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Massive star formation in the Galaxy

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Abstract. Massive stars (M$\gtrsim$ 8 $M_\odot$) are very important for the dynamical and chemical evolution of galaxies. They are however not as thoroughly studied as their low-mass counterparts, because they are on average more distant, they remain deeply embedded in their natal clouds until they reach the main sequence, and they have a destructive influence on their surroundings. Nevertheless, in recent years considerable progress has been made in the study of the earliest phases of high-mass stars. In this contribution we outline the importance of massive stars, the theoretical and observational difficulties associated with them, and show some of the latest results obtained in the study of the earliest stages of their evolution.

1. Introduction

Massive stars (M$\gtrsim$ 8 $M_\odot$; spectral types B3 and earlier) have a significant influence on the morphology and chemical evolution of the Galaxy. During their lifetime they transfer large amounts of energy and momentum to the interstellar medium (ISM) through stellar winds and supernova explosions, creating and sustaining turbulence. Through these phenomena they also enrich the ISM with the products of nucleosynthesis generated in their interior, that are important for the formation of dust grains. With their large output of UV photons, massive stars ionize the surrounding ISM creating HII regions.

Through these energetic processes massive stars can destroy their natal environment, thereby inhibiting any further star formation in the same cloud. On the other hand, through some of the same processes they may also trigger the formation of a new generation of stars. At the borders of a supersonically expanding HII region a dense layer of swept-up molecular material may form between the ionization front and the shock front that preceeds it. This layer may become unstable and fragment; from the dense cores thus formed new stars may form (Whitworth et al. 1994). This so-called 'collect-and-collapse' process has recently been shown to have triggered massive star formation in Sh 2-104 (Deharveng et al. 2003) and RCW 79 (Zavagno et al. 2006; see Fig. 1).

Winds and supernova explosions create bubbles in the ISM, filled with hot tenuous plasma. Many of these are found in our Galaxy (e.g., the Cepheus Bubble, Abrahám et al. 2000; the Orion-Eridanus Bubble, Brown et al. 1995) and in other galaxies (e.g., 30 Doradus in the LMC). The edges of small dense molecular clouds that find themselves inside or at the borders of these bubbles are eroded by the intense UV-radiation, but they may be induced to form (low-mass) stars in their interiors. This is seen for instance in the bright-rimmed globules associated with the Gum nebula (Reipurth 1983), the Cepheus bubble (Reach et al. 2004;

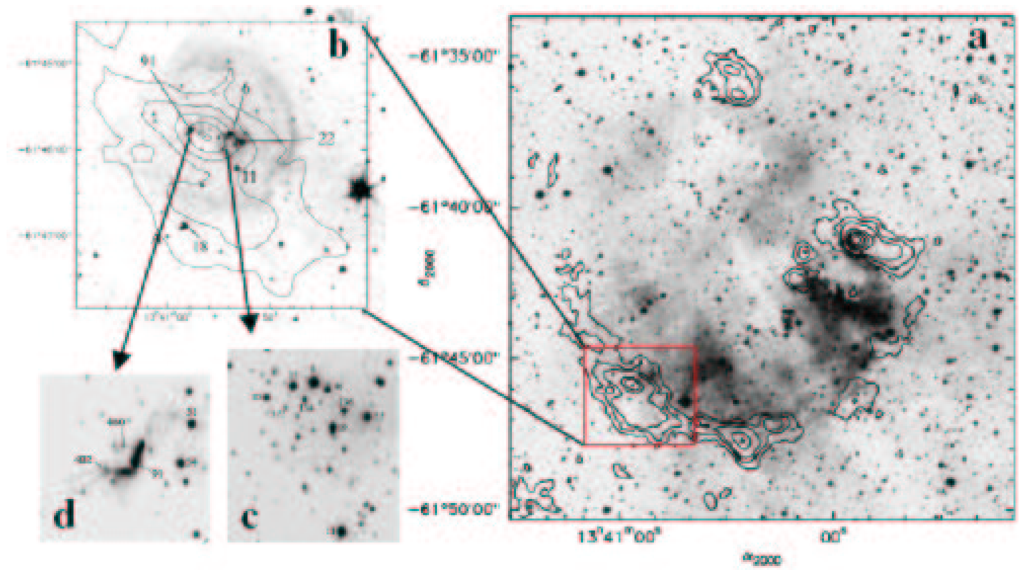

Fig. 1. Triggered star formation in RCW 79 (adapted from Zavagno et al. 2006). **a** Contours of the 1.2-mm continuum emission superimposed on an Hα image. Several condensations are seen on the borders of the HII region; the one marked by the box is associated with an UC HII region. **b** Zoom-in, showing 1.2-mm contours and the Spitzer/IRAC 3.6 μm image. **c** A NIR cluster ionizing the UC HII region. **d** The "filament", a group of possibly high-mass objects, younger than the cluster stars.

