Theories of the massive star formation: a (short) review

Patrick Hennebelle and Benoît Commercçon

Abstract We briefly review the recent numerical works that have been performed to understand the formation of massive stars. After a brief description of the classical works, we review more specifically i) the problem of building stars more massive than $20 \ M_\odot$ and ii) how to prevent the massive cores to fragment in many objects. Multi-D simulations succeed in circumventing the radiative pressure leading to the formation of massive stars although some questions are still debated regarding how is accretion exactly proceeding. While the core fragmentation is slightly reduced by the radiative feedback and the magnetic field when they are treated separately, it is almost entirely suppressed when both of them are included. This is because, magnetic field by removing angular momentum focusses the flow in a compact region. This makes the radiative feedback very efficient leading to a significant increase of the temperature.

1 Introduction

High-mass stars have stellar masses roughly spanning the range $10 - 100 \ M_\odot$. From their birth to their death, high-mass stars are known to play a major role in the energy budget of galaxies via their radiation, their wind, and the supernovae. Despite that, the formation of high-mass stars remains an enigmatic process, far less understood than that of their low-mass (solar-type) counterparts. One of the main differences between the formation of high-mass and low-mass stars is that the radiation field of a massive protostar plays a more important role. Indeed, the massive stellar embryo strongly heats the gas and could even prevent further matter accretion through its radiation pressure. This implies that the radiative transfer must be treated in parallel
to the hydrodynamics, which represents a severe complication mainly responsible for the limited numbers of theoretical studies of this process. As described below, it has been realised that the magnetic field is likely to play an important role as well.

Here is presented a short introduction to the theory of high-mass star formation. We first present the basic principles used to estimate the largest stellar mass that one expects to form in the presence of radiative forces in 1D. We then describe the recent numerical simulations which have been performed to address the two important questions; how to build stars more massive that $20 \, M_\odot$ in spite of the radiative pressure; and how to prevent massive cores from fragmenting in many low mass objects?

2 The issue of circumventing the radiative pressure

2.1 One dimensional estimate

The first estimates of the largest stellar mass that can possibly be assembled are due to Larson & Starrfield (1971) and Kahn (1974). The principle of their analysis is to compare the radiative pressure of a massive stellar embryo to the ram pressure induced by the gravitational collapse of its surrounding massive cloud, in its inner and outer parts. If the luminosity of the central star becomes high enough, the radiation pressure may become important and prevent further accretion onto the central object. Since the radiation pressure is acting on the dust grains, one has to assume that the frictional coupling between the gas and the dust is sufficiently strong so that forces acting on the dust grains are transmitted to the gas.

In the inner part of the collapsing cloud, the temperature becomes high and the dust grains evaporate. There is thus a dust shell whose inner edge is located at the radius, $r$, where the grains evaporate. At this sublimation radius, the radiation pressure is $L_*/4\pi r^2 c$, where $L_*$ is the stellar luminosity and $c$ the speed of light. The dynamical pressure is $\rho u^2$, where $\rho$ is the density and $u$ the infall speed which is given by $u^2 \simeq 2GM_*/r$, where $G$ is the gravitational constant and $M_*$ the mass of the protostar. This leads to the ratio of radiative to ram pressures

$$\Gamma = \frac{L_*/4\pi r^2 c}{\rho u^2} \simeq 1.3 \times 10^{-11} \frac{L_*/L_\odot}{(M_*/M_\odot)^{1/2}} r^{1/2}. \quad (1)$$

Using an analytic estimate for the temperature inside the cloud and based on the assumption that the grains evaporate at a temperature of $\sim 1500$ K, Larson & Starrfield (1971) estimate the radius of the shell to be

$$r \simeq 2.4 \times 10^{12} \frac{(L_*/L_\odot)^{1/2}}{(M_*/M_\odot)^{1/2}} \text{cm} \simeq 3.3 \frac{(L_*/10^3 L_\odot)^{1/2}}{(M_*/8 M_\odot)^{1/5}} \text{AU}. \quad (2)$$

It follows from Eqs. 2.1–2.2 that
\[ \Gamma \simeq 2 \times 10^{-5} \frac{(L/L_\odot)^{6/5}}{(M/M_\odot)^{3/5}}. \] (3)

For a stellar mass of 20 \( M_\odot \), corresponding to a luminosity of about \( 4 \times 10^4 L_\odot \), \( \Gamma \) roughly equals unity. Therefore, according to Larson & Starrfield (1971), the mass at which radiative pressure impedes accretion is around 20 \( M_\odot \).

