Star Formation

https://doi.org/10.1017/S1743921317010742 Published online by Cambridge University Press

Astrophysical Masers:
Unlocking the Mysteries of the Universe
Proceedings IAU Symposium No. 336, 2017
A. Tarchi, M.J. Reid & P. Castangia, eds.

doi:10.1017/S1743921317010742

Perspectives on star formation: the formation of high-mass stars

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Abstract. The formation process of high-mass stars has puzzled the astrophysical community for decades from both a theoretical and an observational point of view. Here, we present an overview of the current theories and status of the observational research on this field, outlining the progress achieved in recent years on our knowledge of the initial phases of massive star formation, the fragmentation of cold, infrared-dark clouds, and the evidence for circumstellar accretion disks around OB stars. The role of masers in helping us to understand the mechanism leading to the formation of a high-mass star are also discussed.

Keywords. stars: formation, ISM: molecules, ISM: kinematics and dynamics

1. Introduction

High-mass stars are defined as those with masses $>8\,M_\odot$ and luminosities $>10^4\,L_\odot$. Following Salpeter's Initial Mass Function (IMF), one sees that high-mass stars are rare objects because for each $30\,M_\odot$ star formed, there are hundred $1\,M_\odot$ formed. These stars have short lifetimes and, because of that, are mainly located in the spiral arms of the galaxies in which they formed (e.g., Urquhart *et al.* 2014). High-mass stars are key elements in galaxies because they dominate their appearance and evolution, are responsible for the production of heavy elements, and influence the interstellar medium through energetic winds and supernovae. They produce enough UV radiation to create HII regions and huge ionized bubbles, and are the most chemically rich sources in the Galaxy, being the best reservoirs of Complex Organic Molecules, in particular of prebiotic ones (building blocks of life) (e.g., G31.41+0.31: Rivilla *et al.* 2017).

2. Challenges

Studying the formation of massive stars represents an observational challenge because high-mass stars are rare objects that are located at large distances. Typical distances of O-type star-forming regions are 5 kpc (Beltrán *et al.* 2006). They have short evolutionary timescales, so it is difficult to trace the earliest phases of their evolution. In addition, massive stars are embedded in rich clusters: only ∼4% of O-field stars might have formed outside clusters (de Wit *et al.* 2005). This makes it very difficult to disentangle their emission from that of the other cluster members and to trace the primordial configuration (initial conditions) of the molecular cloud. Therefore, it is absolutely necessary to carry out high-angular resolution observations, especially at cm and mm wavelengths, to study high-mass protostars.

From a theoretical point of view, massive stars represent a challenge because of their short evolutionary timescales. They form so fast that reach the zero age main sequence while still deeply embedded in the parental cloud and still with active accretion. For stars with masses $>8\,M_\odot$, the pre-stellar evolution is dominated by the Kelvin-Helmholtz timescale. This means that the contraction proceeds very fast and the star starts burning hydrogen while still accreting. According to theoretical predictions, in case of spherical accretion, the radiation pressure of the newly formed OB star should stop the accretion preventing further growth (e.g., Kahn 1974; Wolfire & Casinelli 1987). In the 90's, different theoretical scenarios proposed non-spherical accretion as a possible solution for the formation of OB-type stars (Nakano 1989; Jijina & Adams 1996), and in recent years, theoretical ideas and simulations appear to have converged to a disk-mediated accretion scenario (e.g., Krumholz *et al.* 2009; Kuiper *et al.* 2010; Kuiper & Yorke 2013). As a matter of fact, competing theories that propose very different high-mass star-formation mechanisms (monolithic collapse: Mc Kee & Tan 2002, and competitive accretion: Bonnell & Bate 2006) predict the existence of circumstellar accretion disks.

