SF2A 2022
J. Richard, A. Siebert, E. Lagadec, N. Lagarde, O. Venot, J. Malzac, J.-B. Marquette, M. N'Diaye, D. Briot (eds)

A GRAPH THEORY-BASED MULTI-SCALE ANALYSIS APPLIED TO NGC 2264

B. Thomasson[1], I. Joncour[1] and E. Moraux[1]

Abstract. This paper summarises a work that was recently accepted*. Combining archival data of the Herschel Gould Belt survey with Spitzer data, we probe the span over the 5-36 kAU range, from molecular cloud down to YSOs scales. We highlight the presence of two types of multi-scale structures that we associate with the imprints of two different modes of fragmentation, either monolithic or hierarchical. Despite the fact that the latter represent a marginal proportion, we show that half of the YSOs are formed within them. They also happen to be located at the highest column density ($N_{H_2} = 6 \times 10^{22}$ cm^{-2}) regions within the cloud. By comparing the hierarchical structures properties with a fractal model of fragmentation we developed, we show that the hierarchical cascade does not exist at all scales, but instead there seems to be a specific scale at which this cascade starts. This work shows that young stellar systems are indeed deeply rooted in their close gaseous environment suggesting that part of the star multiplicity may be due to the fragmentation of their gaseous surrounding.

Keywords: open clusters and associations: individual: NGC 2264 - ISM: clouds, Methods: data analysis, Stars: formation

1 Observational context

Spatial properties of young small star-systems suggest that they may originate from a fragmentation's hierarchical cascade Joncour et al. (2018) of the cloud notably over the 1-12 kAU range. However, the observational framework of this cascade remains incomplete in terms of fragments multiplicity. Multi-scale analysis Pokhrel et al. (2018) or tree statistics Houlahan & Scalo (1992) can help to better understand the connection between stellar and gas components. This work* aims at presenting a novel tool based on a graph representation to assess spatial and multiplicity properties within the 5-30 kAU range scale in NGC 2264 molecular cloud.

2 A graph-theoretic based method

From the Herschel data Motte et al. (2010) consisting of five maps of five different resolution, we extracted clumps within five different spatial scales using the getsf algorithm Men'shchikov (2021). By adding the class 0/I YSOs from the Spitzer data Rapson et al. (2014) we connected the objects, represented by a node, that are contained in each other. After this connection we obtain a network from which we separate the disconnected components that represent spatially decorrelated multi-scale structures. The latter are defined in three classes (see left Fig.1): the hierarchical ones which are subdivided into several pieces, the linear ones into one piece and the isolated ones which are singleton. We also define by 'sink' a node that have no counterpart at lower scale but at least one counterpart at higher scale (see example in left Fig.1).

3 Statistics about cloud sub-structures

It has been found that hierarchical and linear classes dominate the structures modes since they contain more than 80% of the total objects of the cloud. Hierarchical structures are highly YSOs-productive with ∼2 YSOs/hierarchical on average *vs* ∼0.2 YSOs/linear. The ratio (#YSOs : #sinks) contained in a class of structure indicates that linears (8 : 45 ratio) are mainly composed of gaseous sinks whereas hierarchies (45 :

[1] Université de Grenoble-Alpes, France
*https://arxiv.org/abs/2206.01154

94 ratio) show a more dominant presence of YSOs. Investigating at the area covered by each class per bin of column density, we can see that the spatial distribution of classes depend on the local column density $N_{\mathrm{H_2}}$. When $N_{\mathrm{H_2}} > 3.10^{22}$ and 6.10^{22} cm^{-2}, hierarchical structures represent respectively 40% and 100% the cloud's area. A peak of linear structures presence at $N_{\mathrm{H_2}} \approx 6.10^{21}$ cm^{-2} could indicate that local physical conditions govern the successive emergence of linear and hierarchical modes within the cloud.

