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Massive Star Formation

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Abstract.

The understanding of the formation process of massive stars requires a detailed knowledge of the physical conditions of the cloud environment which is thought to play a critical role in determining the formation mechanism. In recent years there has been a rapid growth of observational and theoretical studies concerning the formation of massive stars. Here I review observational data gathered during the last few years which are providing key evidence concerning the physical processes that take place during the formation of massive stars.

1. Introduction

Two different mechanisms have been proposed to explain the formation of massive stars: accretion and coalescence. In the first hypothesis (Osorio, Lizano & D'Alessio 1999; Yorke & Sonnhalter 2002; McKee & Tan 2003) it is assumed that massive stars are formed via accretion of gas in dense cores. In the coalescence scenario (see review by Stahler, Palla & Ho 2000) it is proposed that high-mass stars form by the merging of low and intermediate mass stars in a dense cluster environment (Bonnell, Bate & Zinnecker 1998). The role of coalescence and accretion processes in the assembling of a massive star is still under debate.

To discern which of the two competing models best explain the formation of massive stars it is necessary to resort to observational data which would place strong constraints on the theoretical models. Until recently the available observational data concerning how massive stars form were scarce. Studies of high-mass YSOs are observationally more difficult than for low-mass objects because massive star-forming regions lie at considerably larger distances (typically 4 kpc) and because they tend to form in clusters which gives rise to confusion problems. Furthermore, massive stars have much shorter formation time-scales and are intrinsically fewer in number than low-mass stars, so there are fewer targets across the Galaxy at any given time.

The recent advent of aperture synthesis instruments providing high angular resolution, such as BIMA and the SMA; new instrumentation, such as bolometer arrays at mm wavelengths; and fast large-scale mapping capabilities, are changing this state of affairs. In the first part of this review I will concentrate on recent results obtained from moderate angular resolution observations which are giving light on the conditions for massive star formation at scales of parsecs. Then, I will summarize recent results derived from observations with high angular resolution which are giving insight on the formation processes of individual

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high-mass YSOs. Recent reviews on theories of massive star formation have been presented by Bonnell (2002), Yorke (2002) and Tan (2003).

2. The maternities of high-mass stars: Massive dense cores

Surveys of molecular emission in high density tracers (Plume et al. 1992; Juvela 1996; Plume et al. 1997) and of dust continuum emission (Beuther et al. 2002; Faundez et al. 2004), made with single dish telescopes, show that massive stars form in regions of molecular gas with distinctive physical parameters, which we will refer to as massive dense cores[1]. Observations of the CS(5→4) line emission toward massive star-forming regions associated with H_2O masers indicate that massive dense cores have an average radii of 0.5 pc, average density of 8×10^5 cm^{-3}, and average virial mass of $3.8 \times 10^3 M_\odot$ (Plume et al. 1997). Dust continuum observations at 1.2 mm toward a sample of about 150 luminous objects, chosen from the survey of Bronfman et al. (1996) of IRAS sources with colors of UC HII regions, indicate that massive dense cores have an average radii of 0.4 pc, average density of 4×10^5 cm^{-3}, average dust inferred mass of $3.8 \times 10^3 M_\odot$, and average dust temperature of 32 K (Faundez et. al 2004). The physical parameters of the cores independently derived from the two different observational methods are in very good agreement. The molecular line observations further show that massive dense cores have line widths of typically ~ 6 km s^{-1}, much larger than those of the cores associated with low-mass star formation, indicating that they are highly turbulent and implying that their mean pressures are very high, typically $\sim 3 \times 10^8$ K cm^{-3}. The large amount of support provided by the turbulent pressure allows the existence of cores in hydrostatic equilibrium with much larger densities than in low-mass cores.

