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The birth of stars: Initial conditions and physical processes

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In this contribution I summarize the main observations gathered during the last forty years that have led to the present understanding on how stars are formed. Particular emphasis is given to the observations which have allowed a significant progress in the determination of the initial conditions for star formation and in the identification of the physical processes that take place during the birth of stars.

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1. INTRODUCTION

Our current understanding of the star formation process has strongly benefited from a close interplay between observational and theoretical developments. In this contribution I summarize the main observations gathered during the last forty years that have significantly contributed to the understanding of the formation and early evolution of stars.

The star formation field of research started more than fifty years ago, with the wise suggestion made by Bok & Reilly (1947) and Bok (1948) that small optically dark structures with high visual extinction could be the birth sites of low-mass stars. The large opacity of the dust prevented, however, to scrutinize at optical wavelengths inside these globules in search for embedded young stellar objects. At radio, infrared and millimeter wavelengths the opacity of the dust and gas is considerably smaller than in the optical and therefore these wavelengths are better suited for investigating the star formation processes. With the continuous development, during the last four decades, of detectors and the advent of new telescopes in these spectral windows, a wealth of observations have been gathered providing key data about the formation of stars.

In this contribution I mainly focus on isolated star formation. Even though this may not be the dominant mode of star formation, it provides the best laboratory to identify and study the different phenomena taking place in the formation of stars. Emphasis is given to the discussion about the initial conditions for star birth at scales of parsecs, which I refer to as the *maternities* of stars, and at scales of 0.1 pc, which I refer to as the *cradles* of stars, as well as on the phenomena associated with the star formation process. In §2. and §3 present the main observational data gathered concerning the birth of, respectively, low-mass ($0.1 < M < 8 \ \ M_\odot$) and high-mass ($M > 8 \ \ M_\odot$) stars.

2. Birth of low-mass stars

2.1 Initial conditions

Several observations have shown that the maternities of low-mass stars are structures of molecular gas and dust with typically sizes of $0.4 - 2$ pc, average molecular hydrogen densities of $10^3 - 10^4$ cm^{-3}, masses of $5 - 300 \ \ M_\odot$, temperatures of $\sim$15 K, and line widths of $0.5 - 1.5$ km s^{-1} (e.g., Goldsmith 1987). These structures are known as darks clouds since in optical images they are seen as dark patches against the stellar galactic background. An optical image of the dark cloud BHR71 (Bourke et al. 1995) is shown in Figure 1. Dust continuum observations indicate that the density distribution in dark clouds typically follows a power law, $n \propto r^{-\alpha}$, with $\alpha = 1.5$ (Cheung et al. 1980), implying that they are centrally condensed.

Systematic molecular line studies of isolated globules and regions inside dark clouds have shown that the cradles of low-mass stars are structures of molecular gas with sizes of typically 0.1 - 0.4 pc, molecular hydrogen densities of $10^4 - 10^5$ cm^{-3}, masses of 0.3 - 10 $M_\odot$ and temperatures of $\sim$10 K (Myers & Benson 1983; Benson & Myers 1989), usually refereed as low-mass dense cores. Many of them show nearly thermal widths, of $\sim$0.2 km s^{-1} , implying that they are mostly supported by thermal pressure. During the last fifteen years infrared and radio observations have shown that most of the low-mass dense cores harbour embedded sources, providing direct evidence that the cores are active sites of star formation and that Bok's hypothesis is true. An optical image of the low-mass dense core Barnard 68 is shown in Figure 2.

Figure 1: Optical image of the dark cloud BHR 71 (Bourke et al. 1995). The field is approximately $7' \times 7'$ in size. Image taken from Alves et al. (2001).