Valdettaro et al. 2007), and the Orion star-forming region (Lee et al. 2005).

When a supernova explosion occurs inside an existing bubble created by a previous supernova, before the gas inside has had time to cool, a larger bubble is created. When this happens more than once, at various locations in the Galaxy, a system of hot bubbles and corridors is created in the ISM (this plays a major role in models of the ISM, see, e.g., McKee & Ostriker 1977; Cox 2005). These bubbles may break out of the Galactic plane, filling the halo with hot gas. With time this gas will cool and may rain back down onto the plane, replenishing the ISM and enriching it with metals.

Massive stars thus have a great impact on the ecology of our Galaxy (and that of other galaxies). Yet we do not know as much about their earliest evolutionary stages as we do of those of lower-mass stars. In the next Section we shall see why that is.

2. The problem with massive stars

The Initial Mass Function (IMF) is the frequency distribution of stellar masses at birth. It is essentially a histogram of the number of stars as a function of logarithmic mass[1]. It can be represented by a series of powerlaws: $\xi(log m) \propto m^{\Gamma}$, with (Scalo 1998):

$\Gamma = -0.2$ for $0.1 < M < 1.0\ M_{\odot}$,
$= -1.7$ for $1.0 < M < 10\ M_{\odot}$,
$= -1.3$ for $10\ M_{\odot} < M$.

The IMF has a broad peak at masses $0.6-1\ M_{\odot}$, meaning that there is a characteristic mass associated with the star formation process. The shape of the IMF furthermore implies that the number of stars with higher masses decreases rapidly. For example, for every star of 30 $M_{\odot}$, there are 100 stars of 1 $M_{\odot}$. But more massive stars are also more luminous ($L \propto M^{3.2}$) and use up their 'fuel' more quickly, to the extent

[1] The IMF is sometimes defined as the distribution over mass, $\xi(m) \propto m^{\gamma}$, with $\xi(log m) \propto m\xi(m)$; hence $\gamma = \Gamma - 1$.

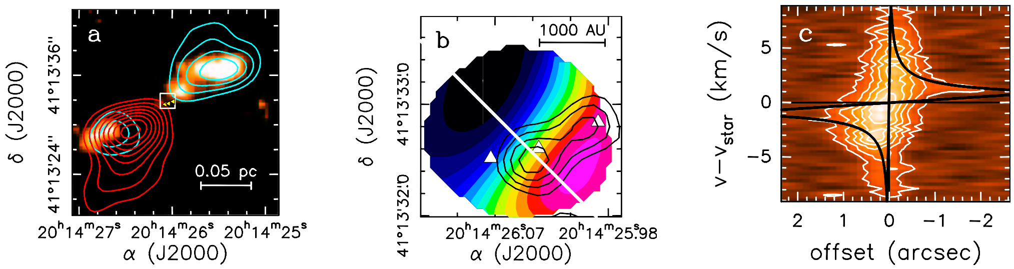

Fig. 2. Circumstellar disk and bipolar outflow associated with IRAS20126+4104 (adapted from Cesaroni et al. 2006). **a** Contours of $HCO^+(1-0)$ emission, tracing a large-scale outflow (light/dark contours: blue/red-shifted emission), superimposed on an image of the 2.2 μm H_2-line emission. The square marks the location of the Young Stellar Object (YSO). **b** Close-up of the core in which the YSO is embedded. Contours indicate the 3.6-cm continuum emission; the colour scale shows the velocity of the $C^{34}S(5-4)$-line, indicating a rotating disk (red- to blue-shifted: SW to NE). The triangles mark the positions of H_2O masers. **c** Velocity of the $C^{34}S(5-4)$ emission as a function of position along the plane of the disk, as indicated by the white line in panel b. The superimposed pattern marks the region from which emission is expected in the case of Keplerian rotation around a 7 $M_\odot$ star.

that the lifetime of a 1 $M_\odot$-star is 2000 times that of a 30 $M_\odot$-star. These two facts combined imply that at any given moment there are 2×10^5 as many 1 $M_\odot$-stars than there are stars of 30 $M_\odot$. Massive stars are thus rare in the Galaxy, and consequently their average distance from the Sun is larger (typically of the order of kpc) than that of low-mass stars. This makes studying them in detail more difficult and requires the use of interferometers.