A more accurate estimate has been done by Wolfire & Cassinelli (1987) by using the optical properties and composition of the mixture of dust grains proposed by Mathis et al. (1977). Assuming an accretion rate of \( 10^{-3} M_\odot \) yr\(^{-1} \) in a 100 \( M_\odot \) cloud, Wolfire & Cassinelli show that \( \Gamma \) is larger than one for any reasonable value of the radiation temperature. They conclude that building a massive star with the “standard” dust grain mixture is difficult and requires reducing the grain abundance by large factors (~4–8). They thus propose, as a solution to the high-mass star formation problem, that the dust abundance could be locally decreased by an external shock or an internal ionization front.

More recently, Kuiper et al. (2010) have also performed 1D calculations for various core masses and confirm largely the results of these early works. In particular, they cannot form objects more massive than 20 \( M_\odot \) even in very massive cores.

### 2.2 Bidimensional multi-wavelengths calculations

Bi-dimensional numerical simulations have been performed, treating the radiation and the dynamics self-consistently. In these studies, it has been assumed that the radiation arises from both the accretion and the stellar luminosity. While the former is dominant during the earliest phases of the collapse, the latter becomes more important at more advanced stages. One of the main motivations of these calculations is to determine whether the presence of a centrifugally supported optically thick disk, inside which the radiative pressure would be much reduced, may allow to circumvent the radiation pressure problem. The first numerical simulations have been performed by Yorke & Sonnhalter (2002) in the frequency dependent case (using 64 intervals of frequency) and in the grey case (one single interval of frequency). The cloud they consider is centrally peaked, has a mass of 60 \( M_\odot \), a thermal over gravitational energy ratio of about 5\% initially, and is slowly rotating. After \( \sim 10^5 \) yr, the central core has a mass of about 13.4 \( M_\odot \) and the surrounding cloud remains nearly spherical. After \( \sim 2 \times 10^5 \) yr, the mass of the central core is about 28.4 \( M_\odot \) and the cloud starts to depart from the spherical symmetry. In particular, the infall is reversed by radiative forces in the polar region while the star continues to accrete material through the equator where the opacity is much higher. This is known as the “flashing light effect”. Once the stellar mass has grown to about 33.6 \( M_\odot \), the central star is no longer accreting although 30 \( M_\odot \) of gas is still available within the computational grid. The infall is then reversed in every directions indicating that the radiative forces are effectively preventing further accretion. If instead of a multi-frequency treatment, the grey approximation is made, the early evolution is similar...
but becomes notably different after $\sim 2.5 \times 10^5$ yr. In particular, there is no evidence of any flow reversal. Instead the material flows along a thin disklike structure, supported in the radial direction by both centrifugal and radiative forces. At the end of the simulation, the mass of the central star is about $20.7 \, M_\odot$.

Kuiper et al. (2010) have performed bi-dimensional simulations using an hybrid scheme for the radiative transfer. While the gas emission is treated using the flux-limited diffusion and the grey approximation, direct multi-frequency irradiation from the central star is also included. In particular, they stress the importance of spatially resolving the dust sublimation front. In the simulations that do not resolve it well, the accretion quickly stops while it continues when the sublimation front is well described. This is because the radiation is more isotropic when the dust sublimation front is not properly resolved, leading to a weak flashlight effect. In their simulations, Kuiper et al. (2010) form objects of mass much larger than the $\approx 20 M_\odot$ that they form in their 1D calculations. For example for a 480 $M_\odot$ clump, they form an object of 150 $M_\odot$ which is still accreting.

### 2.3 Tridimensional calculations

The first 3D-calculations have been performed by Krumholz et al. (2007, 2009). They use a flux-limited and grey approximation to treat the radiative transfer. The most striking aspect they report is certainly the development of the Rayleigh-Taylor instability in the radiatively triggered expanding bubble. As a consequence of the non-linear development of this instability, fingers of dense material can channel through the low density radiatively dominated cavity and reach the central object. They therefore identify three modes of accretion in their simulations, accretion through the disk (the flashlight effect), accretion through the cavity wall, and accretion through dense Rayleigh-Taylor unstable fingers. A quantitative estimate reveals that the latter route accounts for about 40% of the accretion.

