Primordial mass and density segregation in a young molecular cloud

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ABSTRACT

We analyse the geometry of the Pipe Nebula, drawn by the distribution (Q spatial parameter) and hierarchy (Δ spatial segregation) of column density peaks previously detected and catalogued. By analysing the mass and volume density of the cores, we determine that both variables show spatial segregation with a high degree of substructure. In view of the early evolutionary state of the Pipe Nebula, our results suggest that segregation both by mass and by volume density may be primordial, in the sense of appearing early in the chain of physical processes that lead to cluster formation. We propose that volume density, and not mass, is the parameter that most clearly determines the initial spatial distribution of pre-stellar cores.

Key words: stars: formation – ISM: clouds – ISM: individual objects: Pipe Nebula.

1 INTRODUCTION

Most star clusters in the Galaxy have their most massive stars concentrated near their centres. This spatial segregation of mass is thought to be a consequence of an equipartition of energy driven by gravitational stellar encounters (e.g. Meylan 2000; Khalisi, Amaro-Seaane & Spurzem 2007). This is a well-known dynamic process whose evolutionary time depends on the average mass of the cluster stars, on the mass of the spatially segregated stars, and on the relaxation time of the system. The mass segregation effect in stellar clusters does not appear to depend on the local environment (e.g. Dib, Schmeja & Parker 2018) or the initial dynamical configuration (e.g. Domínguez et al. 2017). However, many young clusters with relaxation times longer than their age also show evidence of being mass-segregated; in those cases, the spatial pattern of the mass cannot be explained by the standard two-body relaxation mechanism (Parker et al. 2016).

The formation of stellar clusters is far from being a well-understood process. On the one hand, we have the progenitor giant molecular clouds whose initial conditions in terms of structure in density, temperature and velocity seem to be well known and limited, for the most part, to a narrow range of values (e.g. Sánchez, Alfaro & Pérez 2005, 2007; André et al. 2010, 2013). On the other hand, we have the recently formed stars that are also constrained observationally by an initial mass function (IMF) with a probable universal character (Padoan, Nordlund & Jones 1997; Bastian, Covey & Meyer 2010; Ascenso & Alves 2012; Parker & Goodwin 2012; Parravano; Sánchez & Alfaro 2012), but whose distribution in phase space shows a more variable casuistry (Elmegreen 2009; Sánchez & Alfaro 2009). In between these two states, there are several phases: (i) the magnetohydrodynamic evolution of the cloud towards the formation of pre-stellar nuclei; (ii) the process of perturbation, collapse and fragmentation of the pre-stellar nuclei that gives place to proto-stellar nuclei; (iii) the accretion and/or coalescence of the proto-stellar nuclei favoured or restricted by the density of objects, the magnetic field and turbulence; and, finally, (iv) a group of stars with a characteristic mass distribution undergoing a rapid dynamic evolution in a medium not always free of interstellar matter (Allison et al. 2010; Bressert et al. 2010; Parker & Dale 2013). Additional complications arise for two reasons: the progression of cluster formation and early evolution is intimately linked to the primordial structure of the forming cloud (e.g. Román-Zúñiga et al. 2008; Ybarra et al. 2013); clusters do not form as isolated entities, but they form in families across clouds, and they present abundant substructure (e.g. Román-Zúñiga et al. 2015; González & Alfaro 2017).

We might be able to answer the following question. When and how is the observed mass segregation in young clusters generated? In this paper, we study the spatial structure of a list of pre-stellar column density peaks identified across the Pipe Nebula (Román-Zúñiga et al. 2010). This object is a very young cloud, apparently dominated by a long quiescent state (Lada et al. 2008), with only one core actively forming a small, low-mass stellar cluster (Brooke et al. 2007) and fewer than a handful of additional well-defined cores showing infrared emission indicative of proto-stellar activity (Forbrich et al. 2009). Thus, the Pipe Nebula probably represents an early evolutionary state of the star-formation process. The cloud is possibly at a stage when its structure and evolution is controlled by magnetohydrodynamic physics but just before the onset of the cloud collapse when gravitation is becoming the main driving force. The Pipe Nebula thus sets a lower evolutionary limit for the study of the presence or absence of mass segregation in the earliest stages of the formation of a stellar cluster. The column density peak catalogues of Román-Zúñiga, Lada & Alves (2009) and