In the formation of a star there are two relevant timescales. First, the Kelvin-Helmholtz time during which a protostar contracts until it reaches the main sequence, and during which it derives its luminosity from gravitational contraction: $\tau_{\rm KH} = {\rm E_{grav}/L} = {\rm GM^2/RL}$, with M, R, and L the object's mass, radius, and luminosity, respectively. Second, the accretion time, which is needed for a star to reach its final main sequence mass: $\tau_{\rm acc} = {\rm M}/\dot{\rm M}$. The accretion rate $\dot{\rm M} \sim {\rm a^3/G}$, where ${\rm a} = \sqrt{GM_{core}/R_{core}}$ is the soundspeed; M_{core}, R_{core} are the mass and radius of the molecular core inside which the star is formed and from which it acquires its mass. Using typical values one finds that $\tau_{\rm KH} \approx \tau_{\rm acc}$ for stars of about 6 – 8 $M_\odot$, implying that stars more massive than that reach the main sequence while they are still accreting. Consequently, massive stars do not have a pre-main sequence phase (Palla & Stahler 1993). More importantly, once they reach the main sequence the stars produce large amounts of radiation, the pressure of which should prevent any further accretion onto the stellar core, thus seemingly making it impossible for massive stars to form! Yorke (2004) describes this problem and presents several solutions.

To circumvent the problem of the formation of massive stars, two main competing theories have been proposed: on the one hand non-spherical accretion via a circumstellar disk (Yorke & Sonnhalter 2002) accompanied by outflow (Krumholz et al. 2005) and with high accretion rates (Tan & McKee 2002), and on the other hand coalescence of lower-mass stars (Bonnell & Bate 2002). Both theories have a number of implications and testable predictions. For example, coalescence requires massive star formation to take place in environments of high stellar density ($> 10^6$ pc^{-3}), while accretion models predict the presence of *massive* disks and collimated *massive* outflows around high-mass protostars.

3. Outflows, disks, and toriods

In the limited amount of space available, we cannot give a complete overview of all the pro's and con's of the proposed formation mechanisms. In the following we shall therefore only outline the available evidence in sup-

