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The early stages of stellar cluster formation (Invited contribution)

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Abstract

How stellar clusters form and what determines their richness or stellar density are long-standing questions, intimately related to the fragmentation properties of molecular clouds. We present a summary of observational campaigns carried out by our group, aimed at disentangling which properties, if any, finally control the fragmentation process in the dense parts of molecular clouds, from 0.2 pc to 1000 au scales. We show a tentative correlation between the fragmentation level and the mass-to-magnetic flux ratio, as predicted by theoretical and numerical works, along with a strong correlation with density. Finally, we mention future research lines that involve the new generation of interferometers such as the next-generation Very Large Array.

Resumen

La formación de los cúmulos estelares y los procesos que determinan su riqueza o densidad estelar son preguntas abiertas desde hace mucho tiempo, íntimamente relacionadas con la fragmentación de las nubes moleculares. Se presenta un resumen de las campañas observacionales llevadas a cabo en nuestro grupo con el objetivo de desentrañar qué propiedad, si es que alguna, controla el proceso de fragmentación de las partes más densas de las nubes moleculares, desde escalas de 0.2 pc a escalas de 1000 au. Se presenta una correlación tentativa entre el nivel de fragmentación y el cociente masa-flujo magnético, tal como han predicho numerosos trabajos teóricos y numéricos, además de una correlación fuerte con la densidad. Finalmente, se indican líneas de investigación futuras que involucran las nuevas generaciones de interferómetros como el next-generation Very Large Array.

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1. Introduction

The formation of stellar clusters is an essential and highly evolving topic in Astrophysics. Although this topic has a vital role in Galaxy evolution, the details on how this process takes place are still poorly constrained, in part because it involves a number of physical phenomena. It is widely accepted that stellar clusters form in dense, hierarchically structured and highly dynamic gas clouds (Fig. 1-top), where filamentary structures feed the dense massive cores, usually arranged in a hub-filament system (Fig. 1-bottom-left). As the cloud, and filaments within it, evolve, fragmentation takes place producing the seeds of the future nascent cluster (Fig. 1-bottom-mid), typically located at the hub or the deepest potential well of the cloud (Fig. 1-bottom-right; e.g., Krause et al., 2020). Thus, the process of fragmentation of a molecular cloud is essential to understanding the formation of stellar clusters. This fragmentation process could be controlled by a number of factors such as the density and temperature structure, turbulence, initial angular momentum, stellar feedback, and magnetic fields (see references in Palau et al., 2021). Disentangling which of these factors, if any, dominates

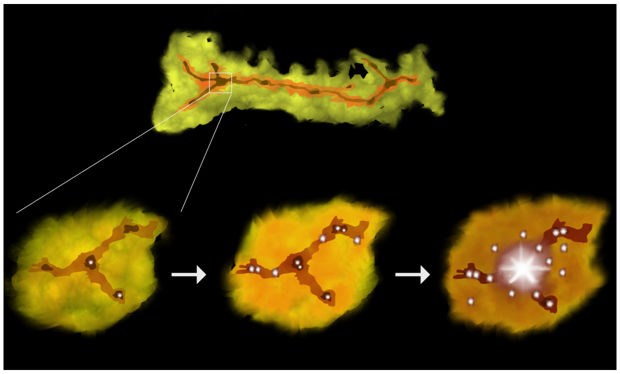

Figure 1. Sketch describing how stellar clusters form (see main text in Sec. 1).

