Modes of clustered star formation

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ABSTRACT

Context. The recent realization that most stars form in clusters, immediately raises the question of whether star and planet formation are influenced by the cluster environment. The stellar density in the most prevalent clusters is the key factor here. Whether dominant modes of clustered star formation exist is a fundamental question. Using near-neighbour searches in young clusters Bressert et al. (2010) claim this not to be the case. They conclude that - at least in the solar neighbourhood - star formation is continuous from isolated to densely clustered and that the environment plays a minor role in star and planet formation.

Aims. We investigate under which conditions near-neighbour searches in young clusters can distinguish between different modes of clustered star formation.

Methods. Model star clusters with different memberships and density distributions are set up and near-neighbour searches are performed. We investigate the influence of the combination of different cluster modes, observational biases, and types of diagnostic on the results.

Results. We find that the specific cluster density profile, the relative sample sizes, limitations in observations and the choice of diagnostic method decides whether modelled modes of clustered star formation are detected by near-neighbour searches. For density distributions that are centrally concentrated but span a wide density range (for example, King profiles) separate cluster modes are only detectable under ideal conditions (sample selection, completeness) if the mean density of the individual clusters differs by at least a factor of ~65. Introducing a central cut-off can lead to underestimating the mean density by more than a factor of ten especially in high density regions. Similarly, the environmental effect on star and planet formation is underestimated for half of the population in dense systems.

Conclusions. Local surface density distributions are a very useful tool for single cluster analysis, but only for high-resolution data. However, a simultaneous analysis of a sample of cluster environments involves effects of superposition that suppress characteristic features very efficiently and thus promotes erroneous conclusions. While multiple peaks in the distribution of the local surface density in star forming regions imply the existence of different modes of star formation, the reverse conclusion is not possible. Equally, a smooth distribution is not a proof of continuous star formation, because such a shape can easily hide modes of clustered star formation.

Key words. Galaxy: open clusters and association, stars: formation, planets: formation

1. Introduction

Most stars form in proximity to other stars within embedded clusters rather than being uniformly distributed throughout molecular clouds (Testi et al. 1999, Carpenter 2000, Lada & Lada 2003, Porras et al. 2003, Allen et al. 2007). The density in young clusters in the Milky Way varies over many orders of magnitude from < 1 stars/pc² in relatively sparse clusters to >10³ stars/pc² in the central areas of dense clusters. The key factor in determining the relative importance of the environment for star and planet formation is the stellar density in the young clusters. Stars forming in the sparse cluster environments are largely unaffected by the presence of their fellow cluster members. By contrast, one can expect a strong influence on star and planet formation by the environment in the densest of these young clusters. Theoretical investigations predict that this environmental influence on star formation might manifest itself in a different initial mass function (Freitag et al. 2006, Pfalzner 2005, 2006, Olczak et al. 2006, 2010). Observations have found indications of a dependence of these properties on the stellar density in young clusters (Hillenbrand & Hartmann 1998, Harayama et al. 2008, Stolte et al. 2010). In dense clusters interactions might lead to a lower disc frequency resulting in a lower planetary system rate and different properties in the planetary system.

For the stellar population as a whole the question is whether the properties of prestellar cores largely determine the stellar properties as in isolated star formation (Shu et al. 2004, Larson 2005, Tan et al. 2006) or whether most stars form in a more dynamic way, where external forces and interactions dominate over initial conditions (e.g. Bonnell et al. 2001, Bonnell & Bate 2006).

So a fundamental question of current star formation research is whether there exists a type of cluster (stellar emembership, density) that is the dominant environment for star formation? At first sight it would seem easy enough to answer this by simply collecting cluster data and determine the distribution of the mean density in young clusters. However, this is hindered by a
number of obstacles. Most star formation occurs inside the spiral arms and close to the center of the Milky Way where it is difficult to identify clusters due to our position within the plane of the Galactic disc. This means we have nothing like a complete census of the young clusters in the Milky Way. In principle, looking at nearby galaxies should help, but the larger distance means that the detection of low-mass clusters is hindered by their low luminosity.

There are different strategies for tackling the issue indirectly. One way is to look at the initial mass function (e.g. Bonnell et al. 2007; McKee & Tan 2008; Bate 2009; Da Rio et al. 2012) or the binary development (e.g. Durisen & Sterzik 1994; Brandner & Koehler 1998; Duchêne 1999; Connelley et al. 2008; Fregeau et al. 2009; Kaczmarek et al. 2011; Marks et al. 2011) in different types of young clusters and compare them to the field properties. Similarities are then interpreted as signs for a dominant cluster model. However, since many cluster modes contribute simultaneously, a one-to-one relation is difficult to establish.

