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Exposing Star Formation through the spatial structure of young stellar objects

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Abstract

We construct a catalog of the smallest significant young stellar substructures, that we call NESTs, by systematically applying a robust clustering method to a sample of 39 star-forming regions (SFRs). These small and compact clumps of young stellar objects (YSOs) reveal the densest discrete modes of star formation in each SFR. A comparison of these stellar substructures with the distribution of massive stars and molecular gas allows us to discriminate major distinct SFR types.

1 Introduction

The current paradigm of star formation (henceforth SF) is that it occurs within the filaments of large molecular clouds undergoing an exceedingly complex collapse process. It is essential, thus, to be able to evaluate the influence of the environment on stellar formation, which in turn is also expected to modify its surroundings.

Recently, large surveys provide the scientific community with unprecedented quality and volume of homogeneous data. This calls for robust statistical techniques to describe and analyse these data in the most accurate, robust and objective way possible to exploit their full potential.

In this work we describe the construction of a homogenous and consistent catalog of significant, small scale spatial substructures of YSOs and show its potential as an analysis tool to describe and understand the variety and complexity of SF.

2 Method

In this section we describe the construction of the catalog of small scale substructures, significant above random expectation.

2.1 Homogeneous sample of regions

A catalog of substructures across star-forming regions needs to start with a homogeneous and consistent sample of SFRs. We use the catalogs provided by the MYStIX (Feigelson *et al.*, 2013) and SFiNCs (Getman *et al.*, 2017) projects, that were designed to obtain the YSO population of regions within 4 kpc from us. Both programs provide the members of the regions from a combination of excess IR sources (using data from *Spitzer* IRAC, 2MASS, and UKIDSS Fazio *et al.*, 2004; Skrutskie *et al.*, 2006; Lawrence *et al.*, 2007), *Chandra* X ray candidates (Weisskopf *et al.*, 2000), and a sample of known OB stars from the literature. MYStIX specifically targets massive regions, and SFiNCs focuses on smaller, closer regions, so there are some differences between programs but we highlight that SFiNCS was specifically designed to complement the MYStIX sample.

Kuhn *et al.* (2014) and Getman *et al.* (2018) provided the substructures retrieved by an isothermal mixture model. Our catalog offers a globally compatible but complementary perspective that enriches our description of the regions. A detailed comparison is out of the scope of this work, but will be given in González *et al.* (in prep).

2.2 Robust and consistent method of substructure retrieval: S2D2

We use the tool S2D2 (Significant, Small DBSCAN Detection) which was presented in González *et al.* (2021), and is available for the community in several implementations [1]. S2D2 is a clustering tool that chooses the parameters for the DBSCAN algorithm (Ester *et al.*, 1996) using nearest neighbour statistics and the one point correlation function (Joncour *et al.*, 2017, 2018) to search for the small scale substructures while guaranteeing statistical significance above random expectation.

Joncour *et al.* (2018) showed that these small and significant structures (called NESTs, for Nested Elementary STructure) could trace the preferential sites of star formation (SF) in pristine regions like Taurus. González *et al.* (2021) presented the final implementation of the method, S2D2, and calibrated it in synthetic clusters of substructured, homogeneous and concentrated spatial distributions. The results were proven to be consistent and robust in a variety of situations, that could describe stellar clusters of different dynamical states and ages.

2.3 Spatial distribution of NESTs: Modes of significant star formation

The NESTs retrieved in SFRs of different characteristics display themselves different spatial distributions. Specifically, González *et al.* (2021) showed that for concentrated distributions (that could represent for example a dynamically evolved open cluster) S2D2 typically retrieved a larger, well populated NEST surrounded by a halo of smaller ones.