2.2 Physical phenomena

2.2.1 Collapse

The star formation process is essentially a contest between the self-gravity and the internal support of molecular clouds. Most of the low-mass dense cores are quiescent, indicating the presence of enough support to make it stable. When the source of support, either magnetic fields or turbulence, is lost the core undergoes collapse. The search for evidence of gravitational collapse started as soon as molecular clouds were discovered, but was only during the late 80's that spectroscopic evidence indicated the presence of collapse in a few cores (Walker et al. 1986; Zhou et al. 1990). The spectra in optically thick lines show double-peaked line profiles, with a bright blueshifted peak, whereas the profiles of optically thin lines show a symmetric single component with a peak center velocity located in between the two peaks. These spectroscopic signatures indicate that the molecular gas in these cores is undergoing inside-out collapse. The observed profiles imply infall motions of $\sim$0.1 km s^{-1} over size scales of $\sim$0.02 pc and mass infall rates of the order of 10^{-6} $M_\odot$ yr^{-1} (Zhou et al. 1993; Myers et al. 1995).

2.2.2 Disks

Molecular clouds are known to rotate, as indicated by the velocity gradients observed across them (see review by Goldsmith & Arquilla 1985). As the collapse proceeds, matter along the rotational axis will fall directly onto the central protostar, but matter away from the axis will be eventually held up by the centrifugal force and form a rotational disk. Thus, disks are expected to

Figure 2: Optical image of the low-mass dense core Barnard 68. The field is approximately $3' \times 3'$ in size. Image taken from Alves et al. (2001).

be formed as a result of conservation of angular momentum in a gravitationally collapsing rotating cloud.

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. One of the first methods used to infer for the presence of disks around young stars was through the study of the spectral energy distribution. If a disk is present it gives rise to excess emission in the near infrared (Strom et al. 1989) and millimeter continuum (Beckwith et al. 1990). A more direct way to probe disks is through high angular resolution imaging of dust continuum emission at infrared and millimeter wavelengths (e.g., Beckwith et al. 1984; Lay et al. 1994; Mundy et al. 1996; Jayawardhana et al. 1998). This type of observations have shown the existence of centrifugal disks with sizes of $100-500$ AU, temperatures of $50-400$ K, masses of $0.001-1 \quad M_{\odot}$ and densities of $10^{7}-10^{9}$ cm^{-3}. High angular resolution molecular line observations at millimeter and submillimeter wavelengths towards a handful of disks have shown evidence for Keplerian rotation (Sargent & Beckwith 1987; Dutrey et al. 1998).

2.2.3 Jets and molecular outflows

A completely unexpected phenomena in the star formation process, discovered in the early 80's, is the presence of highly collimated winds blasted away from the protostar or disk. Cudworth & Herbig (1979) discovered that two Herbig-Haro objects (Haro 1951; Herbig 1952) in the dark

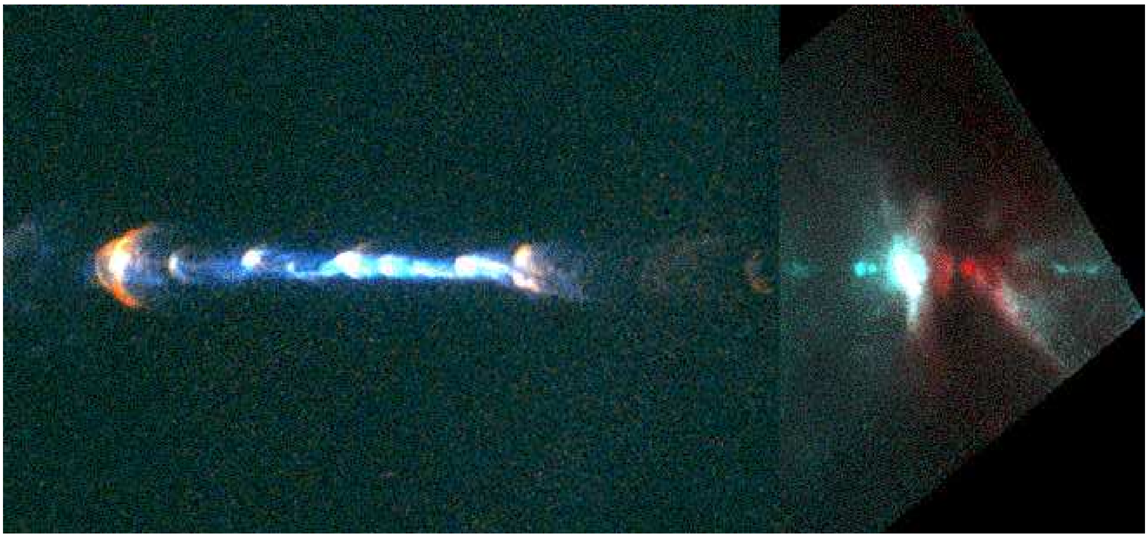

Figure 3: Optical image of a 4 pc long jet being blasted away from a YSO surrounded by a dusty disk located near the right border of the image. Image taken from the Hubble Space Telescope archive.