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It is important to clarify here that not all of these column density peaks can be considered as individual pre-stellar cores. The main reason (also discussed by RALL0910) is that we do not have information on the gas kinematics (either radial velocities or velocity dispersions) for all individual peak positions in order to determine if all objects in our list are independent. As prescribed by Rathborne et al. (2009), in order to determine if a column density peak is an independent core, we would need to confirm that the separation from a neighbouring peak is equal to or larger than the Jeans length (for instance, at $T = 10^4$ K and $n = 10^3$ cm$^{-3}$) and that the radial velocity difference from peak to peak is equal to or larger than the local sound speed. Thus, as mentioned by RALL0910, a significant fraction of our peaks appear to be genuine sub-Jeans structures but we cannot fully identify them as independent pre-stellar cores. However, we have confirmed that significant peaks can currently be found with sub-Jeans sizes and separations in column density maps obtained from Herschel far-infrared emission observations. Sub-Jeans sized or sub-Jeans structured peaks might play a role in the early evolution of the molecular gas of a cloud such as the Pipe Nebula; current discussions suggest that proto-stellar regions in star-forming molecular clouds might be the result of the merging of subsidiary material that flows along filaments (e.g. Roccatagliata et al. 2015; Lee, Hennebelle & Chabrier 2017; Williams et al. 2018). In this sense, sub-Jeans peaks might be able to merge into classical Jeans-sized pre-stellar cores, or even to survive as independent low-mass globules. For these reasons, we consider that it is important to use the complete list of column density peaks for our analysis, as we are looking, precisely, for the significance of the spatial structure driven by different physical variables, along the whole extension and along the various scales of the cloud.

2 COLUMN DENSITY PEAK CATALOGUES

In this study we make use of the column density peak catalogues of RALL0910 obtained from near-infrared, high-resolution (20-arcsecFWHM) visual extinction maps of the Pipe Nebula. These maps were constructed using the near-infrared colour excess method (Lombardi, Alves & Lada 2006) applied to a combination of various near-infrared ($J$, $H$ and $K$, bands) photometry catalogues from surveys performed at the European Southern Observatory (ESO) New Technology Telescope (NTT), the ESO Very Large Telescope (VLT) and the Calar Alto 3.5-m telescope, complemented with photometry from the Two-Mass All-Sky Survey (2MASS). For a fully detailed description of the maps, we refer the reader to RALL0910. Summarizing the methods, significant column density peaks were detected and classified through the application of the CLUMPFIND algorithm (Williams, de Geus & Blitz 1994) to background subtracted versions of the column density maps. Background subtraction was applied by filtering large-scale emission using a wavelet-based technique (Rué & Bijaoui 1997). The catalogue of RALL0910 contains a list of 244 column density peaks. For each peak, they provided: (i) the position of the peak, defined at the pixel with the highest value; (ii) the peak mass, obtained from a conversion from extinction to total mass of H$_2$ using a constant gas-to-dust ratio, and a distance of 130 pc to the cloud; (iii) an equivalent radius, obtained from the area of each region (defined by CLUMPFIND); and (iv) a mean volume density, estimated from the radius and mass assuming a simple spherical geometry. Fig. 1 shows the spatial distribution of the column density peaks across the cloud.

![Figure 1. A map of column density peak positions in the Pipe Nebula. The colour scale indicates the peak value of visual extinction, $A_V$, in magnitudes. At first glance, higher extinction peaks appear to be located in the most populated regions of the map.](https://academic.oup.com/mnrasl/article-abstract/478/1/L110/5040027/fig1)

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In Fig. 2, we present a ($l$, $b$) surface density map of the column density peaks in our sample. We can distinguish four well-defined concentrations (labelled A, B, C and D), the largest and most dense (A) being found at the intersection of the two lineal filaments drawn by the core’s distribution. This region is known as the Bowl, and it has been shown to be consistent with the collisional merging of two well-defined molecular filaments permeated by a magnetic field (Frau et al. 2015). It contains a high concentration of peaks, some of them with peak values above $A_V > 20$ mag (Román-Zúñiga et al. 2009). Two other concentrations appear to be aligned along the denser and longer filament The region labelled B in Fig. 2 is known as the Stem, and it shows the most obvious filamentary morphology in the cloud. The core concentration defining the western end of the filament contains the clump Barnard 59 (labelled C in the figure), and this is the only region in the cloud with active star formation. About 20 protostars are embedded in a region of very high column density; in the centre of this region, values of $A_V$ reach more than several tens of magnitudes. Finally, the concentration labelled D in the figure coincides mostly with the region of the Pipe Nebula known as the Smoke, where the well-known core Barnard 68 is located (Alves, Lada & Lada 2001).