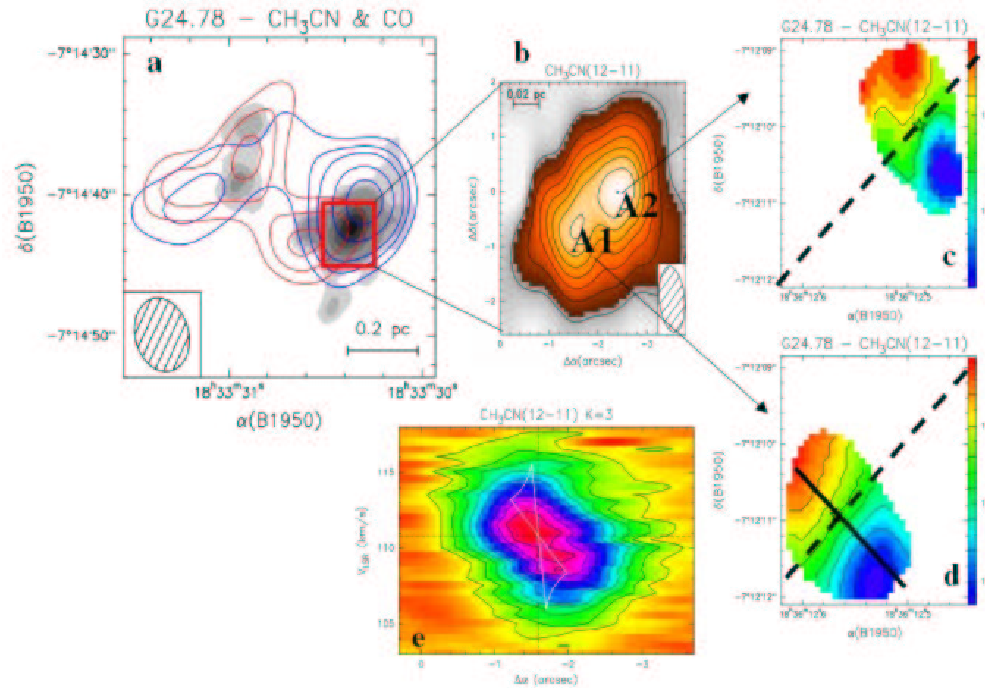

Fig. 3. Cores, outflows, and toroids in G24.78 (adapted from Beltrán et al. 2004). **a** Large-scale outflows in CO (lighter/darker contours for red/blue-shifted emission, respectively) and integrated emission of CH_3CN (gray scale). **b** High-resolution CH_3CN-observations of the western core, revealing two components. **c** Map of the $CH_3CN(12-11)$ line peak velocity for core A2 (red- to blue-shifted: NE to SW). The dashed line indicates the general direction of the large-scale outflow shown in panel a. **d** As c, but for core A1. **e** Velocity of the $CH_3CN(12-11)$, K=3 line as a function of position along the plane of the disk in core A1, as indicated by the continuous line in panel d. The white lines show the pattern for a Keplerian disk around a 20 $M_\odot$ star.

port of the accretion mode of massive star formation.

From the above it is clear that finding (massive) circumstellar disks and massive outflows associated with massive protostars would constitute important evidence supporting the accretion model. Large-scale outflows are easily detected in, e.g., CO and there is ample observational evidence for the presence of massive collimated outflows (Shepherd & Churchwell 1996; Zhang et al. 2001; Beuther et al. 2002, 2004). On smaller scales, water masers have been found to trace collimated gas flows (jets) at the base of larger-scale molecular outflows (e.g., Imai et al. 2000; Torrelles et al. 2003; Goddi et al. 2005; Moscadelli et al. 2005).

Recently much progress has also been made with the observational evidence for circumstellar disks around massive stars. To search for circumstellar disks one needs to know where to look, and one needs a suitable tracer. Cesaroni (2005) gives an overview of the line tracers used in the search for disks around high-mass protostellar objects. As all massive stars form in clusters (this is a consequence of the IMF), the best location to look for massive protostars is towards targets associated with massive star formation, such as UC H II regions, H_2O masers, and IRAS sources of particular colours. In particular one has detected small ($<$ 0.1 pc), hot ($\gtrsim$ 100 K), dense ($\gtrsim 10^7$ cm^{-3}), and luminous ($\gtrsim 10^4$ $L_\odot$) molecular cores. It is commonly thought that

Table 1. Results of disk searches (based on the review by Cesaroni et al. 2007)

Disks around B-stars	Toroids around O-stars
M < 10 $M_\odot$	M > 100 $M_\odot$
R ~ 1000 AU	R ~ 10000 AU
L ~ 10^4 $L_\odot$	L >> 10^4 $L_\odot$
$\dot{M}$ ~ 10^{-4} $M_\odot$ yr^{-1}	$\dot{M}$ > 10^{-3} $M_\odot$ yr^{-1}
t_{rot} ~ 10^4 yr	t_{rot} ~ 10^5 yr
t_{acc} ~ $M/\dot{M}$ ~ 10^5 yr	t_{acc} ~ $M/\dot{M}$ ~ 10^4 yr
t_{acc} >> t_{rot}	t_{acc} << t_{rot}
Equilibrium, circum*stellar* structures	Non-equilibrium, circum*cluster* structures

these so-called *Hot Cores* are the birth sites of stars of type O and B, and in fact they sometimes contain hypercompact HII regions implying the presence of early-type stars inside the cores. The radiation from these stars evaporate the ice mantles around the dust grains, releasing the consituent molecules into the gas phase. Consequently, *Hot Cores* have very rich molecular spectra, facilitating their study. From a study of a dozen *Hot Cores* Fontani et al. (2002) concluded that the molecular clumps are currently undergoing gravitational collapse on timescales (~ 10^5 yr) that appear to imply high mass accretion rates (up to ~ 10^{-2} $M_\odot yr^{-1}$) which may lead to the formation of high-mass stars in their interiors.

One of the best-studied cases is IRAS20126+4104 (Cesaroni et al. 2007, and references therein). This is a ~ 10^4 $L_\odot$ far-IR source, located at the centre of a molecular outflow (Fig. 2a) and deeply embedded in a molecular core. Observations of the core in the $C^{34}S(5-4)$-line reveals the presence of a velocity gradient perpendicular to the direction of the large-scale outflow (Fig. 2b), which is interpreted as being a Keplerian disk rotating around a 7 $M_\odot$ (early B-type) (proto)star (cf. the position-velocity diagram in Fig. 2c).