cloud L1551 exhibit very high proper motions which appear to have a common origin near an embedded infrared source (IRS5) discovered by Strom et al. (1976). Subsequently, Snell et al. (1980) found high-velocity CO emission towards L1551 in the form of two lobes of gas moving in opposite directions from the infrared source. These observations dramatically implied the presence of a collimated stellar wind, blown at velocities of 100 - 200 km s^{-1} from IRS 5. Optical observations have indeed shown that low-mass YSOs are capable of generating highly collimated supersonic jets (Mundt & Fried 1983; Strom et al. 1983). These jets have typically lengths of $0.01-0.1$ pc, velocities of $100-500$ km s^{-1}, hydrogen densities of $10-100$ cm^{-3}, mass loss rates of 10^{-8} $M_\odot$ yr^{-1} and momentum rates of $10^{-6}-10^{-5}$ $M_\odot$ km s^{-1} yr^{-1} (Mundt 1986). The Herbig-Haro objects correspond to shock excited structures formed when the jet collides with the more tenuous interstellar molecular gas.

Molecular line observations also soon showed that bipolar molecular outflows are a very common phenomena in low-mass star forming regions (Goldsmith et al. 1984; see Figure 4). The outflows have typically velocities of $10-50$ km s^{-1}, sizes of $0.1-1$ pc, molecular masses of $0.1-5$ $M_\odot$, mass loss rates of $10^{-7}-10^{-5}$ $M_\odot$ yr^{-1}, momentum of $0.3-30$ $M_\odot$ km s^{-1}, momentum rates of $10^{-6}-10^{-4}$ $M_\odot$ km s^{-1} yr^{-1} and kinetic energies of $10^{43}-10^{45}$ ergs (see review by Bachiller 1996). The bipolar molecular outflows appear 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. Recent observations have indeed shown the existence of parsec-scale jets associated with low-mass YSOs (Eislöffel & Mundt 1997; Yu et al. 1999; see Figure 3).

2.2.4 Low-mass star formation

The observational evidence summarized above indicate that disks, collimated ionized jets and bipolar molecular outflows are intrinsic ingredients of the formation process of low-mass stars as

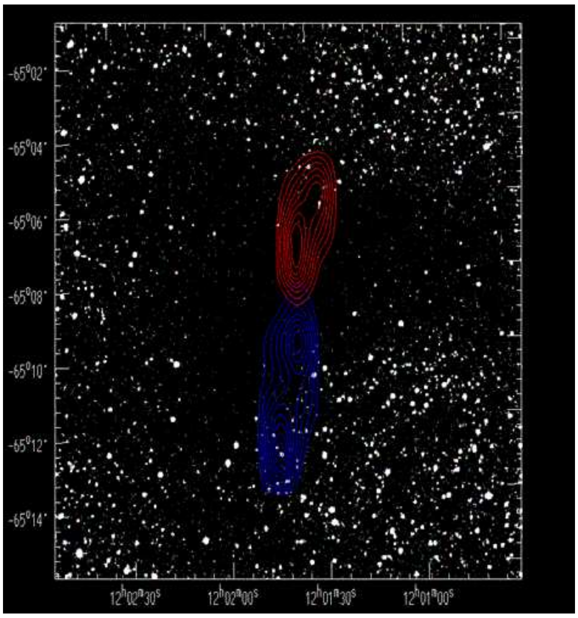

Figure 4: Collimated bipolar molecular outflow in the dark cloud BHR71 (Bourke et al. 1997). The blue and red contours indicate, respectively, blueshifted and redshifted high-velocity CO emission.

is gravitational collapse. These findings provided the basis for the development of the current paradigm of the gravitational collapse of low-mass cores leading to the formation of low-mass stars (Shu et al. 1987; Shu et al. 1993). In this model a self-gravitating core initially supported by magnetic fields looses its support and undergoes an inside-out dynamical collapse. There are four major evolutionary stages: (a) an initial stage in which the central region of a dense core begins to condense quasi-statically through the process of ambipolar diffusion; (b) an accretion stage, characterized by the presence of a central protostar and a circumstellar disk surrounded by an infalling envelope of dust and gas; (c) a phase in which the protostar deposits linear and angular momentum, and mechanical energy into its surroundings through jets and molecular outflows; and finally, (d) a relatively more advanced phase in which the protostar settles onto the ZAMS.