Are the physical characteristics of the massive dense cores summarized above representative of the large scale (~pc) initial conditions for the formation of massive stars? Most of the surveys mentioned earlier have been carried out toward luminous sources, either ultra compact (UC) HII regions and/or luminous IRAS sources, implying that a massive star has been already formed within the core. For instance, the average luminosity of the sources in the samples of Plume et al. (1997) and Faundez et al. (2004) are $9 \times 10^5 L_\odot$ and $2 \times 10^5 L_\odot$, respectively. Therefore, it is possible that the massive luminous embedded objects may have produced appreciable changes, other than heating, to their natal environment. The observational evidence for massive dense cold cores, capable of forming massive stars but before star formation actually begins (massive starless core), was until recently hard to find. Massive starless cores should be characterized by having similar densities and sizes as massive dense cores with embedded high-mass stars, but lower luminosities and cooler temperatures. The recent availability of bolometer arrays allowing large scale maps of dust continuum emission at mm wavelengths is allowing the search for promising candidates, namely mm sources without mid-IR counterparts in large scale surveys.

[1]We adopt here the nomenclature of Evans (1999) for the use of the terms cores and clumps.

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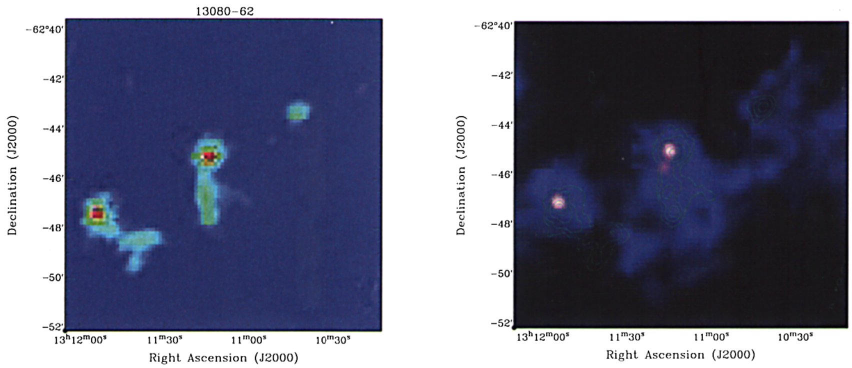

Figure 1. Left: Image of 1.2-mm emission toward IRAS 13080-6229. Right: Image of the MSX mid-infrared emission, overlayed with contours of the 1.2-mm emission.

An example of a recently discovered massive starless core, from the dust continuum emission survey of Faundez et al. (2004), is presented in Fig. 1. The left panel shows an image of the 1.2-mm emission from a region of $\sim 12' \times 12'$, obtained with SIMBA at the SEST, centered on the luminous object IRAS 13080-6229. The right panel shows a 3 color image of the MIR emission, from the same region, made combining the emission in the A (8.8μm; blue), D (14.7μm; green) and E (21.7μm; red) bands of the MSX survey (Egan et al. 1998). The blue extended emission is likely to correspond to PAH emission arising from PDRs whereas the red objects indicate the presence of embedded energy sources. The 1.2-mm source located $\sim 4'$ northwest of IRAS 13080-6229 is below the detection limits in all MSX bands. It is also undetected at far infrared wavelengths by IRAS. The 1.2-mm observations imply that the source has a mass of $\sim$670 $M_\odot$ and a radius of $\sim$ 0.3 pc. Subsequent observations of molecular emission in CS lines show the presence of a molecular core with a radius of $\sim$ 0.3 pc, a virial mass of $\sim$860 $M_\odot$ and a line width of 4.2 km s^{-1}, in good agreement with the dust continuum results. A fit to the SED, using the upper limits at the IRAS wavelengths, gives an upper limit on the dust temperature of 12 K, suggesting that this massive dense core is likely to be in a stage before an internal luminosity source develops. To date there are a dozen massive starless cores already identified (Wyrowski et al. 1999; Sandell 2000; Garay et al. 2004, in preparation). Their physical conditions, except temperature and luminosity, are similar to those of massive cores with embedded massive stars.