We notice that this figure is equivalent to fig. 13 discussed in section 5.2.1 of Román-Zúñiga et al. (2010), except that the current
and volume density distributions for the Pipe Nebula, values of \( \Lambda_V \) are very similar to those of other molecular clouds in the solar neighbourhood analysed using Herschel data.

3 METHOD FOR SPATIAL SEGREATION ANALYSIS

Several algorithms have been proposed for the analysis of mass segregation in stellar systems, and the ones that are particularly useful are those that apply a direct measurement of the radial variation of the surface density or the mass distribution itself (e.g. de Grijs et al. 2002; Gouliermis et al. 2004). Another frequently used method relies on the properties of the minimum spanning tree (MST) edge-length distribution. This approach to the mass segregation analysis was introduced by Allison et al. (2010) and it is founded on the idea that we find mass segregation if massive stars are closer to other massive stars than to any other star. In this definition, there is no need of a spatial singular centre around which the massive stars have to be concentrated, but the stars can cluster around any non-singular position.

We used the MST method on the Pipe Nebula density peak list. Our procedure can be easily summarized as follows. Cores are sorted according to their masses in descending order and an interval of size \( n \) is defined as the number of objects per bin. Then, the MST of the spatial distribution for the \( n \) cores in the interval is calculated, from which the central value of the edge-length distribution, \( I_c \), is obtained. This value \( I_c \) is compared to a value \( I_s \), obtained for a random sample of the same size \( n \) taken from the complete sample. In order to obtain a representative value of this central estimator, \( I_s \), we obtained the average of multiple repetitions. We take the quotient between \( I_s \) and \( I_c \), \( \Lambda \), following the notation of Allison et al. (2010) for the case where \( l \) is the central length. If \( \Lambda > 1 \), then we say we are observing mass segregation.

We also select a step parameter \( s \), which establishes the number of shifted objects between two consecutive bins.

In the same way, we estimated the \( Q \)-spatial parameter (Cartwright & Whitworth 2004) for each bin, which quantifies the projected spatial structure of \( n \) objects per bin, sorted by either mass or density (\( M \) and \( \rho \), respectively). The \( Q \lesssim 0.8 \) values are indicative of a clumpy, subclustered structure, whereas \( Q \gtrsim 0.8 \) values indicate a more centrally condensed distribution. The further the value of \( Q \) from 0.8, the stronger the degree of subclustering or central concentration. There exist clear relationships between \( Q \) and fractal dimension, and \( Q \) and King’s concentration parameter for radial distributions (Sánchez & Alfaro 2009). It is important to notice that if we were facing a clumpy pattern with several clumps whose central regions are dominated by a massive object, the use of the mean as representative of the central value of the distribution would lead us to the wrong result. This is because the long edges connecting the different clumps would produce a larger edge-length average, hiding any sort of mass segregation that could be present in the data. In order to avoid this problem, we use, instead, the edge-length median, as it is more robust against the presence of outliers as the long edges connecting well-separated blobs. This strategy was previously proposed by Maschberger & Clarke (2011), who reformulated the procedure, introducing the median instead the mean for estimating the central value of the edge-length distribution in each bin. A more detailed description of the procedure and its application can be found in Alfaro & González (2016).