3. Birth of high-mass stars

Although the accretion paradigm has been very successful in explaining what is observationally known about the formation of low-mass stars (e.g., Lada 1991; Evans 1999), its applicability to the formation of massive stars remains arguable. The evolutionary time scales of high-mass stars are much shorter than for low-mass stars. Massive stars are expected to affect their environment very soon after a stellar core has formed since their Kelvin-Helmholtz time scale ($\leq 10^4$ yrs for an O star) is short compared to all other relevant evolutionary time scales. They begin burning hydrogen and reach the main sequence before they stop accreting matter from the surrounding protostellar envelopes. The formation of a massive disk, and hence the appearance of molecular outflows and jets, in the accretion phase is thus in principle not clear. In addition, in stage (c), the massive star starts to produce an appreciable output of UV photons and possibly develops strong winds which will drastically affect the physical conditions, structure, and chemistry of their surroundings. Since in this stage the massive star ionizes its surroundings, giving rise to a small region of ionized gas, this phase is usually referred as the ultracompact HII region phase.

Two scenarios have been proposed to explain the process of assembling massive stars: by collisions of lower mass objects (Bonnell et al. 1998) and by accretion (Osorio et al. 1999; McKee & Tan 2002, 2003; Krumholz et al. 2005). In both scenarios 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. 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. 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. On the other hand, a potential problem in forming massive stars by accretion from an infalling envelope is the difficulty of accreting once the protostar has attained a mass ≥ 10 $M_\odot$. The large radiation pressure on dust grains, produced by the intense radiation field of such a protostar, can halt the collapse and reverse the infall (Larson & Starrfield 1971; Kahn 1974; Yorke & Krügel 1977).

How are then high-mass stars actually formed? If massive stars are formed by accretion then we expect that disks, jets, and bipolar molecular 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 (Bally & Zinnecker 2005). In this section I review the 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 and allowing to discriminate among the different hypothesis.

3.1 Initial conditions

3.1.1 The maternities of massive stars

During the last decade intense observational efforts have been carried out to determine the characteristics of the molecular gas and dust associated with massive star forming regions. Surveys of molecular emission in high density tracers (Plume et al. 1992; Juvela 1996; Plume et al. 1997; Shirley et al. 2003) and of dust continuum emission (Beuther et al. 2002a; Mueller et al. 2002; Faúndez et al. 2004; Williams et al. 2004), made with single dish telescopes, show that the maternities of high-mass stars are regions of molecular gas with distinctive physical parameters, with typical radii of 0.4 pc, densities of 5×10^5 cm^{-3} and masses of 4×10^3 $M_\odot$. The dust observations also show that these regions have dust temperatures of typically 32 K, indicating that a luminous energy source has been already formed inside them. These structures, also refereed as massive and dense cores, have typically column densities of 3×10^{23} cm^{-2} (Garay et al. 2007a) which make them very dark at optically wavelengths. They are even dark at infrared wavelengths, being associated with InfraRed Dark Clouds (IRDCs; Menten et al. 2005; see Figure 5).