A region where even higher mass stars are being formed is G24.78+0.08. Millimeter-continuum observations reveal the presence of three cores. In Fig. 3 are shown the observations related to the two westernmost cores (A1, A2; panel b). Beltrán et al. (2004) observed the $CH_3CN(12-11)$-line in both cores (panels c, d) and detected velocity gradients perpendicular to the large-scale molecular outflow. The luminosities, sizes and masses of these rotating structures are much larger than those encountered in IRAS20126+4104, and are therefore referred to as "toroids" rather than as disks. Towards core A1 a hypercompact HII region has been detected, the spectrum of which indicates the presence of an O9.5-star (~ 20 $M_\odot$) (Beltrán et al. 2006b). The rotating structures detected so far are too large and too massive to be stable. The pattern of a Keplerian disk around a 20 $M_\odot$ star is superimposed on the observational data in the position-velocity diagram in Fig. 3e, which shows that the present data are not inconsistent with such a pattern, but the spatial resolution is not high enough to provide a definite answer. With ALMA one should be able to detect a disk, if one is hidden inside the toroid. Support for this comes from the recent detection of infalling motions in the NH_3 lines in core A1, seen in absorption against the bright continuum of the HII region (Beltrán et al. 2006b). On the other hand, it may be that O-type stars do not form via disk accretion but through a different mechanism (such as coalescence) and that no disk will be detected even with ALMA.

Table 1 gives an overview of the results obtained so far in the search for disks around massive protostars.

4. Prestellar cores

In Sect. 2 it was argued that massive (proto)stars reach the zero-age main sequence while still accreting. They thus remain deeply embedded in their natal clouds and their earliest evolutionary phases can only be observed at wavelengths (infrared, (sub-) mm, or radio) that do not suffer so much from the enormous amounts of visual extinction associated with these objects. Furthermore, massive stars evolve rapidly and have a destructive influence on their surroundings once they start to fuse hydrogen. Finding massive protostars is therefore not an easy task. Early studies were made by Molinari et al. (2000) (and references therein) and Sridharan et al. (2002). Promising candidates were found and their immediate environment was studied in (sub-)mm continuum and molecular-line emission (Molinari et al. 1998; Brand et al. 2001; Fontani et al. 2002, 2004a,b, and Beuther et al. 2007, and references therein). It was shown that the sources embedded in the cores are likely to be intermediate- to high-mass protostars.

All of these studies are aimed towards cores where an IR-source is present, indicating that the embedded protostar, although young (as indicated by the absence of detectable radio-continuum emission) is already in a relatively advanced evolutionary phase. Because of the impact of massive protostars on their environment, one cannot derive the initial conditions for massive star formation from these objects.

Observing massive protostar candidates in the mm-continuum, Faúndez et al. (2004); Sridharan et al. (2005) and Beltrán et al. (2006a) found massive dust clumps towards virtually all of their targets, with usually more than one clump per region, sometimes organized in filaments or in clusters. Beltrán et al. (2006a) find a mean clump size, dust temperature, and H_2-density of 0.5 pc, 30 K, and $\sim 10^6$ cm^{-3}, respectively. Their mean L/M-ratio of 99 $L_\odot/M_\odot$ suggests that these objects are in a young, pre-UC HII phase. Interestingly, they also detected massive clumps that are not associated with any mid-IR MSX emission (diffuse nor point-like), and which are thought to be potential prestellar or precluster cores. They have physical properties similar to the other clumps, but have a mass $\sim 3\times$ lower than clumps with an MSX-counterpart, which is possibly due to a lower dust temperature (Beltrán et al. 2006a) . It is in these objects that one may hope to be able to study the physical and chemical conditions necessary for the onset of massive star formation. Prestellar cores in low-mass star forming regions have been extensively studied (e.g., Crapsi et al. 2005). These cores show strong emission in N_2D^+ and N_2H^+, and the ratio between these two is several orders of magnitude higher than normal. At the same time the abundance of several C-bearing molecules (such as CO, CS) is an order of magnitude less than the theoretical value. The observations are interpreted with models that will shed light on the chemical reactions in cores prior to star formation. This work is now being extended also to regions of high-mass star formation (e.g., Fontani et al. 2006), assuming that high- and low-mass prestellar cores have similar physical/chemical properties.