What is the dynamical state of massive dense cores? Two observational signatures suggest that most of them are in approximate hydrostatic equilibrium: (i) self-reversed profiles are rare (Plume el al. 1997); (ii) the masses derived from the dust emission and the virial masses determined from molecular line studies are in good agreement, typically within a factor of two (Faundez et al 2004). The line widths of massive dense cores are very broad ($\sim$ 6 km s^{-1}), much larger than the thermal widths, indicating that a considerable amount of non-

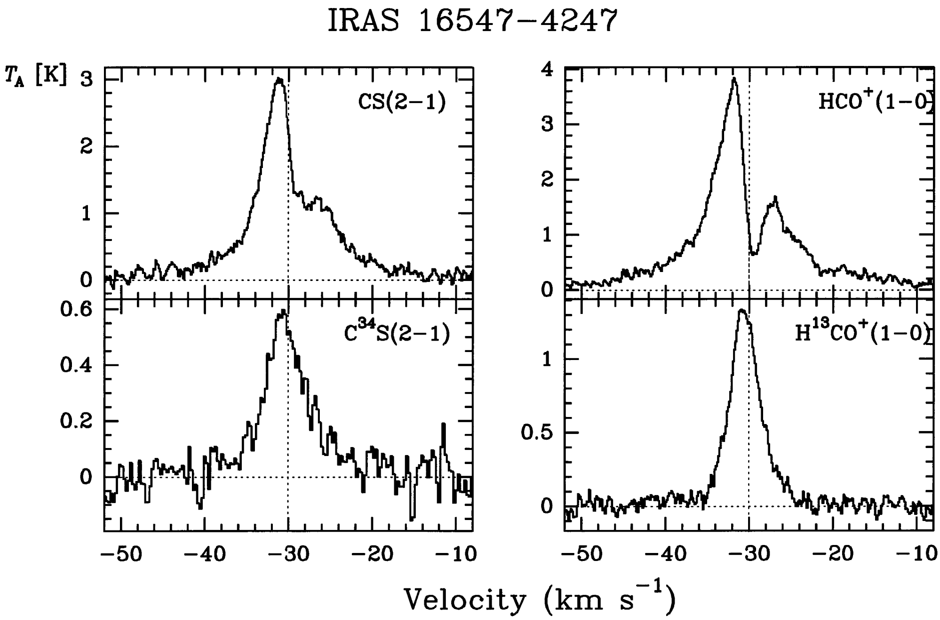

Figure 2. Spectra of molecular line emission from the IRAS 16547−4247 massive dense core. Transitions are given in the upper right corner of the spectra. The vertical dotted line indicates the systemic velocity of the ambient gas of −30.0 km s^{-1}.

thermal support is required to maintain them in equilibrium. The source of support is most likely a combination of turbulence and magnetic fields. A dozen massive dense cores have line profiles indicative of large scale inflow motions (Snell & Loren 1977; Garay et al. 2002, 2003; Wu & Evans 2003). This is illustrated in Fig. 2 which presents line emission profiles from a massive dense core thought to be in an early stage of evolution (Garay et al. 2003). The spectra in optically thick lines (CS J=2→1, HCO^+ J=1→0) show double-peaked line profiles, with a bright blue-shifted peak, whereas the profiles of optically thin lines ($C^{34}S$ J=2→1, $H^{13}CO^+$ J=1→0) show an approximately symmetric single component with a peak center velocity located in between the two peaks. These spectroscopic signatures suggest that the bulk of the molecular gas in this core is undergoing large-scale inward motions. Using the simple model of contracting clouds of Myers et al. (1996), the observed profiles imply an inward speed of ~0.7 km s^{-1}. This speed is smaller than the free-fall velocity expected at the outer radius of the core, suggesting that the collapse is not dynamical. The mass infall rate associated with the large scale inflow of matter is of the order of $10^{-3} - 10^{-2}$ $M_\odot$ yr^{-1}.

Where are massive stars formed within the massive dense cores? This is an important issue because their location is likely to be a useful indicator of the formation mechanism. To address this, and other questions, we recently undertook a multiwavelength study of a sample of 18 luminous IRAS sources in the southern hemisphere thought to be representative of young massive star-

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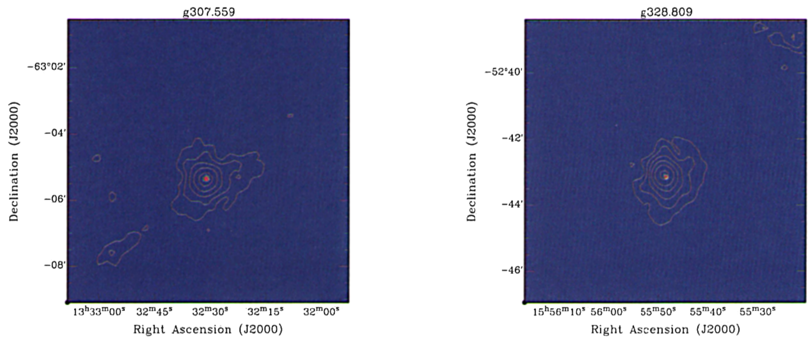

