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STAR FORMATION AND EARLY EVOLUTION OF YOUNG CLUSTERS

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RESUMEN

Caracterizar muestras grandes de estrellas jóvenes y estudiar la evolución dinámica de los cúmulos estelares son los principales temas de este trabajo. La revisión se basa en observaciones multibanda de las regiones formadoras de estrellas, así como en las propiedades de agrupamiento observadas en la distribución espacial de estrellas en cúmulos jóvenes, en comparación con las simulaciones de N-cuerpos que reproducen sus subestructuras fractales. Estos son resultados observacionales y teóricos recientes relacionados con las primeras fases de la evolución de los cúmulos, cuyas condiciones iniciales de formación de estrellas podrían estar bajo efecto de fuentes ionizantes.

ABSTRACT

Characterizing large samples of young stars and studying the dynamical evolution of stellar clusters are the main subjects of this paper. The review is based on multi-band observations of star-forming regions, as well as the clustering properties observed in the spatial distribution of stars in young clusters, compared with N-body simulations that reproduce their fractal sub-structures. These are recent observational and theoretical results related to the early phases of the clusters evolution, whose initial star-forming conditions could be under effect of ionizing sources.

Key Words: ISM: clouds — open clusters and associations — stars: pre-main sequence

1. INTRODUCTION

Understanding the different scenarios of star formation is one of the major problems in astrophysics, affecting planet and galaxy formation. In spite of the large number of different clusters found in the Galaxy, their relative occurrence is poorly studied and still requires statistical investigation about clustering properties of stellar groups. This paper is focused on two approaches: (i) the use of multi-band observations to identify and characterize large samples of young stars, and (ii) discussing the structure of the spatial distribution of stars, on the light of N-body simulations that include feedback of ionizing sources.

In the first part, we review the characterization of the young stellar population associated with Canis Major R1 (CMa R1), and the efforts that have been employed to decipher the original scenario of this intriguing star-forming region that could be related with supernova events (Sect. 2). The second part is dedicated to the fractal analysis of young clusters, which results are compared with simulations for artificial clouds and clusters, aiming to depict the early evolution of stellar groups (Sect. 3).

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2. STAR FORMATION SCENARIO IN CMA R1

The molecular clouds associated to CMa R1 are excellent examples to illustrate the sequential star formation. Gregorio-Hetem et al. (2009) verified the presence of a 10 Myr stellar cluster in the opposite side of the star formation propagation associated to the arc-shaped ionized nebula Sh 2-296. This nebula contains several young clusters ($\sim$ 1-5 Myr), but its origin is not clear since different scenarios (stellar winds, old SN remnant) have been evoked to explain the almost circular distribution of the cloud material and young population all around the entire CMa OB1/R1 association (Fernandes et al. in prep.).

2.1. *Young Stellar Population*

The search for young stars in the direction of Sh 2-296 is based on the detection of X-ray sources with typical characteristics of T Tauri and Herbig Ae/Be stars, as indicated by the near-infrared (NIR) colors estimated from *2MASS* data. In a similar analysis that Barrado et al. (2011) performed for the young cluster Collinder 69, *XMM* data covering part of Sh 2-296 were obtained to verify the coexistence of clusters having different ages, and to provide an inventory of the stellar population in both sides of the molecular cloud (Santos-Silva et al. in prep.). Figure 1 (top panel) shows the projected position of the X-ray sources distributed in four *XMM* fields