5. Upper mass limit

Much effort is dedicated to finding the shape of the IMF at low masses, by making deep IR surveys of low-mass star forming regions, looking for Brown Dwarfs (0.013 $M_\odot < M < 0.075\ M_\odot$), objects with masses between the deuterium- and the hydrogen-burning limits. Objects with $M < 0.013\ M_\odot$ are planets, thus defining a clear lower-mass cut-off to the stellar IMF. But what about the high-mass end of the IMF: can stars of any mass form? Theoretically it seems they can (e.g., Figer 2005 and references therein), and stellar evolutionary models have been constructed of stars of up to $10^3\ M_\odot$ (e.g., Bond et al. 1984), but are such massive stars actually found? Because of the value of the slope of the IMF for $M > 10\ M_\odot$ (see Sect. 2), stars more massive than 150 $M_\odot$ can only be found in clusters with a total stellar mass of $> 10^4\ M_\odot$. Such a cluster must furthermore be young enough ($\lesssim 3$ Myr) that the most massive members have not yet exploded as supernova, but also old enough ($\gtrsim 1$ Myr) for stars not to be embedded in their natal cocoons anymore; it must be near enough to be resolved in individual stars. In our Galaxy the Arches Cluster near the Galactic Center is one of the very few, if not the only one, that satisfies these criteria. Figure 4 shows the IMF of this cluster, taken from Figer (2005). The

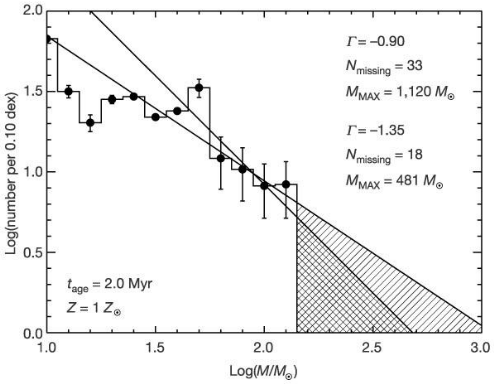

Fig. 4. The IMF of the Arches Cluster (Figer 2005). The line fitted to the four highest mass bins has a slope $\Gamma = -0.9$; also shown is a line with the Salpeter slope ($\Gamma = -1.35$). The other numbers are for the highest mass expected for these slopes, and the number of stars missing.

line with slope −0.9 is a fit through the four bins of highest mass, and with it the maximum predicted stellar mass is $\sim 10^3$ $M_\odot$. The steeper line drawn in Fig. 4 has the slope equal to the Salpeter-value of −1.35, and predicts a maximum mass of ~ 500 $M_\odot$. The highest mass actually found is $\lesssim 130$ $M_\odot$, implying that with either slope there is a deficit (33 or 18) of stars with higher masses. Figer (2005) concludes that if there is no upper mass cutoff, the chances of finding no stars of mass beyond what is found are 10^{-8} if 18 are expected, and 10^{-14} if 33 are expected. These observations therefore point towards the existence of a mass cutoff at ~ 150 $M_\odot$.

There are a number of stars which one suspects to have higher masses (up to 250 $M_\odot$), such as the "Pistol Star" and another Luminous Blue Variable in the Quintuplet Cluster, that both have L> 10^6 $L_\odot$ (Figer et al. 1998; Geballe et al. 2000), but there is uncertainty as to their distance, temperature, and singularity and consequently also their mass is uncertain. On the other hand, from an analysis of stars in the cluster R136 in the LMC Weidner & Kroupa (2004) have concluded there exists an upper mass cutoff around 150 $M_\odot$ there as well.

6. Conclusions

The study of the earliest phases of massive stars poses several problems, both observational and theoretical. Stars more massive than $\sim 6-8$ $M_\odot$ reach the main sequence while still accreting and the consequent radiation pressure should halt any further accretion. One way out of this dilemma is non-spherical accretion at a high rate through a massive circumstellar disk. For B-stars the presence of such a disk has been observationally established in a number of cases. Around O-type stars only massive, rotating, non-equilibrium structures ("toroids") have been found so far. It is not known whether this is a consequence of a lack of resolution or whether O-stars form via a different mechanism (such as coalescence).

The initial conditions in molecular clumps prior to the onset of star formation, are studied in prestellar cores, found in mm-continuum surveys of high-mass star forming regions. Crucial parameters are the deuteration fraction and the depletion factor.

There appears to be an upper limit of ~ 150 $M_\odot$ to the most massive stars that can form in practice.

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