We use simulations to characterize the spatial distribution

[1] `https://starformmapper.org/algorithms/`

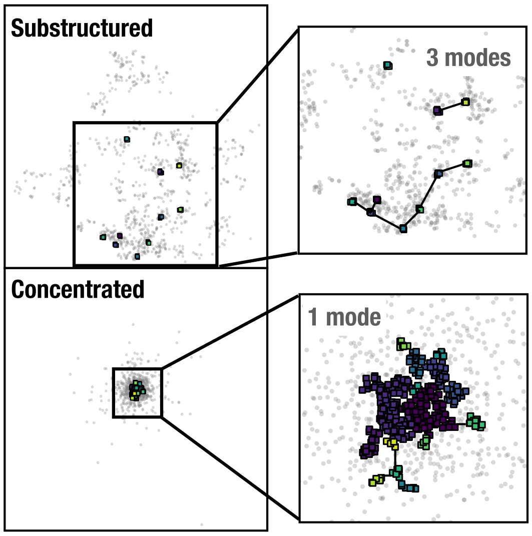

Figure 1: Example of the NESTs and modes retrieved in a substructured (top) and concentrated (bottom) synthetic region. Grey dots represent the stars in the regions, coloured squares the stars belonging to NESTs, and the lines in the right, zoomed plots show the edges of the NEST tree shorter than the threshold used to separate the modes, as described in the text.

of NESTs using the minimum spanning tree (MST) of the NESTs (using the minimum distance between elements of each NEST as inter-NEST distance) and separate the different discrete modes of SF in each region by pruning the branches larger than 25% the size of the region, as measured by the equivalent radius of the convex hull of the region. This 25% ratio was calibrated in the simulations from González *et al.* (2021) to ensure that the synthetic concentrated regions have one significant mode of SF while substructured ones are multimodal, as it should be by construction (González *et al.*, in prep). An example of the modes obtained in a substructured and a concentrated synthetic region is shown in Figure 1.

3 Results and discussion

We found 255 NESTs organized in 68 modes in 37 regions out of the 39 regions comprising the whole sample. More than half of these regions, 20, are unimodal, while the remaining 17 show complex substructure at large scale with at least two modes of significant star formation.

3.1 Relationship of SF modes and the distribution of molecular gas and massive stars

We now compare the significant substructures from our catalog with the spatial distribution of molecular gas and massive stars. We consider that a mode of SF is embedded in the natal cloud if its convex hull overlaps with the 99.5% contour of most intense emission in the 500 μm *Herschel* map (Pilbratt, 2010). Thus this analysis is limited to the 33 regions whose maps were available in the archive [2]. The potential influence of massive stars is assessed for each mode by checking whether the MYStIX and SFiNCs programs had catalogued OB stars in the area. We classify the SF modes in four different types according to these criteria, as is shown in Table 1.

Table 1: Types of SF modes, classified as described in the text.

Type	Embedded	Massive	Number of modes
T1	YES	NO	21
T2	YES	YES	11
T3	NO	NO	10
T4	NO	YES	15
Total			57

Specific examples of each of the modes in Table 1 are shown in Fig. 2. T1 modes (embedded, without OB stars) seem to trace areas of active SF of low mas stars and are the majority type in unimodal regions. In T4 modes (not embedded, with OB stars) we expect the massive stars to have contributed to the expulsion of gas, potentially hindering SF locally. Despite the presence of massive stars in T2 modes (embedded, with OB stars) there is still very dense gas in their surroundings, indicating that SF is still active. In a significant fraction of T3 modes (not embeded, without OB stars) there is a visual overlap with a filament or gas structure, although the required intensity limits have not been reached to be classified as embedded and SF may be be over or less efficient. The specific interplay between YSOs, gas and massive stars in T2 and T3 modes is not completely clear and needs to be individually assessed.

4 Summary and conclusions

Through our catalog of NESTs, significant small scale structures within the spatial distribution of YSOs we are able to trace the significant, discrete modes of SF in an objective, homogeneous and robust way. This allows us to analyse the relationship of the modes of SF with other variables in their environment.

We classify the modes of SF according to their relationship with the molecular gas and massive star spatial distributions, finding categories that help understand the complexity and variety that SF can display even within a single region. A deeper understanding of the complexities of SF requires also to study the relationship of the SF modes with other variables, like the evolutionary status of YSOs (González *et al.*, in prep) or their kinematics.

Acknowledgments

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[2] The Herschel Science Archive (HSA) is hosted on ESA's servers at the European Space Astronomy Centre (ESAC) near Madrid, Spain. The HSA, along with the archives of ESA's other science missions, is developed and maintained by the ESAC Science Data Centre.