Another method is to measure the local surface density distribution in different cluster environments. Recently several observational studies (e.g. Gutermuth et al. 2005; Bressert et al. 2010; Kirk & Myers 2012) tried to answer above questions by analyzing large samples of young stellar objects concerning their local surface density, \( \Sigma \), predominantly in the solar neighborhood. Here it is argued that if different discrete modes existed they should manifest themselves as peaks in a surface density distribution (e.g. Strom et al. 1993; Carney et al. 2000; Weidner et al. 2004; Wang et al. 2009; Bressert et al. 2010).

This simple approach has the advantage that it does not rely on the definition of stellar groups, but uses the local separation from the star to its nearest neighbours. The local surface density is simply defined as \( \Sigma = (n - 1)/\pi r_n^2 \) where \( n \) is the considered number of nearest neighbours including the star itself and \( r_n \) is the distance to the \( n \)-th neighbour. Higher values of \( n \) give a lower spatial resolution, but smaller fractional uncertainty (Casertano & Hut 1985; Gutermuth et al. 2009).

Using this method (Bressert et al. 2010) found no peaks in the combined surface density distribution of several clusters in the solar neighborhood (see their Fig. 1). They concluded from the absence of such peaks that star formation is continuous from isolated to densely clustered. In addition, they deduce a mean stellar surface density of 20 stars/pc\(^2\) for the star forming regions in the solar neighbourhood and concluded that the environment plays a minor role in star and planet formation because only a small fraction of stars is found in high-density regions.

In the present study we will discuss the effect of different cluster density profiles, the dependency on the sample selection and the influence of observational constraints on the obtained results. We will demonstrate that local surface density measurements are rather limited in their ability to determine different star formation modes due to superposition effects. Therefore the question whether dominant modes of clustered star formation exist in the solar neighborhood is still open.

2. Method

2.1. Cluster types

The determination of the general shape of the stellar density distribution of young clusters can be observationally challenging. Due to the presence of a significant amount of dust in young embedded clusters, not all stars are yet visible and even in young exposed clusters crowding in the central high density regions poses problems even with high resolution instruments like the HST (e.g. McCallahean & Stauffer 1994).

A century ago Plummer (1911) found that

\[
p(r) = \frac{3M}{4\pi r^4} \left(1 + \frac{r^2}{a^2}\right)^{-5/2},
\]

(1)

provides a good fit to the density distribution of globular clusters. Here \( M \) is the total cluster mass and \( a \) is the Plummer radius, a scale parameter for the cluster core size \( r_c \). This model is widely used for all types of star clusters, largely thanks to its success in fitting globular cluster profiles, but also because of its convenient analytical form.

King (1966) found an improved empirical law, leading to the so-called family of King models. These consist of an energy distribution function of the form

\[
f_k(E) = \left\{ \begin{array}{ll}
\rho_0 (2\pi\sigma_k^2)^{-3/2} e^{-\phi_0/(2\sigma_k^2)} - 1 & : \ E > 0 \\
0 & : \ E \leq 0
\end{array} \right.
\]

(2)

with \( \phi_0 = \Psi - \Phi \) and \( \Psi = -\Phi_0 \) being the relative energy and relative potential of a particle, respectively. Here \( f_k(E) > 0 \) for \( \phi_0 > 0 \) and \( \sigma_k \) is the King velocity dispersion. The stellar density distribution can only be obtained by numerical integration. The King parameter \( \rho_0 = \sqrt{\Psi/\sigma_k^2} \) characterizes the sequence of King profiles with decreasing relative size of the cluster core \( r_c/r_{hm} \) for increasing \( W_0 \), where \( r_{hm} \) is the half-mass radius.

In the following we investigate two types of model clusters - those based on Plummer and King distributions. While the Plummer distribution is well approximated by a King model with \( W_0 \approx 4 \), young clusters are best represented by King models with \( W_0 \geq 7 \) (e.g. Hillenbrand & Hartmann 1998; Sung & Bessel 2004; Harfst et al. 2010). Thus the term “King model” is used here as equivalent to King distributions with high \( W_0 \).