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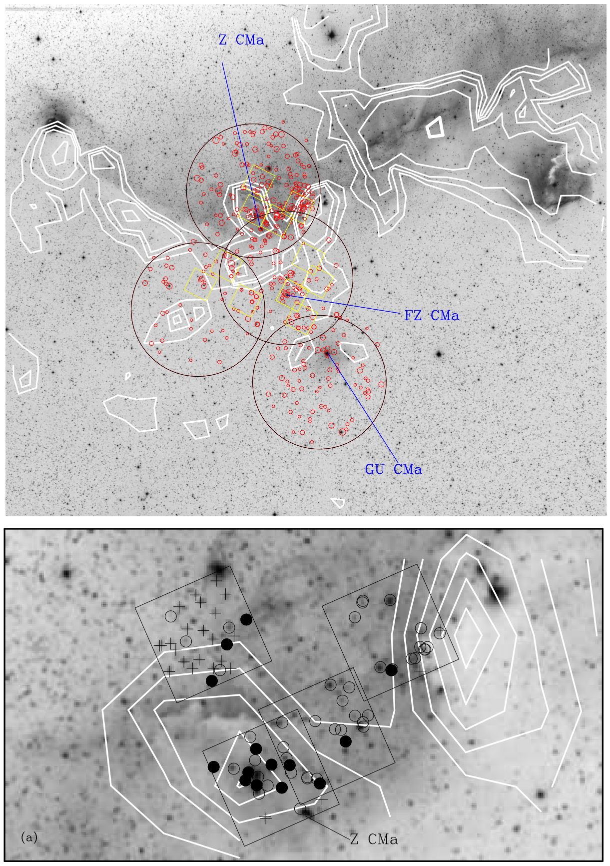

Fig. 1. Optical (DSS) image of CMa R1 superimposed by a ^{12}CO map (white contours). East is in the upper side and North is to the right. *Top panel*: Areas observed by *XMM* (large circles). Field E is near to Z CMa; field C is in the intermediate region (around FZ CMa), while field W is in a region without gas (near to GU CMa). *Bottom panel*: a zoom on field E that was partially covered by *Gemini* spectroscopy (squares) revealing young stars with disk (filled circles) and without disk (open circles).

compared with the gas and dust distribution: field E is located in the inner part of the cloud (to the East), field W is outside the cloud, in an area without molecular gas (to the West), while fields C and S cover the intermediate region, along the border of the cloud.

Fernandes et al. (2015) developed a spectroscopic analysis of the young stars associated with Sh2-296 by using *GMOS/Gemini* spectra obtained for optical counterparts of *XMM* sources. The methodology is similar to the study of the Lupus Molecular complex developed by Mortier et al. (2011). Typical features of young stars were inspected to confirm the nature of the candidates that are mainly T Tauri stars. Figure 1 (bottom panel) shows the spatial distribution of the disk-bearing stars, described in Sect. 2.2.

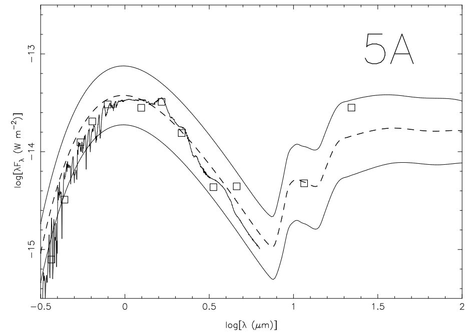

Fig. 2. Example of SED fitting with the use of GADisk code for one of T Tauri stars studied by Fernandes et al. (2015) in order to estimate its circumstellar emission.

2.2. *The fraction of circumstellar disks*

The circumstellar structure of the young stars in Sh 2-296 was evaluated by Fernandes et al (2015) using the GADisk code (Hetem & Gregorio-Hetem 2007), based on genetic algorithms, which reproduces the spectral energy distribution (SED). Figure 2 illustrates the SED fitting based on a disk model (Dullemond et al. 2001) used to estimate the contribution of the circumstellar disk (f_c) to the total emission (f_T) of the star+disk system. Among 58 young stars studied by Fernandes et al. (2015), only 8 present significant circumstellar emission ($f_c > 0.3$ f_T) and can be considered disk-bearing.

Aiming to improve the statistics in finding disk candidates in the CMa R1 region, Gregorio-Hetem et al. (2015b) searched for NIR counterparts of *XMM* sources by selecting those with available data in the *WISE* Catalogue. Only 205 *XMM* sources having a single NIR counterpart were selected, avoiding possible misidentification that could occur in the case of multiple counterpart candidates. Figure 3 (left panel) shows the distribution of the selected sources in the K-[3.6] *vs.* H-K diagram and the expected locus of stars with NIR excess, found in the box delimited by dashed lines.