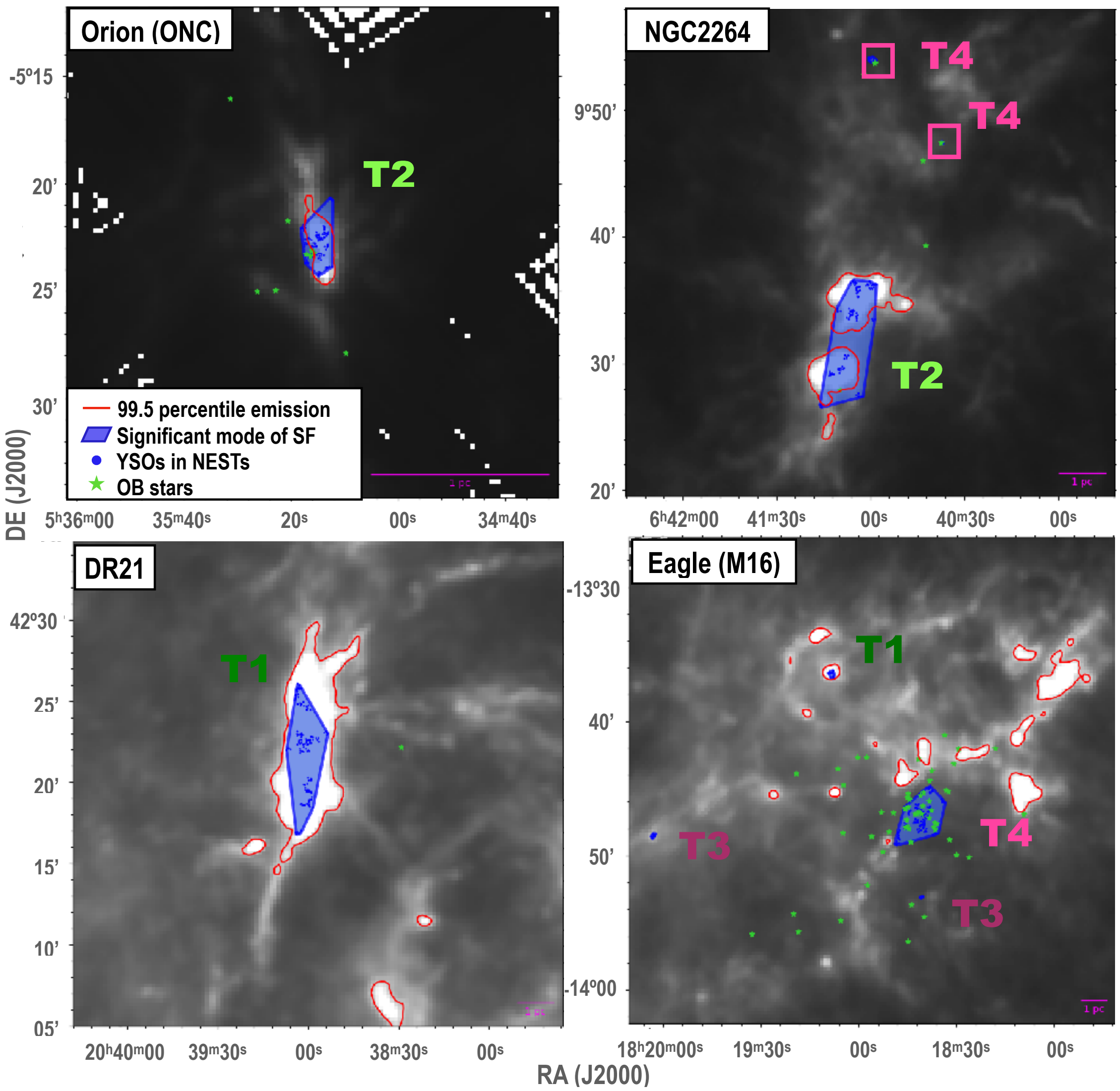

Figure 2: Maps of regions showing the types of modes of SF, tagged accordingly. Herschel 500 μm emission is in grayscale, with the 99.5 percentile contour shown in red. Green stars are OB stars, blue dots represent stars in NESTs, and the convex hull of each mode of SF is displayed in blue.

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