Figure 3. Images of radio continuum emission at 4.8 GHz toward massive dense cores, overlayed with contours of 1.2-mm dust continuum emission. Left: IRAS 13291-6249. Right: IRAS 15520-5234.

forming regions. The objects were selected from the survey of Bronfman et al. (1996) based on the characteristics of the observed CS(2→1) line profiles. Radio continuum observations, carried out using ATCA, show the presence of UC HII regions in most of these massive dense cores, implying that they have ongoing massive star formation as already indicated by their high luminosities. A comparison of the radio images with 1.2-mm continuum images, obtained with SIMBA at SEST, show that the UC HII regions are usually located at the peak of the dust continuum emission (see Fig. 3). Young massive stars appear, thus, to form at the center of the massive dense massive cores. Observations have also shown the existence of luminous massive dense cores that are undetected at radio wavelengths. Examples are IRAS 16272−4837, with a luminosity of $2.4 \times 10^4 L_\odot$ and a mass of $2 \times 10^3\ M_\odot$ (Garay et al. 2002), and IRAS 23385+6053, with a luminosity of $\sim 1.6 \times 10^4 L_\odot$ and a mass of $\sim$470 $M_\odot$ (Molinari et al. 1998). None of these massive dense cores have been detected in sensitive radio continuum observations, suggesting they are in an early evolutionary stage, prior to the appearance of ultra compact regions of ionized gas.

Dust continuum studies indicate that the density dependence with radius of massive cores can be approximated with power-law distributions, $n \propto r^{-p}$, with average values of p in the range between 1.5 and 1.8 (van der Tak et al. 2000; Beuther et al. 2002a; Mueller et al. 2002). However, the individual values of p exhibit a large spread, ranging from 0.8 to 2.5, which is likely to reflect the presence of clumpiness and fragmentation within massive dense cores. In fact, observations with high angular resolution show that massive dense cores are clumpy, exhibiting internal substructures, both spatially and in velocity (e.g., Molinari et al. 2002). Accumulation and coalescence processes among small clumps, formed by the fragmentation of a collapsing massive dense core, are likely to play an important role in the formation of the most massive clumps (Nakano 1966; Molinari et al. 2002). These are likely to be the seeds for the formation of individual high-mass stars and is the topic of the next section.

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3. The embryo gas: Hot molecular cores

High angular resolution observations of emission in molecular lines excited at high temperatures and high densities (e.g., NH_3 lines) have shown the existence of small (< 0.1 pc), dense ($> 10^7$ cm^{-3}), and hot ($T_K > 100$ K) structures of molecular gas, with masses in the range $10^2 - 3 \times 10^2\ M_\odot$ (see Garay & Lizano 1999; and references therein). These structures, referred to as hot molecular cores, are thought to correspond to the embryo gas from which massive protostars feed. The high temperatures do not necessarily imply the presence of an internal heat source, since the hot gas could also be tracing surface layers of externally heated dense cloud cores (Kaufman, Hollenbach, & Tielens 1998). The determining characteristic of a hot molecular core hosting an embedded high-mass YSO is its luminosity. The determination of the bolometric luminosity of hot cores is not easy however, mainly due to the present lack of angular resolution across the range of frequencies in which the bulk of the energy is emitted. In what follows we refer to objects hosting an embedded young massive protostar as hot cores.

The association, or lack of it, of hot molecular cores with compact regions of ionized gas is thought to indicate evolutionary stages. Hot cores in an early evolutionary stage, still undergoing an intense accretion phase, are distinguished by being luminous but not associated with an UC HII region (eg. Cesaroni et al. 1994; Hunter et al. 1998; Molinari et al. 1998). The high-mass accretion rate of the infalling material quenches the development of an UC HII region (Yorke 1984), and the free-free emission from the ionized material is undetectable at centimeter wavelengths (Walmsley 1995). These hot cores are then the precursors of UC HII regions. Hot cores with embedded UC HII regions, implying that a massive star has already formed at their centers, most likely mark the oldest stage of the collapse phase.