3. Theoretical models: predictions and differences

The two competing theories that discuss the formation of high-mass stars are:

Monolithic collapse. This models predicts that massive stars form via monolithic collapse of a massive turbulent core fragmented from the natal molecular cloud (Mc Kee & Tan 2002, 2003). The forming star gathers its mass from this massive core alone. In the monolithic collapse, massive stars should form in (almost) isolation. The core mass function is similar to the IMF (Krumholz *et al.* 2005). In the turbulent core accretion, the accretion rates are high, of the order of 10^{-2}–$10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$, as often observed in high-mass star forming regions (e.g., Beltrán *et al.* 2011). The monolithic collapse process is slow and quasi-static and starts with a strongly peaked density distribution ($n \propto r^{-1.5}$). Given the non-zero angular momentum of the collapsing core, this model predicts the existence of protostellar accretion disks around massive stars. These accretion disks have been recently found around early-B to late-O type stars (see Beltrán & de Witt 2016 for a review).

The existence of truly isolated massive stars is one of the caveats of the model, because as concluded by de Wit *et al.* (2005), only 4% of O-field stars might have an origin outside of a young cluster. Another caveat of the model is the existence of monolithic pre-stellar cores. There have been few claims of their existence (Tan *et al.* 2013; Peretto *et al.* 2014; Wang *et al.* 2014; Sanhueza *et al.* 2017), but in many cases, the cores are not massive or dense enough to form a massive star. Finally, one of the main problems of the core collapse model is how to prevent fragmentation. It has been proposed that protostellar heating could reduce significantly fragmentation because it would increase the Jeans masses (Krumholz *et al.* 2007), or that fragmentation could be controlled by the magnetic field, as suggested by the magneto-hydrodynamics simulations of Hennebelle *et al.* (2011) and Commerçon *et al.* (2011, 2012). In these simulations, highly magnetized cores show a low level of fragmentation, while cores where turbulence dominates over magnetic field show a high fragmentation level.

Competitive accretion. This model predicts the initial fragmentation of a molecular cloud in low-mass cores of Jeans masses, which form stars that compete to accrete unbound gas from the common gas reservoir (Bonnell *et al.* 1997; Bonnell & Bate 2006), that is, from the whole cloud. The cloud experiences global collapse and the stars located near the center of the gravitational potential accrete at a higher accretion rate because of a stronger gravitational pull. A special case of interaction is that causing a merging of low-mass stars, which is predicted for unusually high stellar densities, of the order of 10^8 stars per cubic parsec, although the density could be smaller if the mergers are binary systems, in that case it would be $\sim 10^6$ stars per cubic parsec (Bonnell & Bate 2005). In

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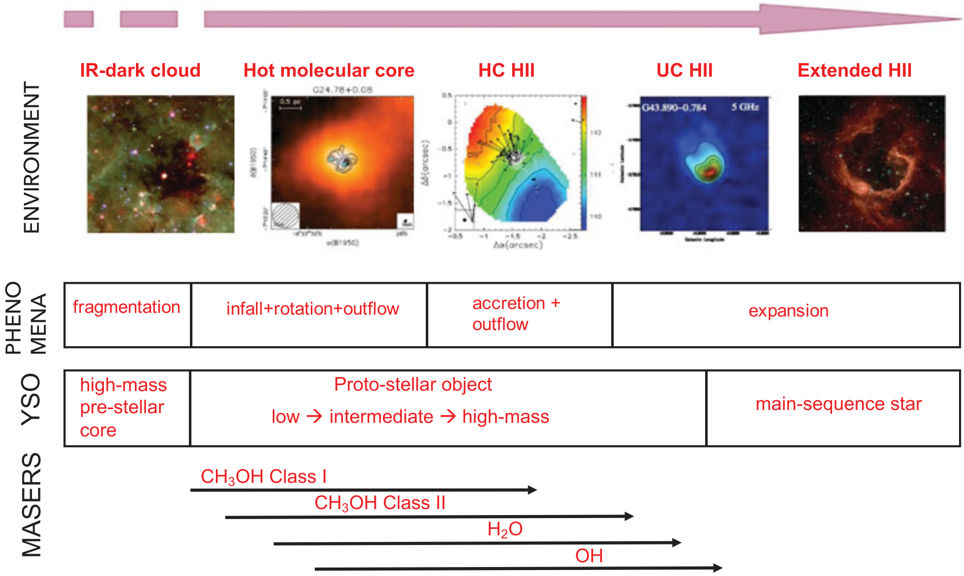

Figure 1. Evolutionary sequence for high-mass stars: from cold IRDCs to chemically rich HMCs to HII regions.

the competitive model, massive stars should always form in clustered environments, as very often observed. The model reproduces the full IMF (Bonnell *et al.* 2004) and the accretion is Bondi-Hoyle. The collapse is a fast, dynamical, and gravity-driven process. The collapse starts with a uniform gas density distribution. In the original competitive accretion model, disks were not predicted, or were very small, because severely affected or destroyed by tidal interactions with the other member of the protocluster (Cesaroni 2006). In more recent updates, the competitive accretion model also predicts the existence of disks around the most massive members in the cluster, although it is not clear how disturbed, large, or transient these disks can be.

