentation. Because of the rotation slowdown owing to the magnetic braking (most efficient at scales $<200$–$300$ AU), the infall velocity on the fragment is
thus greater. For massive dense cores, the accretion is larger than for low-mass ones and the amount of energy radiated away at the FHSC surface, the accretion luminosity, is thus much larger. Depending on the initial conditions, we find three totally different behaviors.

1. For a spherical massive dense core, without turbulence and magnetic field, we find that the core’s envelope heats efficiently (SPHYDRO model) because the radius at which the accretion luminosity is released is small (FHSC radius). We also find that contrary to the low-mass regime, the optically thick regions are much more extended, up to ∼150 AU (∼10 AU for the low-mass case). Only one fragment is formed.

2. In the MU130 model, the magnetic braking is too low to transport outward angular momentum produced by the initial turbulence. Seven fragments have formed by the end of the calculations. The fragmentation zone extends over a few thousands AU, at which accretion luminosity is first released through a radiative shock. Disks with radius ∼100–200 AU are also formed around the fragments, which give a second accretion shock at the disk edges. The infalling gas thus encounters several accretion shocks before being accreted onto several FHSCs, which lowers the accretion luminosity.

3. For highly magnetized and turbulent massive dense cores (MU2 model) we find very similar results to the SPHYDRO model, i.e., a single fragment, because of the magnetic braking that lowers the radius at which the accretion luminosity is released to the FHSC radius.

4. We find an intermediate behavior for lower magnetization degrees (MU5 model), where the core fragments into two objects of similar properties. The latter model may be the most realistic one, in accordance with observations (see hereafter).

### 4.2. Astrophysical Consequences

Our results suggest that the combined effect of magnetic fields and radiative transfer could control the early fragmentation of the core and we speculate that this could lead either to the formation of isolated massive stars or OB associations. The MU2 model gives rise to a single fragment with a large reservoir of mass ∼10 M⊙ stable against fragmentation. The strong magnetic field case is thus a preferred scenario for non-runaway massive stars (i.e., not ejected from a cluster) that are found in isolation. Our proposed scenario does not exclude the formation of close massive binaries and OB associations. Fragmentation in massive binary system can possibly occur in more massive cores or in cores with different initial conditions than ours (for example, with stronger density fluctuations initially). They could also form during the second collapse phase as it has been shown in the low-mass star formation framework (Machida et al. 2008). OB associations can also form by global collapse of a giant molecular cloud containing several massive magnetized dense cores. In addition, the MU5 model produces two fragments that are also associated with a relatively high Jeans mass reservoir. Contrary to previous lower resolution studies (Krumholz et al. 2007, 2009; Peters et al. 2011), the secondary fragment is not produced by disk fragmentation, but rather by collapse along a filamentary structure. One can expect that this early fragmented system will also give rise to a close massive binary system following results of Bonnell & Bate (2005).

Recently Girart et al. (2009) reported observations of a hot molecular core (HMC) in the massive star-forming region G3141 and concluded that the gravitational collapse of the HMC is controlled by magnetic field. They also observed a spin-down in the HMC which suggests that magnetic braking is acting and removing angular momentum. Last but not least, they inferred a mass-to-flux over critical mass-to-flux ratio of 2.7 which corroborates our results. At later evolution stages, Bestenlehner et al. (2011) observed a very massive star of ∼150 M⊙ in apparent isolation from the massive cluster R136, which could be formed from a highly magnetized dense core rather than being ejected from the dense cluster. Bontemps et al. (2010) reported imaging of massive dense cores with high angular resolution. They found that fragmentation in massive core tends to lead to fewer high-mass fragments inconsistent with a pure gravroturbulent fragmentation (which would correspond to the MU130 model). Their results support our findings on the enhanced effect of the magnetic braking and radiative transfer when mass increases.

### 5. CONCLUSION AND PROSPECTS

In this Letter, we propose a new mechanism to suppress initial fragmentation of highly magnetized massive dense cores and speculate that it can lead to massive star formation. Our scenario differs from previous work, since it does not invoke stellar mergers as in the competitive accretion scenario (Bonnell et al. 2001), nor low-mass protostars’ radiative feedback and high column density (Krumholz & McKee 2008), and nor disk fragmentation (Krumholz et al. 2009; Peters et al. 2011). We investigate the early stages of the collapse and fragmentation of turbulent, massive, and magnetized dense cores with RMHD calculations. We show that the combined effect of magnetic braking and radiative transfer suppresses fragmentation in the case of a strong magnetic field as it has been shown in the low-mass star formation framework (Commerçon et al. 2010; Tomida et al. 2010). Magnetic braking transports angular momentum outward, and the accretion rate on the FHSC is thus larger. As shown in Commerçon et al. (2011a), all the infall kinetic energy is radiated away at the first core accretion shock and allows greater heating. The interplay between magnetic fields and radiative transfer is independent of the initial conditions other than magnetic field strength. In addition, this interplay can only be caught in self-consistent RMHD models with thermal (re-)emission and radiative shocks. This effect is expected to become stronger with appropriate physical models for the second collapse and second core formation and for protostellar evolution (see, e.g., Krumholz et al. 2007). To reach the final stellar mass, the subsequent evolution of the forming protostars can then follow a disk accretion scenario (Kuiper et al. 2011; Seifried et al. 2011). Further work will imply detailed fragmentation and resolution studies (e.g., Federrath et al. 2011) and the introduction of sink particles to follow a longer dynamical range. We also neglect in this work ionization and protostellar feedbacks which influence further time evolution (Peters et al. 2011; Cunningham et al. 2011).

As a conclusion, we speculate that highly magnetized dense cores are the seed of massive stars and good candidates for massive star-forming regions.

Calculations have been performed on the THEO cluster at MPIA and on the JADE cluster at CINES. B.C. thanks Romain Teyssier and Henrik Beuther for useful discussions.

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*Commerçon, Hennebelle, & Henning*
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