This criterion indicates 60 objects with NIR excess, but this is the first step in the identification of disk-bearing stars. The sample was refined by comparing our candidates with the criteria from Koenig & Leisawitz (2014) to classify YSOs based on *WISE* colors. Figure 3 (right panel) shows the [3.4]-[4.6] *vs.* [4.6]-[12] diagram and the Class I, II and III regions (dotted lines) suggested according to the distribution of objects associated to Taurus Molecular cloud (Rebull et al. 2010). T Tauri stars and a Herbig Ae star associated with Sh2-296 (Fernandes et al. 2015) are also included in Fig. 3 in order to illustrate the distribution of known disk-bearing objects.

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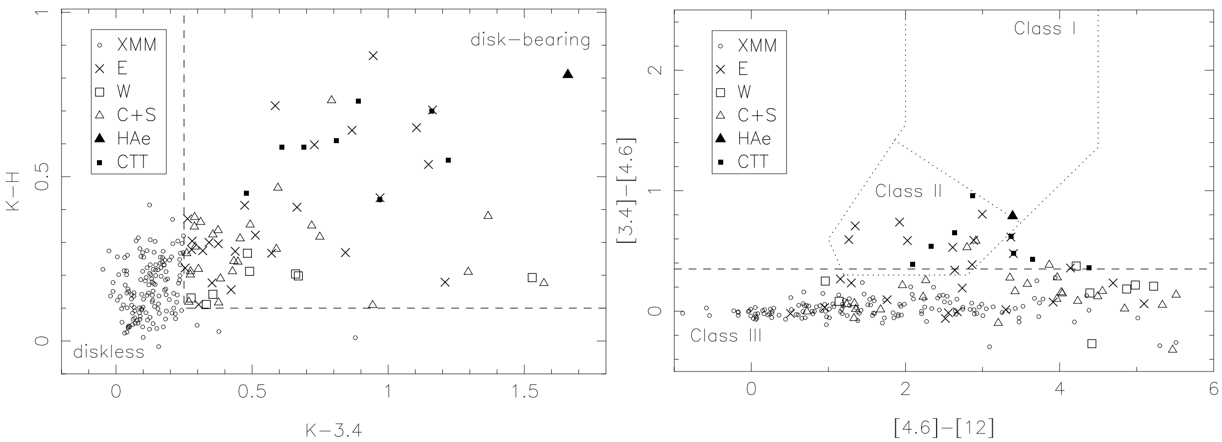

Fig. 3. *Left:* Color-color diagram combining data from *2MASS* and *WISE* 3.6μm band used to select candidates showing NIR excess (separated by dashed lines). *Right:* *WISE* colors of Class II and III candidates compared with the criteria proposed by Koenig & Leisawitz (2014). Filled symbols indicate confirmed young stars showing more than 30% of circumstellar contribution in the total luminosity. Our disk-bearing candidates are found above the dashed line.

This analysis provided the separation in different class candidates, which are listed in Table 1 showing that only 16 of the studied *XMM* sources probably are Class II objects, most of them (75%) located in the field E, where the younger stars (<5 Myr) of the sample are mainly found and larger amounts of cloud material are concentrated. On the other side of the cloud (field W), which mainly contains older (>10 Myr) stars, there are very few objects with NIR excess, and only one disk-bearing candidate.

In spite of the youth of the sample associated with Sh2-296, a very low fraction (<8%) of disk-bearing stars is found, which is not usual when compared with most of the star-forming regions (e.g. Haisch et al. 2001, Fedele et al. 2010). Would be possible that some external factor caused the disks disappearing among the young stars in CMa R1? Similar hypothesis was raised by Hernández et al. 2008, for γVel cluster (5Myr, 10% of disk fraction), suggesting that stellar winds or strong radiation fields probably produced the disks dispersion.

It is interesting to note the low number of disk candidates also occurring in a larger census of YSO candidates, performed by Fischer et al. (2016) on the entire Canis Major OB1 Association (covering $10^o \times 10^o$), based on *WISE* colors. They found about 480 Class I and Class II candidates distributed in this whole area, which gives an YSO projected spacial density ($\sim$ 5 per square degree) smaller than that found by us ($\sim$ 16 per square degree). Fischer et al. (2016) estimated that Class II/Class I ratio varies from 0.4 to 8.3, which is unexpected if this parameter traces age and the YSOs are due to the same SN event. They argue that, once less massive clouds show larger Class II/Class I ratios, this quantity is determined as a function of initial conditions of star formation.