These results have been questioned by Kuiper et al. (2012) who performed bidimensional calculations with a flux-limited scheme similar to the one used by Krumholz et al. (2009) and the hybrid scheme which is used in Kuiper et al. (2010). The results turn out to be quite different. In the first case, a radiatively dominated bubble is launched but is quickly stopped and falls back towards the equatorial plane. In the second case, the bubble keeps expanding leading to a radiatively driven outflow. One of the important consequence is thus that accretion occurs exclusively through the disk. As these simulations are bidimensional, it is unclear whether they completely rule out the development of the Rayleigh-Taylor instability which could be largely seeded by the non-linear fluctuations induced by the turbulence in 3D. They nevertheless suggest that the dynamics of the radiatively dominated cavity is largely determined by the treatment of the radiative feedback in particular its frequency dependence.
3 The issue of fragmentation

The second drastic problem in the context of massive star formation is how to avoid fragmenting the massive cores in many objects. For example in the simulations that have been performed by Dobbs et al. (2005), the 30 solar mass core they simulate, fragments in about 20 low mass objects thus preventing the formation of high mass objects. While it remains possible that large mass objects could be formed in very massive clumps through competitive accretion (e.g. Bonnell et al. 2004), it is important to treat in any case, the physics of the fragmenting cores properly which is the task that the studies described below have addressed.

3.1 Hydrodynamical radiative calculations

Tridimensional calculations have been performed by Krumholz et al. (2007) using the grey approximation for the radiative transfer. Their initial conditions (aimed at reproducing the model of McKee & Tan (2003) consist in a centrally peaked $100\,M_\odot$ cloud with a density profile proportional to $r^{-2}$. The initial turbulence within the cloud is sufficient to ensure an approximate hydrostatic equilibrium. Turbulent motions first delay the onset of collapse but, as the turbulence decays, the cloud starts to collapse. Comparison is made with runs for which an isothermal equation of state is used. In particular, Krumholz et al. (2007) find that, when the radiative transfer is taken into account, the gas temperature inside the cloud is higher than in the isothermal case, by factors up to 10, which are depending on the cloud density. As a consequence, the cloud is fragmenting much less when radiation is taken into account than when isothermality is used. It is important to note at this stage that centrally condensed cores are less prone to fragmentation than cores having flatter density profiles as shown by Girichidis et al. (2010). Indeed the radiative hydrodynamical simulations performed by Commerçon et al. (2011) clearly show that cores which initially have a flat density profile, are undergoing significant fragmentation as shown by the top left and bottom left panels of Fig. [I]

3.2 MHD barotropic calculations

Another important process that must be included in the treatment of massive cores, is the magnetic field. Indeed, in the context of low mass cores, magnetic field has been found to drastically reduce the fragmentation (Machida et al. 2005, Hennebelle & Teyssier 2008). Hennebelle et al. (2011) have been running a set of barotropic simulations for various magnetic intensities. The initial conditions consist in 100 $M_\odot$ cores with a smooth initial density profile and a turbulent velocity field (with a ratio of turbulent and gravitational energies of about 20%). The fragmentation is delayed and reduced when the magnetic flux is strong enough (typically for mass-to-
Fig. 1 Column density within central part of massive collapsing cores. Left: hydrodynamical case, the core is largely fragmenting eventhough radiative feedback is treated. Right: RMHD simulation (initial mass-to-flux of 2), the fragmentation is entirely suppressed due to the combination of magnetic field and radiative feedback (Commerçon et al. 2011).

flux smaller than 5). The number of objects decreases up to typically only a factor of two for the strongest magnetisation that was explored. Thus, Hennebelle et al. (2011) conclude that magnetic field in itself cannot suppress the fragmentation in many objects. The reason of this limited impact is largely due to the magnetic diffusion induced by the turbulent velocity field, which reduces the magnetic field in the central part of the collapsing core where fragmentation is taking place. Similar conclusion has been reached by Peters et al. (2010) who even included photo-ionisation from the central star.