Is there evidence of infall motions in hot molecular cores? Direct kinematic evidence has been reported in a few cases (Keto, Ho & Haschick 1988; Zhang & Ho 1997; Young, Keto & Ho 1998; Hofner, Peterson & Cesaroni 1999). The presence of infalling motions is established by position-velocity diagrams exhibiting the classic "C" or "O" shapes consistent with radial motions projected along the line of sight. The observed collapsing cores have typically masses of $\sim 150\ M_\odot$, radii of ~ 0.04 pc, infall velocities of $\sim$4 km s^{-1} and mass infall rates of $\sim 7 \times 10^{-3}\ M_\odot$ yr^{-1}. Indirect evidence for the presence of collapse motions have been reported for a few hot cores (G34.24+0.13MM, W3(H_2O), IRAS 23385+6053) through model fitting of their spectral energy distribution (Osorio et al. 1999). The inferred mass infall rates are typically $1 \times 10^{-3}\ M_\odot$ yr^{-1}. Further evidence that these objects are in fact tracing very early stages of massive star formation, is provided by their association to H_2O masers, bipolar molecular outflows, jets, and/or warm dust emission but no detectable, or weak, thermal emission from ionized gas.

4. Observed phenomena toward high-mass YSOs

Now lets turn our discussion to the original question: Are massive stars assembled by collisions of lower mass stellar objects or is accretion the main source of mass growth? If massive stars are formed by accretion then we expect that disks, jets, and bipolar outflows will be generated in their early stages of evolution. On the contrary, if they are formed via collisions of lower-mass stars neither disks nor jets are expected. In this section I will review recent observations that are allowing to discriminate among the different hypothesis.

4.1. Bipolar molecular outflows

Although the recognition that outflows are produced by stars of all masses was established early with the detection of powerful molecular outflows toward a few high-mass star forming regions, only recent systematic surveys have shown that molecular outflows is a common phenomenon toward high-mass protostellar objects (Shepherd & Churchwell 1996; Zhang et al. 2001; Beuther et al. 2002b). The data gathered in these studies show that outflows in massive star forming regions are substantially more massive and energetic than those associated with low-mass YSOs. Massive molecular outflows have typically masses of 50 $M_\odot$, mass outflow rates of 10^{-3} $M_\odot$ yr^{-1}, mechanical forces of 10^{-2} $M_\odot$ km s^{-1} yr^{-1}, kinetic energies of 2×10^{47} ergs and mechanical luminosities of 20 $L_\odot$ (Churchwell 2000; Beuther et al. 2002b). These results indicate that the massive outflows are driven by high-mass stars which are indeed more energetic and hence are able to inject more energy into their surroundings than low-mass stars. In fact, it has been found that the mass outflow rate, force, and mechanical luminosity of the molecular outflows are tightly correlated with the stellar luminosity of the driving source (Shepherd & Churchwell 1996; Beuther et al. 2002b), suggesting that there is a strong link between accretion and outflow for a wide range of luminosities. The large masses and energetics associated with the luminous outflows raise, however, several questions which have not yet been answered, such as: What is the origin of the mass in massive outflows? What is the driving mechanism of the luminous outflows? Are they momentum driven by highly collimated jets as in low-mass stars (Masson & Chernin 1993)? Although the physics of the high-mass outflows remain to be addressed, it has been suggested that a common driving mechanism could operate across the entire mass or luminosity range (Richer et al. 2000).

4.2. Jets

In low-mass YSOs, the bipolar molecular outflows are often accompanied by highly collimated stellar jets (Rodríguez 1997). Although these two phenomena appear at very different spatial scales, both observations and theory show that the small scale jets and the large scale bipolar molecular outflows are intimately connected. The evidence for collimated jets associated with high-mass YSOs was, until recently, scarce. New radio continuum observations with high angular resolution are, however, rapidly increasing their number. About ten luminous ($L > 1 \times 10^4$ $L_\odot$) massive young stellar objects are already known to be associated with highly collimated jets (see Garay & Lizano 1999). One of the most spectacular cases is the parsec-scale radio jet associated with IRAS 18162-2048 that drives the HH80-81 outflow (Martí, Rodríguez, & Reipurth 1993). Proper motion studies of the IRAS 18162-2048 (Martí, Rodríguez, & Reipurth 1998) and Cepheus A HW2 (Rodríguez et al. 2001) jets, show clumps in the jet moving

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away from the driving source at tangential velocities of ~ 500 and 950 km s^{-1}, respectively.