Krumholz *et al.* (2005) proposed that the model could not work because the virial parameters and accretion rates were too low. The high velocities of the gas relative to stars and the low accretion rates would not allow the low-mass stars to accrete enough mass to become massive ones. In addition, radiation pressure should stop Bondi-Hoyle accretion above 10 $M_\odot$. Finally, another caveat of the model is that feedback, especially of ionized gas from OB-type stars, was not taken into account. Bonnell & Bate (2006) have answered to most of these criticisms and proposed that initially the relative velocities between gas and stars are low and the turbulence is locally small, which allows the low-mass stars to accrete mass. Regarding the low accretion rates, they should be higher if one considers the local cluster core and not just the global cloud. Finally, regarding feedback from OB-type stars, if accretion proceeds mostly through disks, then all the mass flow is channeled into a relatively small area that intercepts only a small fraction of the incident UV flux. In addition, most of the radiation escapes through the polar regions and does not significantly interact with infalling gas (Krumholz *et al.* 2009; Peters *et al.* 2010) that proceeds unhampered onto the central star (Dale *et al.* 2005).

4. Evolutionary sequence

Figure 1 shows the evolutionary sequence of a high-mass star, with the different phenomena (fragmentation, rotation, infall, outflow) and young stellar (or pre-stellar) objects

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(YSOs) associated. Because of the short timescales needed to form a massive star and the difficulty to trace the earliest stages of its formation, to define an evolutionary sequence for high-mass stars is not easy. The formation of a massive star initiates with the fragmentation of a cold cloud, usually dark at infrared wavelengths that is known as infrared-dark cloud (IRDC). Subsequent infall and heating inside each core eventually leads to the formation of chemically rich hot molecular cores (HMCs), which are the cradle of high-mass stars. Accretion continues onto high-mass protostars that gain mass. The UV-radiation from the young embedded star will develop a bubble of ionized gas, known as hypercompact HII (HC HII) region that will start expanding, becoming first an ultracompact HII (UC HII) region and later on, an extended or giant HII region. Finally, the gas is dissipated by the ionized winds, exposing the newly formed OB star. Note that IRDCs and HMCs are the typical environments associated with the different phenomena, but they not represent evolutionary phases by themselves. Therefore, inside IRDCs we can find from embedded protostellar objects up to more evolved compact HII regions. Regarding the masers, the first in appear, already in the earliest phases, are the Class I and Class II methanol masers, then the water masers, and finally the hydroxyl masers. However, it is very difficult to define an evolutionary sequence only with masers because the different types can be found almost in all the evolutionary stages.

4.1. *Infrared-dark clouds*

The onset of massive star formation takes place inside cold ($T < 20$ K), massive (10^3–$10^4\ M_\odot$), parsec-scale (1–5 pc) clouds known as IRDCs. These clouds, which have volume densities of 10^4–10^5 cm^{-3}, are seen in absorption at infrared wavelengths and in emission at millimeter and sub-millimeter wavelengths (e.g., Pérault *et al.* 1996; Egan *et al.* 1998; Carey *et al.* 1998; Rathborne *et al.* 2006). Although IRDCs have very different morphologies, they often appear as filaments (e.g., the "snake" nebula: Wang *et al.* 2014; or the "Nessie" nebula: Jackson *et al.* 2010; Goodman *et al.* 2014).