### 3.3 MHD radiative calculations

The first simulations that include both MHD and radiative feedback in the context of massive star formation, have been recently performed by Commerçon et al. (2011). These simulations show that the combination of magnetic field and radiative feedback is indeed extremely efficient in suppressing the fragmentation. The reason is that magnetic field and radiative feedback are in a sense interacting (Commerçon et
al. 2010) and their combination leads to effects that are much stronger than expected. This is because, as pointed out by Hennebelle et al. (2011) magnetic field, even in the presence of turbulence, leads to efficient magnetic braking which reduces the amount of angular momentum in the central part of the cloud where fragmentation is taking place. Thus, the accretion is initially much more focussed in a magnetized core than in a hydrodynamical core when turbulence is included because in hydrodynamical simulations, a large amount of angular momentum prevents the gas to fall in the central object. Consequently, the accretion luminosity which is $\propto \dot{M}/R$ is much higher because the mass of the central object and the accretion rate onto the central object are larger. Also the radius at which accretion is stopping is smaller (since there is less angular momentum). Consequently, the temperature in magnetized cores is much higher than in hydrodynamical cores making them much more stable against fragmentation. This is illustrated in Fig. 2 which shows the temperature as a function of density in four cases. The first panel shows the case of a cloud with no turbulence and no magnetic field which is purely spherical initially. In this case, the flow is extremely focussed and fall directly in a single central object. The second panel shows the temperature distribution for a turbulent and unmagnetized cloud while the third and fourth panels show this distribution for two magnetic intensities. Clearly the hydrodynamical case with turbulence has the lowest temperatures while the most magnetized case (fourth panel) presents much higher temperatures which are comparable to the one obtained in the purely spherical case (first panel) that is naturally focussed.
4 Conclusion

We have presented a brief review of the recent studies which have been performed to explain the formation of massive stars. Multi-D simulations including radiative feedback agree that it is possible to build stars more massive than predicted by the 1D spherical case in which radiative pressure prevents further accretion. The details, however, of how this accretion exactly proceeds are still a matter of debate. The fragmentation of massive cores is slightly reduced when either the radiative feedback or the magnetic field are present. However when both are treated simultaneously, the fragmentation is very significantly reduced because magnetic field focusses the gas which leads to a more efficient radiative feedback and higher temperatures.

References

1. Bonnell, I., Vine, S., Bate, M., 2004, MNRAS, 349, 735
2. Commercçon, B., Hennebelle, P., Audit, E., & Chabrier, G., Teyssier, R. 2010, A&A, 510L, 3
3. Commercçon, B., Hennebelle, P., Henning, T., 2011, ApJ, 742L, 9
4. Girichidis, P., Federrath, C., Banerjee, R., Klessen, R., 2011, MNRAS, 413, 2741
5. Hennebelle, P., Teyssier, R., 2008, A&A, 477, 25
6. Hennebelle, P., Commercçon, B., Joos, M., Klessen, R. S., Krumholz, M., Tan, J. C. & Teyssier, R. 2011, A&A, 528, A72
7. Kahn, F. 1974, A&A, 37, 149
8. Krumholz, M., Klein, R., McKee, C. 2007, ApJ, 665, 478
9. Krumholz, M. R., Klein, R. I., McKee, C. F., Offner, S. S. R., Cunningham, A. J. 2009, Science, 323, 754
10. Kuiper, R., Klahr, H., Beuther, H. & Henning, T. 2010, ApJ, 722, 1556
11. Kuiper, R., Klahr, H., Beuther, H. & Henning, T. 2012, A&A, 537, 122
12. Larson, R., Starrfield, S. 1971, A&A, 13, 190
13. Machida, M., Matsumoto, T., Tomisaka, K., Hanawa, T., 2005, MNRAS, 362, 369
14. Mathis, J., Rumpl, W., Nordsieck, K. 1977, ApJ, 217, 425
15. McKee, C., Tan, J. 2003 ApJ, 585, 850
16. Peters, T., Banerjee, R., Klessen, R., MacLow, M.-M., Galván-Madrid, R., Keto, E., 2011, ApJ, 729, 72
17. Price, D., Bate, M., 2009, MNRAS, 398, 33
18. Wolfire, M., Cassinelli, J. 1987, ApJ, 319, 850
19. Yorke, H., Sonnhalter, C. 2002, ApJ, 569, 846