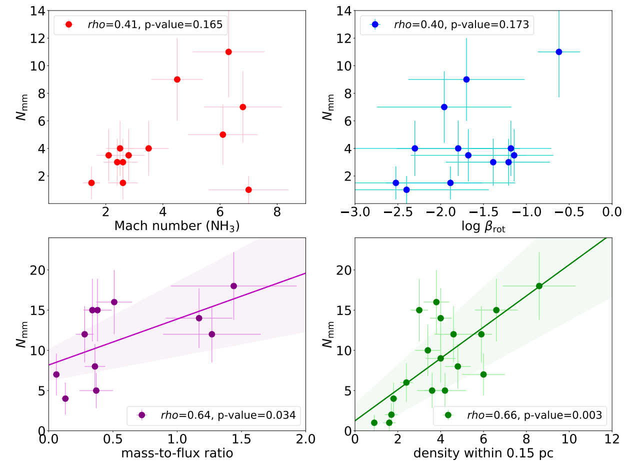

Figure 2. Summary of correlations between the fragmentation level, $N_{\rm mm}$, and several parameters of the parental structures (Palau et al., 2014, 2015, 2021).

the fragmentation process is a big challenge from an observational point of view.

2. Observations of the different factors influencing the fragmentation level

In order to study the different factors influencing the fragmentation process, several observational campaigns were conducted from 2010 to 2020. The objects under study were selected to be massive dense cores (masses 100–1000 $M_{\odot}$, and sizes of 0.1–0.5 pc) with limited stellar feedback, which are supposed to be the cradles of the future stellar clusters. Two main samples were built for this purpose. To characterize their fragmentation level, we studied these samples using millimeter interferometers at subarcsecond angular resolution (yielding spatial resolutions of about 1000 au at 2 kpc). Regarding the characterization of the massive dense cores, single-dish observations of millimeter/submillimeter continuum emission and line emission were performed. In addition, Very Large Array (VLA) NH_3 (1,1) observations were gathered for all the regions of the sample. A first sample with all these data is presented in Palau et al. (2013, 2014, 2015). From these works, a study of the fragmentation level, $N_{\rm mm}$, vs. several parameters was performed. $N_{\rm mm}$ is estimated by counting the number of millimeter compact sources within the same field of view of 0.1 pc for all the regions. The top panels of Fig. 2 show the results for $N_{\rm mm}$ vs. the Mach number and $N_{\rm mm}$ vs. the rotational-to-gravitational energy ratio, $\beta_{\rm rot}$. In these two cases, the Spearman's rank correlation coefficient ρ is around 0.4, and the p value is > 0.16, indicating that there is no correlation.

The second sample was built by requiring that Submillimeter Array (SMA) polarization data were available (mainly from Zhang et al., 2014, and the SMA archive). The data were carefully analyzed in a uniform way and no correlation was found for $N_{\rm mm}$ vs. mass-to-magnetic flux ratio *unless* the velocity field was treated as the magnetic field, i.e., separating the large-scale component from the small-scale component by means of the two-point-correlation function. When doing this, the result of the bottom-left panel of Fig. 2 was found, revealing a tentative correlation ($\rho \sim 0.64$, and $p \sim 0.034$) consistent with numerical and theoretical works: the higher the mass-to-flux ratio, the higher the fragmentation level because the magnetic field is offering less support against gravity. It is important to stress that if the velocity field is not separated into a large-scale and a small-scale component, no correlation is found, consistent with the analysis performed in other works such as Beuther et al. (2024). Finally, the bottom-right panel of Fig. 2 shows a strong correlation ($\rho \sim 0.66$, and $p \sim 0.0035$) of $N_{\rm mm}$ with the density averaged within the common field of view of the second sample, of 0.15 pc. Again it is important to note that in order to recover such a strong correlation, the density needs to be calculated within the field of view where fragmentation is assessed, and that there is no strong correlation with the density *structure* or the density power-law index of the parental core as found also by Beuther et al. (2024).

In summary, when the samples are studied carefully in a uniform way, a tentative correlation of $N_{\rm mm}$ with the mass-to-flux ratio and a strong correlation with the density are revealed, suggesting that these factors could potentially be important in the fragmentation process. Future promising research lines focus on the chemical content of the cluster members, such as the detection rate of hot corinos in the nascent cluster and the possible dynamic link between the different cluster members. In this sense, the ngVLA will be of pivotal importance to image the details of the gas linking large-scale structures of the parental core with the compact sources of the cluster, allowing us to further understand this fascinating process of stellar cluster formation.

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