Do massive pre-stellar cores exist? One of the open questions in massive star formation is how *pre-stellar* are the cores embedded in IRDCs. The high sensitivity Spitzer and Herschel observations have shown that many IRDCs present evidence for active star formation. Some of them show enhanced, slightly extended 4.5 μm emission, called "green-fuzzies", and maser emission, all indicators of the presence of molecular outflows, broad SiO emission which indicates shocked gas, bright 24 μm, associated with embedded protostars, or 8 μm, probably from HII regions (Chamber *et al.* 2009; Cyganowski *et al.* 2009; Jiménez-Serra *et al.* 2010). Large surveys have been carried out with MSX, Spitzer, and Herschel to search for massive starless cores by looking for cores IR-quiet at 24 or 70 μm and with temperatures below 15 K (e.g., Beltrán *et al.* 2006; Motte *et al.* 2007; Chambers *et al.* 2009; Rathborne *et al.* 2010; Butler & Tan 2012; Tigé *et al.* 2017). As a result of these searches many candidates have been proposed as starless (Duarte-Cabra *et al.* 2013; Tan *et al.* 2013; Cyganowski *et al.* 2014; Peretto *et al.* 2014; Wang *et al.* 2014; Sanhueza *et al.* 2017), but in many cases their densities or masses are too low, especially when observed at observed high-angular resolution. Even the best starless candidates identified with ALMA in Cycle 0, like for example G28.37+0.07 C1-S (Tan *et al.* 2013), appear to be active and associated with molecular outflows when observed at higher sensitivity with ALMA in Cycle 2 (Tan *et al.* 2016). In conclusion, if massive pre-stellar cores do exist, they are very rare objects. In fact, Motte *et al.* (2007) have been proposed that starless massive cores might do exist but would be short-lived ($< 10^3$ yr), and therefore difficult to "catch".

What does it control fragmentation? Another open question related to the first stages of evolution of a high-mass star is what controls fragmentation. High-angular resolution sub-millimeter observations of IRDCs show evidence of different levels of fragmentation (Zhang *et al.* 2009; Bontemps *et al.* 2010; Longmore *et al.* 2011; Palau *et al.* 2015; Rathborne *et al.* 2015; Fontani *et al.* 2016; Henshaw *et al.* 2017; see Fig. 2). In many cases, the masses of the fragments are of a few tens of $M_\odot$. Since these cores are cold ($T <$ 20 K) and dense ($n \sim 10^4$–10^5 cm^{-3}), their Jeans masses are $M_{\rm Jeans} \sim$1–5 $M_\odot$. Therefore, these fragments have super-Jeans masses and cannot be only thermally supported. Other support mechanisms such as turbulence of magnetic field are required to account for the large masses observed. 3D radiation-magneto-hydrodynamics simulations of Hennebelle *et al.* (2011) and Commerçon *et al.* (2011, 2012) suggest that magnetic field and radiative transfer strongly interplay at the early stages of star formation. In these simulations, highly magnetized cores, identified thanks to a low mass-to-flux over critical mass-to-flux ratio show a low level of fragmentation, while cores where turbulence dominates over magnetic field show a high fragmentation level. Fontani *et al.* (2016) have confronted real ALMA observations of the fragmented IRDC IRAS 16061−5048c1 with the simulations of Commerçon *et al.* (2011) and concluded that magnetic field indeed plays a crucial role in the fragmentation process even though the cloud fragments. Note that one very important piece is still missing in these comparisons, and this is the strength of the magnetic field. However, dust polarization observations, or even better, Zeeman effect measurements, carried out with ALMA should allow us to estimate it.

4.2. *Hot molecular cores*

High-mass protostars are deeply embedded in chemically rich HMCs. The high temperatures ($T > 100$ K) achieved when the protostar starts heating the surroundings produce the evaporation of the grain mantles giving rise to this rich chemistry (e.g., G31.41+0.31: Rivilla *et al.* 2017). Hot cores have typical sizes of 0.1 pc, luminosities $> 10^4\,L_\odot$, and high densities of $\sim 10^7$ cm^{-3}. Hot molecular cores are associated with young massive protostars but also with more evolved objects that have already developed a HC or UC Hii, like for example G24.78+0.08 (Moscadelli *et al.* 2007; Beltrán *et al.* 2007). One of the hottest topics in the star formation field is how a massive young stellar object gathers its mass. High-mass star-forming theories appear to converge to a disk-mediated accretion scenario, but what do the observations tell us? Do true accretion disks around massive stars really exist?