The most luminous YSO object presently known to host a jet is IRAS 16547−4247, which has a luminosity of 6.2×10^4 $L_\odot$. This YSO exhibits a well collimated triple radio source, with the central source thought to be a jet powered by a massive star in the process of formation and the outer radio lobes being regions of shocked gas at the working surfaces of the jet (Garay et al. 2003). The remarkable similarity between the IRAS 16547−4247 triple radio system and those associated with low luminosity YSOs (e.g. Serpens FIRS1) suggest that high-mass YSOs pass through similar evolutionary phases. In summary, the recent observations indicate that the jets found in the formation of low-mass stars are also produced in high-mass stars. Since jets are thought to be a consequence of an accretion process, it is plausible to conclude that the formation process of massive stars also undergoes an accretion stage. However, there are no yet detailed studies of the radio jets and molecular outflows associated with massive YSOs that might allow to conclude that they correspond to scaled-up version of the MHD flows invoked for low-mass objects.

4.3. Disks

Observations of low-mass star forming regions have amply revealed that the collapse of the parental rotating cloud results in the formation of a circumstellar disk, which through accretion builds up most of the final mass of the protostar. The evidence for the appearance of disks in the formation process of high-mass stars is, on the other hand, not abundant. This may be a result of both, intrinsic reasons and observational difficulties. Massive protostars begin hydrogen burning while still accreting matter; the rapid onset of UV luminosity will quickly photo-evaporate the disks. Furthermore, disks are deeply embedded within the massive dense cores, hence their emission is outweighted by the envelope emission. Aperture synthesis observations are thus required to resolve the extended emission. Recent sensitive high angular resolution observations of dust and molecular gas emission are beginning to show the presence of circumstellar disks around young massive protostars (Cesaroni et al. 1997; Zhang, Hunter, & Sridharan 1998; Hunter et al. 1999; Shepherd & Kurtz 1999). The disks have sizes of typically $\sim 10^3$ AU, masses of $\sim 10 M_\odot$ and their orientations are roughly orthogonal to the outflow symmetry axis. Kinematical studies of the IRAS 20126+4104 disk show that its motions are consistent with Keplerian rotation around a 20 $M_\odot$ star (Zhang et al. 1998). In other cases rotation in combination with collapse or expansion motions are detected.

A powerful tracer of the very earliest stages of the massive star formation process is methanol maser emission. Interferometric observations towards a few massive star forming regions show that the CH_3OH masers are frequently distributed in linear patterns with dimensions of typically 3×10^3 AU and exhibiting linear velocity gradients across the chains (e.g., Norris et al. 1998). In some sources the motions of the methanol maser spots are essentially Keplerian implying the presence of bound disks around central masses of $10 - 20$ $M_\odot$ (Ellingsen, Norris & McCulloch 1996; Norris et al. 1998). The conclusion that methanol masers delineate edge-on circumstellar disks rotating around high-mass YSOs has been recently challenged by de Buizer (2003) who find that the methanol masers are aligned with molecular hydrogen emission. Since H_2 emission is associated with shocks, they propose that methanol masers are tracers of outflows.

5. Massive star formation scenario

The observations discussed in §2 show that high-mass stars are born within massive dense cores, with typical radii of ~0.4 pc, densities of $\sim 10^6$ cm^{-3}, masses of a few 10^3 $M_\odot$, and line widths of $\sim$ 6 km s^{-1}. It appears that a significant fraction of the total mass of massive dense cores is in the form of molecular gas, as suggested by the similar values of the masses derived from the dust continuum emission (gas mass) and virial mass (total mass), indicating that the gas dominates the gravitational potential. Moreover, the observations provide clear evidence that high-mass stars are preferentially born near the center of the massive dense cores. In addition, OB stars are found concentrated near the center of young stellar clusters. This is unlikely to be the result of dynamical evolution since the ages of the stars are smaller than the required collisional relaxation times (Hillenbrand & Hartmann 1998; Bonnell & Davies 1998). The questions of how an individual massive star forms and how the cluster forms are therefore closely related. Whatever mechanism may be invoked, an overall model for the formation of massive stars should explain these observational facts.

