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THE MATERNITIES OF HIGH-MASS STARS

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RESUMEN

La comprensión del proceso de formación de las estrellas masivas requiere de un conocimiento detallado de las condiciones físicas de la nube ambiente materna ya que éstas juegan un papel crítico en la determinación del mecanismo de formación. En esta contribución se hace una revisión de recientes resultados derivados a partir de observaciones de la emisión de gas y polvo de regiones de formación estelar los cuales han provisto evidencia fundamental con respecto a las condiciones iniciales para la formación de estrellas masivas.

ABSTRACT

The understanding of the birth process of massive stars, known to be formed in clusters, requires a detailed knowledge of the physical conditions of the parental cloud which are thought to play a critical role in determining the formation mechanism. In this contribution I will review recent results from observations of the gas and dust emission towards massive star forming regions which are providing key evidence concerning the initial conditions for the formation of cluster of massive stars. These observations have allowed to characterize the physical properties of massive and dense cores and to identify them in different stages of their early evolution.

Key Words: **ISM: CLOUDS — STARS: FORMATION**

1. INTRODUCTION

The formation processes and initial evolutionary phases of massive star birth are still not well understood (e.g., Garay & Lizano 1999). 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; McKee & Tan 2003) it is assumed that massive stars are formed via accretion of gas in dense cores. In the coalescence scenario 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. As such, much observational effort has been performed during the last decade to investigate the early stages of high-mass star formation.

Surveys of emission in molecular lines excited at high temperatures and densities (Mauersberger et al. 1986; Cesaroni et al. 1992, 1994) have shown that the presence of hot and dense molecular cores (HMC's) is a common phenomenon towards massive star forming regions. The emerging consensus is that HMC's correspond to the cradles of massive stars, signalizing thus their birth place. HMC's are characterized by having diameters < 0.1 pc, temperatures > 100 K, densities $> 10^7$ cm^{-3} and luminosities in the range $10^4 - 10^6\ L_\odot$(Kurtz et al. 2000). Whether the bulk of the luminosity is due to the accretion process or due to nuclear burning by the massive protostar is not well determined. These surveys raised new questions, including Where are hot molecular cores found? and How are they formed?

Understanding the formation and early evolution of massive stars requires knowledge of the physical conditions of their birth environment. In particular, observations of the HMC environment at spatial scales of parsecs may hold the key to distinguish between different modes of HMC formation, such as fragmentation, competitive accretion or coalescence. In this contribution, I will summarize the observational data gathered during the last few years that have shed light on the processes taking place in the formation of high-mass stars and on the initial conditions for the formation of HMC's.

2. THE MATERNITIES OF MASSIVE STARS

In this section we discuss the observed and derived properties of the maternities of massive stars, namely of the molecular structures giving birth to clusters of massive stars. Several systematic studies have been carried out during the last decade to determine the characteristics of massive star forming regions (MSFR's) using as probe either molecular line emission from high density tracers (Plume et al. 1992, 1997; Juvela 1996; Shirley et al. 2003) or dust continuum emission (Beuther et al. 2002; Mueller

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et al. 2002; Williams et al. 2004; Faúndez et al. 2004). The physical parameters of the maternities independently derived from the two different observational methods are in very good agreement. From a survey of 1.2 millimeter dust continuum emission, Faúndez et al. (2004) found that the dust cores harboring recently formed massive stars have typically sizes of 0.4 pc, masses of 5×10^3 M$_\odot$, densities of 2×10^5 cm^{-3}, dust temperatures of 32 K and luminosities of 2×10^5 L$_\odot$. From a survey of molecular emission in several transitions of CS, Plume et al. (1997) found that high-mass stars are formed in molecular cores with typical radii of 0.5 pc, densities of 8×10^5 cm^{-3}, and virial masses of 4×10^3 M$_\odot$. Clearly the mm dust continuum and high density molecular line emissions are tracing the same structures. We conclude that massive stars are formed in regions of molecular gas and dust with distinctive physical characteristics, which we will refer to as massive and dense cores (MDCs). The molecular line observations further show that MDCs have remarkable wide line widths, typically 6 km s^{-1}, much larger than those of the cores associated with low-mass star formation, indicating that they are highly turbulent.

The physical conditions within massive and dense cores are unlikely to be homogeneous, however. In fact, several dust continuum studies have shown the presence of steep density gradients within MDCs (e.g., van der Tak et al. 2000, Mueller et al. 2002, Beuther et al. 2002, Williams et al. 2005). The density dependence with radius can be approximated by power-law distributions, $n \propto r^{-p}$, with average values of p in the range between 1.3 and 1.8. The individual values of p exhibit, however, a large spread, which is likely to reflect the presence of clumpiness and fragmentation within massive and dense cores (e.g., Molinari et al. 2002; Beuther & Schilke 2004).