Summarizing, we analyse the spatial pattern of the density peak using the methodology formerly proposed by Allison et al. (2010) but reformulated by Maschberger & Clarke (2011) to account for a possible underlying fractal pattern. This approach has been suc-
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Figure 3. The $\Lambda$ parameter as a function of $M$ and $\rho$ for the Pipe Nebula density peak sample. We used bins of 40 elements with a sequence parameter $s$ of 10 elements. Both $M$ and $\rho$ appear to be spatially segregated but the high $\Lambda_{\infty}$, for the 40 densest cores, strongly suggests that this variable is mainly responsible for drawing the geometry of the cores of the Pipe Nebula.

cessfully applied to different observed and simulated star-forming regions (i.e. Alfaro & González 2016; Dorval et al. 2016; Parker & Wright 2016; Parker, Dale & Ercolano 2015) and it appears to be especially suitable for the analysis we plan to perform using the core population of the Pipe Nebula. Note that we can apply the method to any variable, not only to mass. The two physical variables we analyse in this study are $M$ and $\rho$, both estimated for each single core in our sample.

4 RESULTS AND DISCUSSION

We have applied the methodology described in Section 3 to both physical variables, $M$ and $\rho$, for the column density peaks of the Pipe Nebula. A value of $n=40$ has been taken as the initial number of objects for the analysis of our data set, with a step of $s=10$. Fig. 3 shows the results of this analysis for both variables. We can see that $\Lambda$ is greater than 1 (at a 2$\sigma$ confidence level) for both the most massive and the most dense objects, but the latter are clearly more segregated than the most massive objects.

Fig. 4 displays the spatial parameter $Q$, as a function of $M$ and $\rho$, using the same binning parameters. For $M$, $Q$ reaches a peak value near 0.6, but the rest of the bins show values well below 0.8, while for $\rho$, the peak value of $Q$ is near 0.55, also with most bins showing values well below 0.8. Although all $M$ intervals show a clumpy structure, the two most massive bins present the lowest $Q$ values, supporting – in the sense given by Parker (2018) – a degree of mass segregation, consistent with the $\Lambda$ analysis. Moreover, the spatial pattern shown by $\rho$ is much more clumpy, with a monotonic decreasing function of $Q$ versus $\rho$. These results indicate a high level of substructure, uniformly distributed across the filaments of the Pipe Nebula, induced by $\rho$. This is consistent with the two-point correlation function analysis shown by Román-Zúñiga et al. (2010). Our quantitative analysis translates into the observable spatial plane the different distributions of either the 40 most massive cores, or the 40 densest nuclei, as shown in Fig. 5. Red contours correspond to the distribution by $\rho$ and black contours correspond to the distribution by $M$. We focus here on two main features: (i) the 40 most dense cores appear to be mainly concentrated in the three vertices drawn by the filamentary distribution of the cores of the Pipe Nebula; (ii) the 40 most massive nuclei show a structure that is not so clumpy but is distributed in a more extended way, along the main filaments of the Pipe Nebula.

In other words, both $M$ and $\rho$ draw a hierarchical spatial distribution, where the densest and most massive absorption peaks are not distributed over the entire surface of the cloud but form singular concentrations, as seen in Fig. 5. The plots of both $\Lambda$ and $Q$ and the core surface-distribution map indicate that the highest degree of spatial substructure is driven by $\rho$ and, to a lesser extent, by $M$. The
former appears to be the main agent driving the primordial spatial segregation of the pre-stellar cores, at least in the Pipe Nebula.

Our results support the fact that clustering might have a primordial origin (as suggested by RAL0910), and that star cluster properties such as $M$ and $\rho$ segregation, and fractal patterns might also be the result of a primordial organization of the gas. Recent results in the Orion B Cloud (Parker 2018), also using the MST method, are compatible with this theory. We have to take into account the fact that the observable substructure in young star clusters is much more complex (Schmeja, Kumar & Ferreira 2008; Sánchez & Alfaro 2009), and processes such as hierarchical merging, collaborative accretion (Elmegreen, Hurst & Koenig 2014) and stellar feedback might play crucial roles in the observed structure of stellar clusters, even at early phases of evolution (Lada & Lada 2003). Given the evolutionary state of the Pipe Nebula, very early in the formation process of a stellar system, we can conclude that primordial $M$ and $\rho$ segregation have been present since the very initial collapse, but whereas $M$ shows a marginal segregation, $\rho$ is controlling and drawing the clumpy spatial pattern of the cores at this evolutionary time. Thus, further numerical and observational follow-ups should also be devoted to studying not only how the mass evolves, but also how the volume-density distribution evolves.

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