How are massive dense cores produced? Is it a gradual condensation process or is it a fast process caused, for example, by shocks within a turbulent medium? Larson (1982) suggested that dense cores might be formed by a gradual dissipation of turbulent motions in larger clouds. This will cause the gravitational contraction of the large cloud while still remaining nearly in virial equilibrium, reducing its size and increasing its internal velocity dispersion. The gas is funneled down to the center of the core where it is accreted by the central object at high rates. This hypothesis finds observational support in the recently detected massive dense cores in which a central massive object has already been formed whereas the gas on scales of ~0.4 pc is still undergoing inflow motions towards the mass concentration at the center.

How are high-mass stars formed? In the two main theoretical ideas, the birth of massive stars is envisioned as an event associated with a very dense environment. In the coalescence model the determining parameter is the stellar density whereas in the accretion model it is the gas density. In the accretion induced collisions mechanism (Bonnell et al. 1998) the process of building up massive stars by collisions with lower mass objects is more efficient at the center of the cluster where considerable more dynamical interactions take place, qualitatively explaining one of the observational facts. For stellar mergers to be responsible for the formation of massive stars stellar densities of $\geq 10^8$ stars pc^{-3} are required (Bonnell 2002). Several observations at infrared wavelengths, which are able to probe the population of newly formed stars deeply embedded in molecular clouds, do indeed show that massive stars form at the center of young rich clusters, with sizes of 0.2-0.4 pc, containing a high density of low-mass stars (Megeath et al. 1996; Carpenter et al. 1997). The young embedded dense clusters have, however, stellar volume densities $\leq 10^4$ stars/pc^3, which are at least four orders of magnitude smaller than that required theoretically.

The accretion hypothesis requires that the parental cores be dense enough such that upon collapse the ram pressure of the associated accretion inflow overcame the radiative forces on dust. It appears that in isolated massive dense cores the first stellar objects formed are high-mass stars and that their formation takes place near their central regions. This observational evidence is consistent with the hypothesis that the formation of massive stars proceeds via accretion in very dense cores. In the turbulent and pressurized dense core accretion model (McKee & Tan 2003), the collapse of a massive dense core is likely to produce the birth of a stellar cluster, with most of the mass going into relatively low-mass stars. The high-mass stars are formed preferentially at the center of the core, where the pressure is the highest, and in short time scales of $\sim 10^5$ yrs (Osorio et al. 1999; McKee & Tan 2002).

The recently gathered observational evidence, summarized in this review, are providing valuable clues to understanding the formation of massive stars and allowing us to discern between the two theoretical possibilities. The new data show that bipolar molecular outflows, jets, and disks appear to be intrinsic to the formation process of high-mass stars. Flow energetics and jet radio luminosities appear to scale with the luminosity of the central source. The discovery that the phenomena of molecular outflows and jets are also basic components of the formation process of massive stars provide strong support to the hypothesis that massive OB stars are formed via accretion through a disk in a manner analogous to the formation of low-mass stars. A key difference between the high-mass and low-mass formation via accretion is in the mass accretion rate. Mass accretion rates as high as 1×10^{-2} $M_\odot$ yr^{-1} have been estimated in collapsing cores associated with high-mass star forming regions (Zhang & Ho 1997; Hofner at al. 1999), whereas those associated with the formation of low-mass stars are typically $\sim 10^{-6}$ $M_\odot$ yr^{-1}. The problem posed by the radiative forces on dust halting the accretion inflow can be overcomed through the high accretion rates (Wolfire & Cassinelli 1987). The large values of the mass accretion rates are consistent with the predictions of the inside-out collapse model for a dense medium with a large amount of initial hydrostatic support (Osorio et al. 1999; McKee & Tan 2003).

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