4 Further focus on the hierarchical structures

We focus on the hierarchical structures, in particular the multiplicity of fragments per number of sources, scale after scale. The number of fragments as a function of scale is represented in right Fig.1. We observe two distinct regimes: a range of scales for which the structure is linear (13 - 26 kAU) and a range of scales for which we observe multiplicity (1.4 - 13 kAU). This curve is compared with a fractal, scale-free model. The data do not reproduce scale-free behaviour over the whole range of scales considered. To test the reliability of this plateau at large scales, we tested geometry effects, convolution effects towards higher resolutions, and the persistence of clumps at long wavelengths. It turns out that none of these effects can explain the plateau from 13 kAU.

5 Conclusion

In this work we highlighted the presence of a hierarchical cascade in NGC 2264. This cascade produces the majority of young stars as stellar groups despite not being fractal since it starts at a 13 kAU spatial scale. Hierarchical mode is exclusive for $N_{\mathrm{H_2}} > 6.10^{22}$ cm^{-2} regions. As linearity and hierarchy depends both on scale and column densities, more work needs to be done to compare star clusters with these multi-scale structures that compose the larger environment.

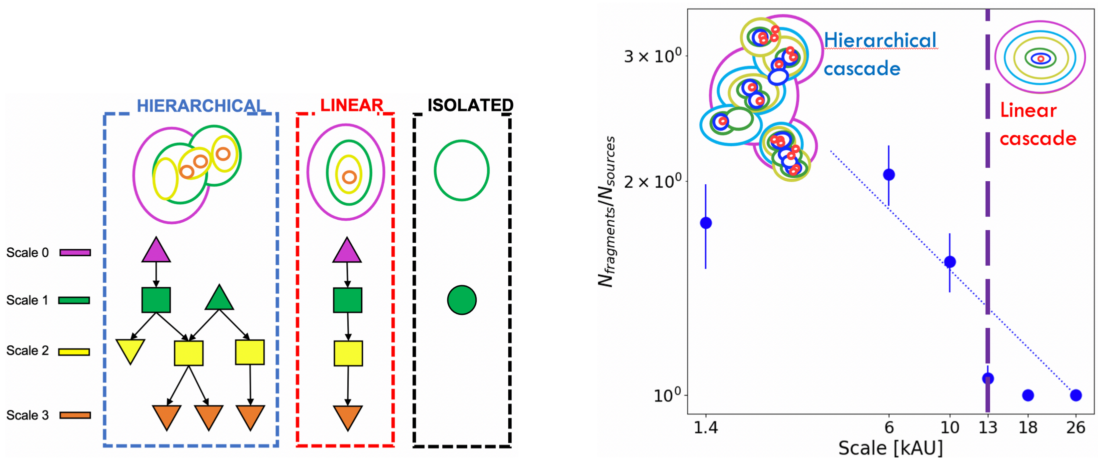

Fig. 1. Left: We label three classes of structures: hierarchical, linear and isolated; as well as four classes of nodes: source, intermediate, sink, isolated represented as an upward triangle, square, downward triangle and circle respectively. **Right:** Average number of fragments inside each structure as a function of the scale. Blue dotted line represents the expectation of a scale-free model. Purple long-dotted line splits the scales between the linear regime and the hierarchical regime.

References

Houlahan, P. & Scalo, J. 1992, The Astrophysical Journal, 393, 172

Joncour, I., Duchne, G., Moraux, E., & Motte, F. 2018, Astronomy and Astrophysics, 620, A27

Men'shchikov, A. 2021, A&A, 649, A89

Motte, F., Zavagno, A., Bontemps, S., et al. 2010, Astronomy and Astrophysics, 518, L77

Pokhrel, R., Myers, P. C., Dunham, M. M., et al. 2018, The Astrophysical Journal, 853, 5

Rapson, V. A., Pipher, J. L., Gutermuth, R. A., et al. 2014, The Astrophysical Journal, 794, 124