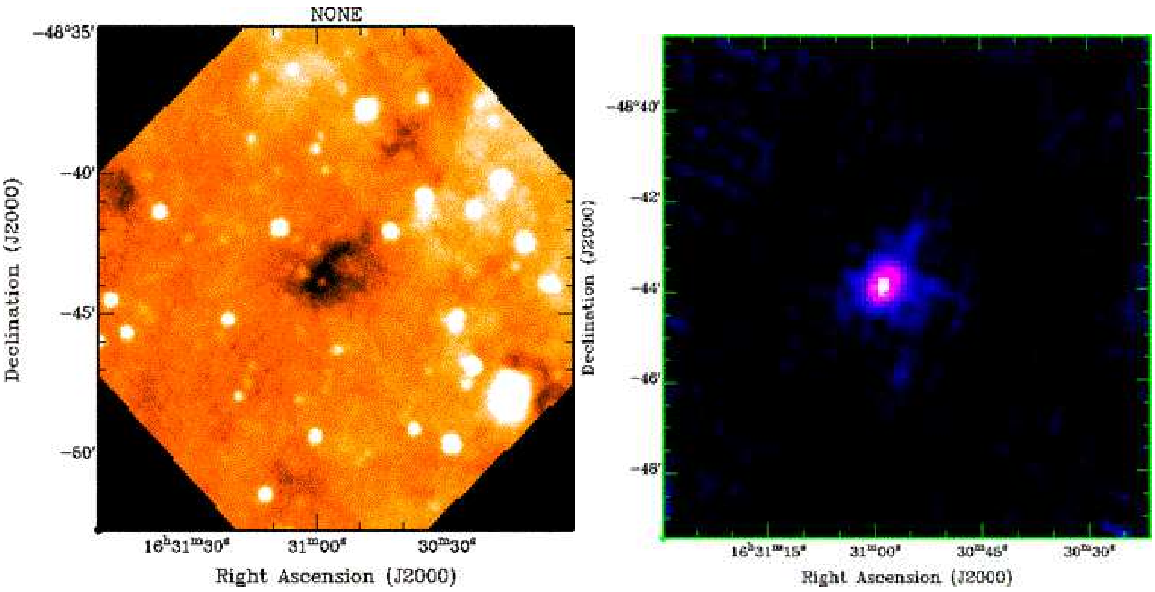

Figure 5: Massive and dense core G335.58-0.28. Left: Infrared image at 8μ from the MSX survey of the Galactic plane. Here the core is seen as an IRDC, namely in silhouette against the galactic background. Right: Image at 1.2 mm. Here the core is seen in continuum emission due to dust (Garay et al. 2002).

The observed line profiles of most of the massive dense cores are nearly Gaussian suggesting that they are in approximate hydrostatic equilibrium (Plume el al. 1997, Mardones 2003). The line widths are, however, very broad (~ 6 km s^{-1}), much larger than the thermal widths, indicating that a considerable amount of non-thermal support is required to maintain them in equilibrium. The source of support is most likely a combination of turbulence and magnetic fields. The mean pressures associated to the turbulent motions 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. The observed radial intensity profiles of the dust continuum emission from massive dense cores are usually well fitted with power-law intensity profiles, indicating that they are centrally condensed. The radial density profiles can be approximated with power-law distributions, $n \propto r^{-p}$, with average values of p in the range between 1.3 and 1.9 (Beuther et al. 2002a; Mueller et al. 2002; Williams et al. 2005). 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. These are likely to be the seeds for the formation of individual high-mass stars.

Are the physical characteristics of the massive and dense cores summarized above representative of the large scale (∼pc) initial conditions for the formation of massive stars? Most of the observed massive dense cores are associated with either ultra compact (UC) HII regions and/or luminous IRAS sources, implying that a massive star has been already formed within them. The observational evidence for cold massive and dense 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 ($T_d < 15$ K). The bulk of their low luminosity is expected to be emitted in the (sub)millimeter range, thus promising candidates should be mm sources without mid-IR counterparts. To date there are a dozen massive dense starless cores already identified (Wyrowski et al. 1999; Sandell 2000; Garay et al. 2004). The later authors searched for millimeter sources, using the dust continuum emission survey of Faúndez et al. (2004), without counterparts at mid infrared (MSX) and far infrared (IRAS) wavelengths, discovering four massive cold cores. The lack of detections in the IRAS bands prevents a determination of the dust temperature, but indicates an upper limit of $\sim$ 17 K. Their physical conditions, except temperature and luminosity, are similar to those of massive dense cores with embedded massive stars indicating that they can be genuinely associated with the initial conditions for the formation of massive stars. Garay et al. (2004) suggested that these massive dense cold cores are likely to be in early stages of evolution, before an internal luminosity source develops, and that they will eventually collapse to form high-mass stars.