Disks around early B-type and late O-type (proto)stars. Circumstellar disks have been detected around stars with masses up to 25–30 $M_\odot$ by means of NIR and MIR (e.g., IRAS 13481−6214: Kraus *et al.* 2010; CRL 2136: de Wit *et al.* 2011), and (sub)millimeter (e.g., IRAS 20126+4104: Cesaroni *et al.* 2014) interferometric observations. ALMA high-angular resolution observations have allowed us to study in detail the velocity field of these circumstellar disks. The observed velocity gradients have been modeled and are consistent with Keplerian rotation (e.g., G35.20−0.74N: Sánchez-Monge *et al.* 2013; G35.03+0.35: Beltrán *et al.* 2014; AFGL 4176: Johnston *et al.* 2015; G11.92−0.61 MM1: Ilee *et al.* 2016). The radii of these disks are approximately a few 1000 au, although for some sources observed at very high-angular resolution, the radii can be as small as 300–400 au (Beltrán & de Wit 2016, and references therein). Their masses are of a few $M_\odot$. For true acretion disks candidates, the mass of the disk is always smaller than (or similar to) the mass of the central star, $M_\star$. This suggests that these structures could be rotationally supported.

Disks around early O-type (proto)stars. For higher mass stars, with luminosities $>10^5\,L_\odot$ and spectral types earlier than O6–O7, the situation is different. What has been found around these objects are huge and massive rotating structures called toroids. These toroids have masses of a few 100 $M_\odot$ and sizes of several 1000 au, which suggests that

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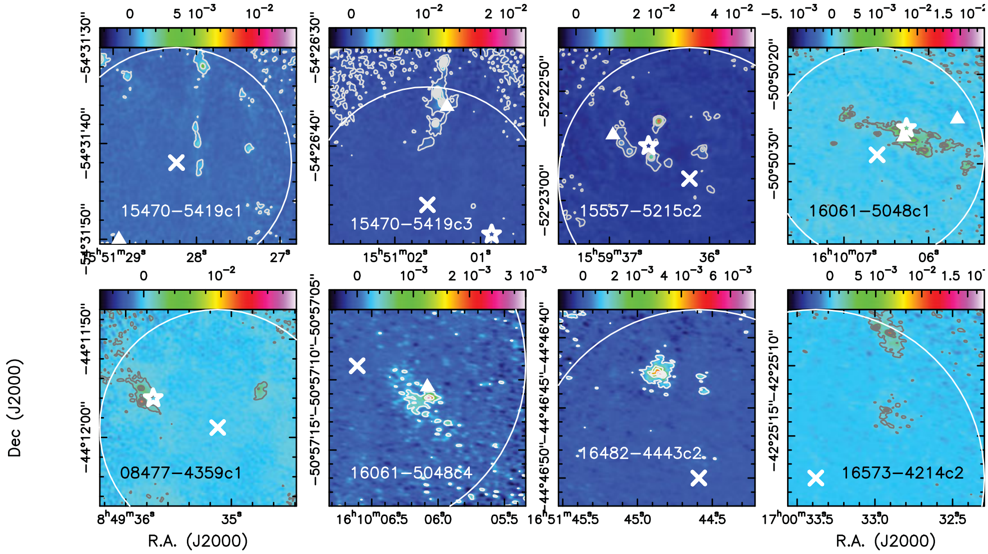

Figure 2. ALMA 278 GHz dust continuum emission maps of a sample of IRDCs showing different levels of fragmentation (Fontani *et al.*, in preparation). The white crosses and circles indicate the ALMA phase center and primary beam, respectively, the stars the position of IR sources, and the triangles the H_2O maser spots.

they are probably surrounding protoclusters. The mass of these toroids is much higher than that of the central star, and therefore, Keplerian rotation is not possible (on scales of 10^4 au) because the gravitational potential of the system is dominated by the toroid and not by the central star. In addition, the mass of the toroid is higher than the dynamical mass, which suggests that these structures might be undergoing fragmentation and collapse.