The mechanism of formation of massive and dense cores is still poorly known. Is it a gradual condensation process or is it a fast process caused, for example, by shocks within a turbulent medium? The morphologies of the MDCs may shed some light on this issue. Of the cores observed by Faúndez et al. (2004), 24% are associated with filamentary structures, whereas 23% show clumpy morphologies. The common appearance of elongated structures suggests that gravitational instabilities in filaments are likely to be an important mechanism of core formation (Larson 1985; Tilley & Pudritz 2003). The clumpy structure could be explained if the cores are formed by turbulent shocks (Padoan et al. 2001). Therefore, both gravitational fragmentation and turbulent shocks seem to play a fundamental role for the origin of the massive and dense cores.

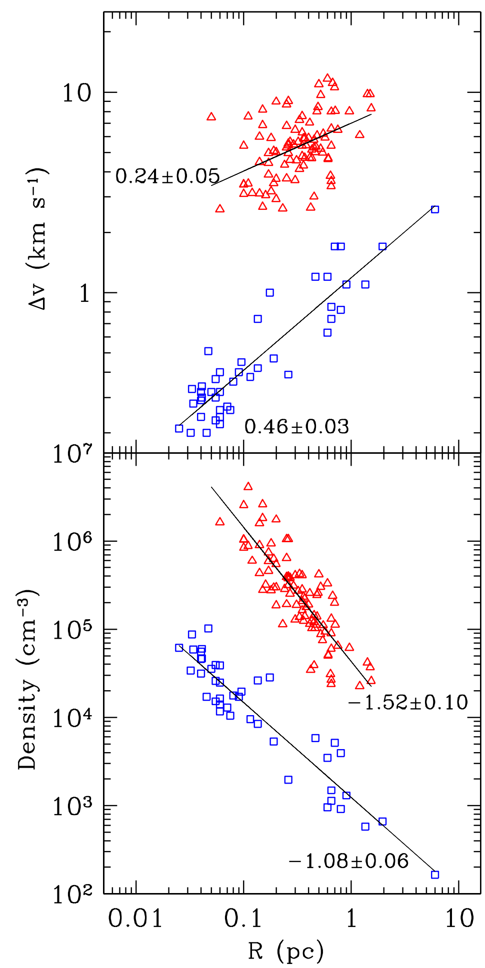

Fig. 1. Correlations between physical parameters of molecular cores. Top: Line width versus radius. Bottom: Density versus radius. Squares: Dense cores in dark clouds. Data from Myers (1983). Triangles: Massive and dense cores. Lines are least squares linear fits to the data points.

Several studies have shown that significant correlations exist between the line width, size and density of molecular clouds (cf. Larson 1981, Myers 1983). Do MDCs follow the same relationships? Fig. 1 plots the line width versus size (upper panel) and the density versus size (lower panel) relationships for massive and dense cores. The data for MDCs have been taken from Plume et al. (1997), Shirley et al. (2003), and Garay et al. (2006). For comparison also plotted are the values observed for dense cores in low-mass clouds (Myers 1983). Fig. 1 clearly shows that although correlations exists between the parameters of MDCs, the relationships are not the same for the different type of cores. At a given size, massive and dense cores have much broader line widths than cores in low-mass clouds. The physical basis for the line width versus size relationship is still poorly understood. The different relationships may reflect differences in the initial physical conditions of the different type of cores. Assuming that the cores are in virial equilibrium, the shift in line width at a fixed cloud size could be explained as due to differences in their molecular densities. The line widths of MDCs are roughly 7 times larger than those of low-mass cores, which would imply, if virialized, that their molecular densities are typically greater by a factor of 50 (as illustrated in the lower panel of Fig. 1).

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; Mardones 2003); (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). Mardones (2003) analyzed the CS(2→1) line profiles from a large sample of MDCs and found that the bulk of them are fairly symmetric, suggesting that most MDCs appear to be stable against gravitational collapse. The broad line widths of MDCs, more than 30 times greater than the thermal widths for CS lines, implies 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.

Where are massive stars formed within the massive and dense cores? This is an important issue because their location is likely to shed some light on the formation mechanism of high-mass stars. To address this question, Garay et al. (2006a,b) undertook millimeter and radio continuum observations towards a sample of 18 luminous (L> 2×10^4 L$_\odot$) IRAS sources thought to be representative of young massive star-forming regions. The dust continuum observations, obtained using the SIMBA bolometer array at SEST, showed that the IRAS sources are indeed associated with massive and dense cores. The radio continuum observations, carried out using ATCA, showed that most of these MDCs are associated with UC H II regions, implying that they have ongoing massive star formation as already indicated by their high luminosities, and that the UC H II regions are usually located at the peak of the dust continuum emission (see Fig. 2). These observations show that massive stars are preferentially born at the center of MDCs.