3.1.2 The cradles of massive stars

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 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.

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. The high-mass accretion rate of the infalling material, as high as 1×10^{-2} $M_\odot$ yr^{-1}, quenches the development of an UC HII region, 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.

3.2 Physical phenomena

3.2.1 Collapse

Mardones (2003) found that a small fraction ($\sim 4\%$) of massive dense cores have line profiles indicative of large scale inflow motions (see Figure 6). Using the simple model of contracting clouds of Myers et al. (1996), the observed profiles imply inward speeds of $\sim$0.5 km s^{-1}. This speed is smaller than the free-fall velocity expected at the outer radius of the cores, 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}.

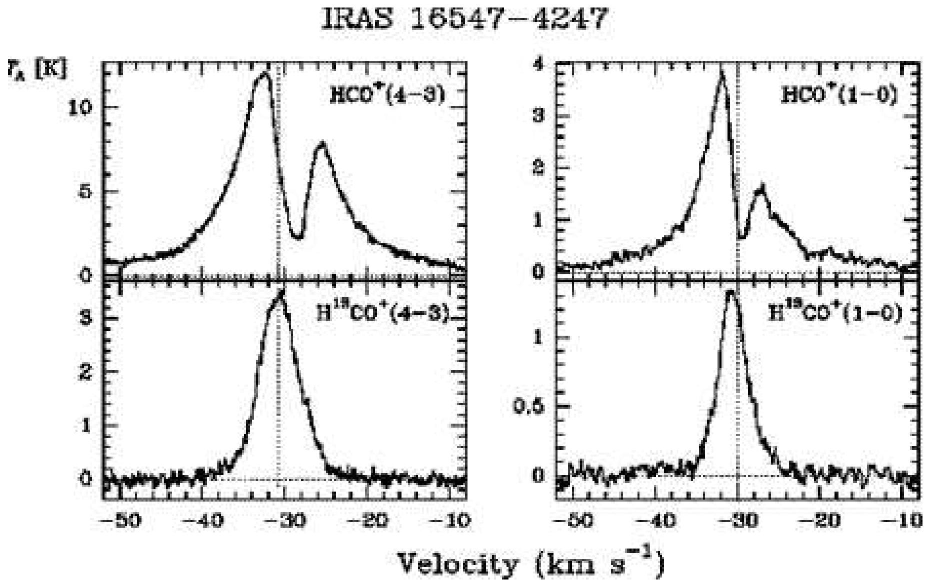

Figure 6: Molecular line profiles observed towards the massive and dense core G343.126-0.062. Top: Optically thick HCO$^+$ emission. Bottom:Optically thin H^{13}CO$^+$ emission (Garay et al. 2003; 2007b).

Direct kinematic evidence of infall motions in hot molecular cores has been reported in a few cases (e.g., Young et al. 1998; Hofner et al. 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 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}.

3.2.2 Jets

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 jets show clumps moving away from the driving source at tangential velocities of 500 to 1000 km s^{-1} (Martí et al. 1998; Rodríguez et al. 2001)

The most luminous YSO object presently known to host a jet is IRAS 16547$-$4247, which has a luminosity of $6.2 \times 10^4\ \ L_\odot$. 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). Brooks et al. (2003) detected towards this object a chain of H$_2$ 2.12 μm emission knots that delineate a large scale ($\sim$ 1.5 pc) collimated flow. The geometry of the flow implies that it is driven by the thermal jet. 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.

3.2.3 Bipolar molecular outflows

Recent systematic surveys have shown that molecular outflows is a common phenomenon toward high-mass protostellar objects (Shepherd & Churchwell 1996; 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, with 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 $L_\odot$. 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 (see Figure 7). 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? 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).

3.2.4 Disks

The evidence for the appearance of disks in the formation process of high-mass stars is 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 (e.g., Shepherd & Kurtz 1999). The disks have sizes of typically $\sim 10^3$ AU, masses of ~ 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.