TABLE 1

SELECTING DISK CANDIDATES IN CMA R1

	Total	E	C+S	W
2MASS candidates[a]	205	90	68	47
NIR excess	60	25	27	8
Class II locus	16	12	3	1
Diskless[b]	44	13	24	7

[a] *XMM* Sources with a single NIR counterpart; [b] objects showing NIR excess (Fig. 3), but appearing in the Class III locus ($[3.4] - [4.6] < 0.35$ in Fig. 4).

The conclusions from the identification and characterization of the stellar population associated to CMa R1, indicating at least two different episodes of star formation, and a very low fraction of disks, can be clues about the early evolution of this cloud and respective stellar groups. The study of gas dynamics is needed to verify if an external factor has accelerated the disks dissipation. Such study, related to dynamical evolution of clouds and clusters may provide hints on the physical conditions and original cloud structure, similar to those examples mentioned in the next section.

3. DYNAMICAL EVOLUTION OF STELLAR CLUSTERS

A detailed study of the dynamical conditions of the gas associated to stars clusters can bring us valuable information about the clustering properties and the effects of a possible ionizing source. Parker

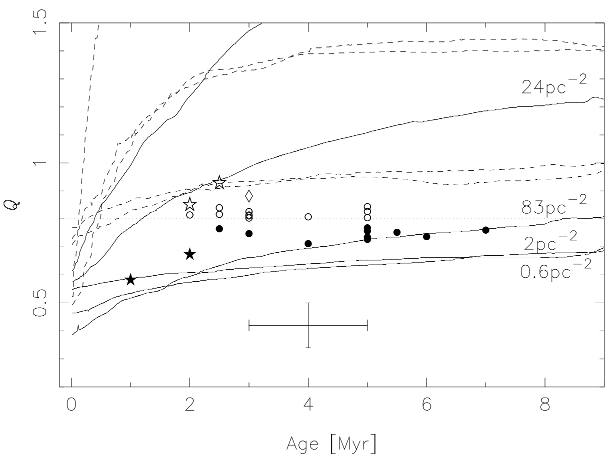

Fig. 4. Q parameter as a function of age obtained for young clusters (open and filled symbols from Gregorio-Hetem et al. 2015) compared with results from modelling different initial conditions (dashed and full lines from Parker et al. 2014).

et al. (2014), for instance, developed simulations that adopt feedback from ionizing sources and stellar winds, providing information on spatial distribution of the gas as well as the stars. With N-body simulations these authors reproduced the initial conditions based on observed star-forming regions, like the filamentary structures revealed by *Herschel* data (e.g. André et al. 2010). The substructures found by Parker et al. (2014) in the points distribution of artificial data sets are also consistent with hydrodynamical simulations (e.g. Schmeja & Klessen 2006; Bate 2012; Dale et al. 2012; Girichidis et al. 2012).

In the structural analysis of surface stellar distributions, the parameter Q proposed by Cartwright & Whitworth (2004) has been used to distinguish fractal substructures from centrally concentrated profiles. When measuring the minimal spanning tree of a stellar distribution, the parameter Q is defined by the ratio between $\bar{m}$ (normalized mean edge length) and $\bar{s}$ (mean separation of points). Examples of young clusters showing similar $\bar{m} \sim 0.5$, like IC2391 that have $\bar{s} = 0.74$ and IC348 ($\bar{s} = 0.49$) present different structure, indicated by their estimate of Q. While IC2391 ($Q < 0.8$) has fractal substructures, IC348 ($Q > 0.8$) has centrally concentrated profile.

Gregorio-Hetem et al. (2015a) studied the fractal statistics of 25 young clusters, which Q parameter and age were compared to the simulations from Parker et al. (2014). Figure 4 shows that this sample of clusters coincides more likely with the models that adopt feedback from ionizing source and supervirial conditions.

The virial ratio, relating kinetic and potential energies, is used to estimate the evolution of the system. A subvirial fractal will collapse more quickly and form a dense core (Allison et al. 2010), while a supervirial fractal will expand (Parker et al. 2014). These are open issues related to the star formation processes and the early phases of the clusters evolution that could have evolved from filamentary structures, which are observed as the scenario for prestellar cores formation via gravitational instability.

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