In a recent study carried out with ALMA, Cesaroni *et al.* (2017) have observed six early O-type star-forming regions looking for circumstellar disks. The 1.4 mm dust continuum emission has revealed that some of the cores fragment in few sources, while others, like G31.41+0.31, do not fragment at all. The CH_3CN observations with an angular resolution of $0.2''$ have revealed that i) three of the cores show signatures of Keplerian rotation, with the position-velocity (PV) plots showing the typical butterfly pattern; ii) three of the cores show velocity gradients that suggest rotation, but the PV plots are not consistent with Keplerian motions; and iii) G17.64+0.16 shows no hints of rotation. The luminosity-to-mass ratio as a function of the distance to these sources, including the O-type star AFGL 4176 observed by Johnston *et al.* (2015), shows that true accretion disks are found for sources with an intermediate evolutionary stage, while those with questionable disk evidence are the younger sources (Cesaroni *et al.* 2017). The explanation for the non-detection of Keplerian disks around these young sources could be that their disks are so embedded that their emission is difficult to disentangle from that of the envelopes. Alternatively, disks might start small and grow up with time. On the other hand, for the most evolved source in the sample, G17.64+0.16, the molecular gas might have dispersed and therefore, no disk is found.

Disks versus toroids Disks and toroids are different from a point of view of stability. While accretion disks around Herbig Ae stars and bona-fide Keplerian disks around early B- and late O-type (proto)stars have masses $<0.3\,M_\star$ and a stability Toomre's Q parameter >1, suggesting that they are stable, toroids have all masses $>0.3 M_\star$ and $Q<1$.

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Disks and toroids are also dynamically different. Disks around Herbig Ae and those in Keplerian rotation around high-mass stars have dynamical masses higher than those of the central star, while toroids around O-type stars have dynamical masses much smaller, and therefore cannot be centrifugally supported and could be susceptible to gravitational collapse and fragmentation. The ratio of the free-fall time, $t_{\rm ff}$, and the rotational period at the outer radius, $t_{\rm rot}$, is also higher for disks than for toroids. This suggests that if the structure rotates fast, the infalling material has enough time to settle into a centrifugally supported disk, otherwise, the infalling material does not have enough time to reach centrifugal equilibrium and the rotating structure is a transient toroid.

Typical infall rates, $\dot{M}_{\rm inf}$, in intermediate- and high-mass (proto)stars are of the order of 10^{-3}–$10^{-2}\,M_\odot$/yr, while typical accretion rates, $\dot{M}_{\rm acc}$, estimated from the mass loss rate of the associated outflow, are of the order of 10^{-4}–$10^{-3}\,M_\odot$/yr (Beltrán & de Wit 2016). $\dot{M}_{\rm inf}$ are always higher than $\dot{M}_{\rm acc}$, and in some cases up to a factor 1000. This could be a result of stellar multiplicity if the infalling material is not accreted onto the single star driven the molecular outflow but onto a cluster of stars. This explanation seems plausible for the most massive O-type (proto)stars, because as already explained, the sizes and masses of the rotating toroids suggest that they are enshrouding stellar (proto)clusters. However, this explanation cannot solve the problem for the intermediate-mass protostars and probably neither for the B-type (proto)stars. For intermediate-mass protostars with $M_\star \simeq 2$–$3\,M_\odot$, the $\dot{M}_{\rm inf}/\dot{M}_{\rm acc}$ ratio is still 20–300, with mass of the structure of $\sim$0.3–1.4 $M_\odot$. Therefore, although these disks could be circumbinary disks, it seems unlikely that they are circumcluster structures surrounding several members. The apparent implication of this is that the infalling material needs to pile up in the disk and results in disk masses that are tens to hundreds of solar masses given the observed rates. This is massive and suggests a gravitationally unstable disk inducing variable, "FUOri-like" accretion events onto the central object. And this is what has been recently discovered in the high-mass regime by Caratti o Garatti *et al.* (2016). These authors have discovered the first disk-mediated accretion burst from a young stellar object of $\sim$15 $M_\odot$, S255 NIR 3. The NIR photometry reveals an increase in brightness of 2.5–3.5 magnitudes and NIR spectroscopy reveals emission lines typical of accretion bursts in low-mass protostars, but orders of magnitude more luminous, confirming our prediction.

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