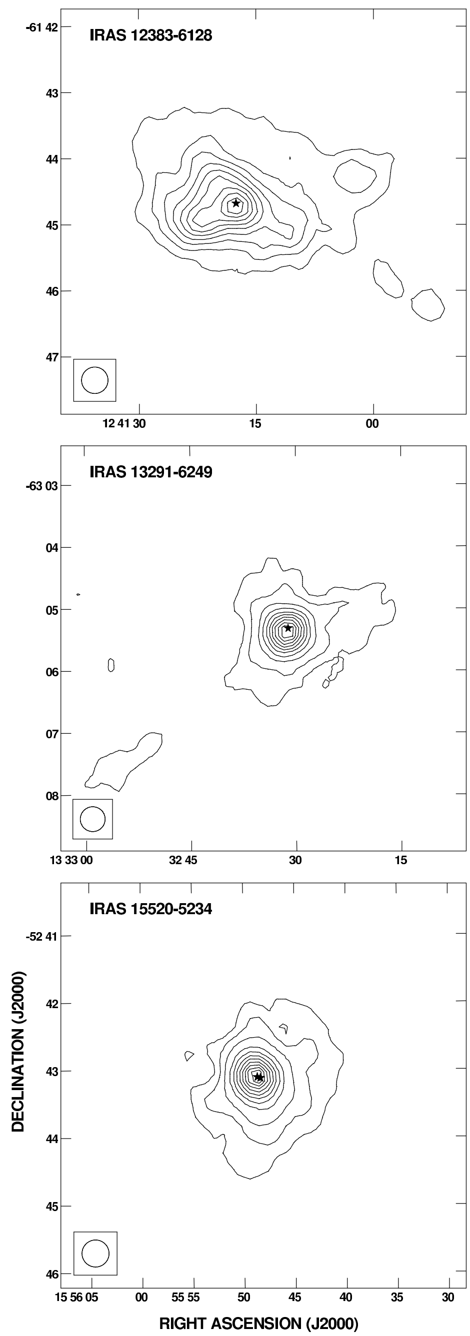

Fig. 2. SEST/SIMBA maps of the 1.2-mm dust continuum emission towards young massive star forming regions. FWHM beams are shown in the lower left corner. The stars indicate the position of the UC H II regions.

The surveys have also allowed to identify massive and dense cores in very early stages of evolution. A few luminous MDCs have not been detected in sensitive radio continuum observations, suggesting they are in a very early evolutionary stage, prior to the appearance of ultra compact regions of ionized gas. 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). The surveys have also shown the existence of a dozen MDCs with line profiles indicating that the bulk of their gas is undergoing large-scale inward motions (Snell & Loren 1977; Garay et al. 2002, 2003; Wu & Evans 2003). Model fits to the observed profiles indicate inward speeds of typically $0.5 - 1.0$ km s^{-1}. 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}, showing that massive stars are formed under very high mass accretion rates.

3. MASSIVE AND DENSE COLD CORES

Are the physical characteristics of the massive and dense cores summarized above representative of the large scale ($\sim$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) H II regions and/or luminous IRAS sources, implying that a massive star has been already formed within the core. The fast stellar winds and strong ionizing radiation from the young massive star (or stars) are expected to have a profound impact on the MDC from which they form, drastically changing its internal structure and chemistry and ultimately destroying it. To address this question requires the search of massive and dense cores in the earliest stage of evolution, previous to the formation of a central massive object. These 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. Massive cores in early stages of evolution are likely to be below the detection limits of IRAS and MSX and to find them we need to resort to mm/sub-mm observations.

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. Garay et al. (2004) used the 1.2-mm dust continuum survey of Faúndez et al. (2004) to find massive starless cores in the vicinity of cores associated with IRAS sources. They searched for millimeter sources without counterparts at mid infrared (MSX) and far infrared (IRAS) wavelengths, detecting a handful of candidates. They find that these dust cores are cold (T$<$ 17 K) but that their masses, sizes and densities are similar to those of cores with embedded massive stars, indicating that they can be genuinely associated with the initial conditions of massive star formation. In addition, molecular line observations show that their linewidths are broad ($\sim$ 4 km s^{-1}) which is only characteristic of massive and dense cores. The virial masses derived from the linewidth of CS observations are in agreement with the masses estimated from the dust emission. We suggest that these massive and dense cold cores will eventually collapse to form high-mass stars, and that their physical conditions are representative of the initial conditions for the formation of massive stars.

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