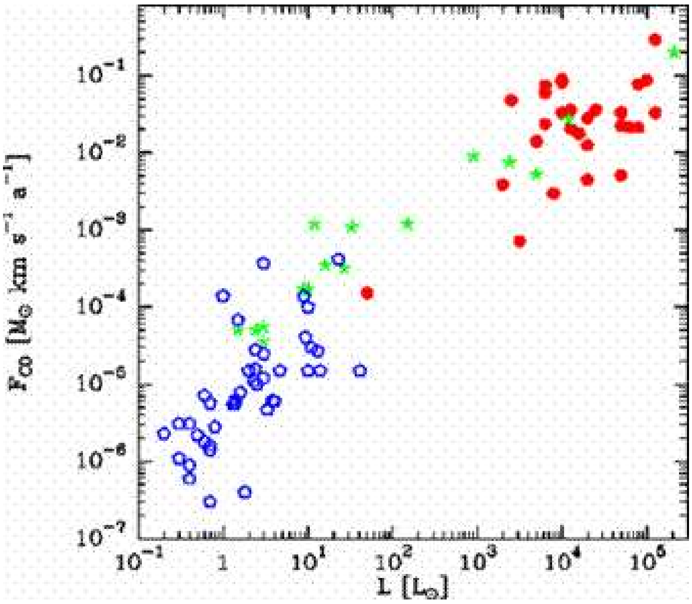

Figure 7: Momentum rate of molecular outflows versus stellar luminosity of the driving source, for a sample of YSOs with a wide range of luminosities (Beuther et al. 2002b).

3.2.5 High-mass star formation

The recently gathered observational evidence, summarized in this section, 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) showed that for inflows with mass accretion rates $\dot{M} \geq 10^{-3}\, M_\odot$ yr^{-1} the ram pressure is sufficiently strong to overcome the radiative forces on dust by the luminous central star, allowing continuous accretion to form massive stars. 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).

4. SUMMARY

In this contribution I reviewed the observational data obtained during the last forty years that have led to the present understanding on how stars are formed. The main observational evidence gathered, concerning the initial conditions and the physical processes that take place in the star birth, can be summarized as follows.

The maternities of low-mass stars are molecular structures with typical radii of ∼0.4 pc, densities of a few $\sim 10^3$ cm^{-3}, masses of a few $10\ M_\odot$, and line widths of ~ 1 km s^{-1} , known as dark clouds. The maternities of high-mass stars are molecular structures with typical radii of ∼0.4 pc, densities of a few $\sim 10^5$ cm^{-3}, masses of a few $10^3\ M_\odot$, and line widths of ~ 6 km s^{-1} , known as massive and dense cores. The line widths of massive dense cores are much greater than those of dark clouds implying that a considerable amount of non-thermal support is required, most likely turbulent gas motions, to maintain them in equilibrium. The large amount of support provided by the turbulent pressure allows the existence of massive dense cores in hydrostatic equilibrium with much larger densities than in dark clouds.

The cradles of low-mass stars are structures of molecular gas with sizes of typically $0.1 - 0.4$ pc, molecular hydrogen densities of $10^4 - 10^5$ cm^{-3}, masses of $0.3 - 10\ M_\odot$ and temperatures of ∼10 K, known as low-mass dense cores or Bok globules. The cradles of high-mass stars are regions of molecular clouds of exceptionally high density, up to a few 10^8 cm^{-3}, high temperatures, up to ~ 250 K, and masses of typically a few $10^2\ M_\odot$, known as hot molecular cores.

Disks, highly collimated ionized jets and bipolar molecular outflows are found associated with both low-mass and high-mass YSOs, implying that these phenomena are basic components of the formation process of stars of all masses. The jets and bipolar outflows driven by massive stars are considerably more massive, luminous, and energetic than those associated with low-mass stars.

The recently gathered observational evidence provides strong support to the hypothesis that high-mass stars are formed from the collapse of massive pre-stellar cores, rather than by an accumulation process, 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 $1 \times 10^{-2}\ M_\odot$ yr^{-1} have been estimated in collapsing cores associated with high-mass star forming regions, whereas in those associated with the formation of low-mass stars the mass accretion rates are typically $\sim 10^{-6}\ M_\odot$ yr^{-1}. We conclude that the paradigm of low-mass star formation can be extended to stars of all masses.

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