2.2. Diagnostics

In order to determine the conditions for which local surface density allows to distinguish different spatial modes of star formation, we construct a representative set of numerical cluster models that spans the expected parameter space. We generated model clusters with Plummer and King stellar density profiles containing 100, 1000 and 10000 stars. Each cluster has a half-mass radius of \( r_{hm} = 1 \) pc. So configurations with different numbers of stars imply different volume and surface densities. In our model clusters the mean surface densities are 12.6, 126 and 1260 stars/pc\(^2\), respectively. The distributions have been set up as single stars only, so without primordial binary population.

To ensure equally statistically significant results each cluster population was generated repeatedly with different random seeds for a total of 10\(^5\) stars for each of the considered cases.

We used a tree-based algorithm to reduce the computational effort for the near neighbour search (Kennel 2004).

As already pointed out by Casertano & Hut (1985) an intermediate number of neighbours has the advantage of neither missing small dense structures nor introducing artificial overdensities produced by strongly bound multiple systems. We tested the influence of the number of nearest neighbours (3-27) on the resulting surface density diagnosed for our King models. For the clusters with 1000 and 10 000 stars no obvious difference was visible in the results averaged over the set of simulations. Only the results for the cluster consisting of 100 stars depends slightly on the number of neighbours considered. However, even these differences are within the error bars. So we included the contribution of 8 nearest neighbours throughout our investigation.
In some respect our model clusters represent the ideal of what one would like to observe. However, in observations of even the closest star forming regions it is nearly impossible to detect each and every star of the cluster. One reason is that due to limitations in the spatial resolution of telescopes, crowding becomes a severe problem in the central regions of dense clusters. For example, the Spitzer Space Telescope as used in the study of Bressert et al. (2010) can only marginally resolve the inner 0.3 pc of the Orion Nebula Cluster. To avoid observational biases due to crowding they excluded this inner cluster area from their analysis. This means that so-obtained values of the average stellar density only regarded as lower limits. For high-resolution telescopes like the HST this is less of a problem.

Another limitation is the maximum contrast an instrument can image. This means that low-mass stars are less likely to be detected close to massive stars and therefore the surface density around massive stars, which are mostly located in the central dense area is underestimated.

Finally, magnitude limits of a given survey impose a limit on the faintest observable isolated object. With decreasing mass the number of stars in a star cluster grows rapidly, so the estimated density is a strong function of the magnitude limit. Usually, field contamination imposes another serious observational bias. However, the young members of star forming regions can usually be rather well separated from the much older population of field stars.

The observational limitations outlined above basically affect studies of any star-forming region. The effect of all these limitations is to lower estimates of the cluster density. This is particularly true for the maximum local density that is typically highest where crowding and massive stars impose the most severe observational biases.

**3. Single clusters**

**3.1. Cluster density profile**

First we compare single model clusters with a Plummer profile to those with a King ($W_0 = 12$) profile. Note that all models have normalized half-mass radii ($r_{hm} = 1$ pc). Plummer models are commonly used as initial models for numerical simulations of young star clusters. However, observations of very young star clusters ($< 3$ Myr) typically show a more concentrated distribution close to that of an isothermal sphere. From a numerical point of view a King model with $W_0 = 12$ is a rather good representation of such an isothermal sphere. The basic difference between these two models is the stellar density in a King model with $W_0 = 12$ increases much more towards the cluster center than in a Plummer model.

This is clearly visible in Fig. 1(b) which shows the projected radial number profile of both models. Their maxima roughly correspond to the half-mass radius $r_{hm}$. Whereas the Plummer-model clusters (gray lines) contain only a small fraction of stars at small (projected) distances to the cluster centre, their fraction in King-model clusters (black lines) is considerably larger. In the local surface density plot (Fig. 1(b)) this translates into a sharply peaked asymmetric distribution for the Plummer model and a Gaussian-shaped distribution for the King model. Most stars in the Plummer-shaped cluster share the same local density that marks roughly the maximum local density of the entire cluster. In contrast, the King-shaped cluster has a long high-density tail that extends well beyond the maximum local density of the Plummer model. In the cumulative local surface density distribution (Fig. 1(c)) this difference is encoded in the steeper slope at the end of the distribution for Plummer-type clusters.

**3.2. Incompleteness**

As described in Sec. 2.3 observations of real star clusters always suffer from observational limitations and potentially influence the resulting surface density distribution. Here we mimic these observational limitations by applying “filters” to the data in our diagnostics. First we emulate the observational resolution of the Spitzer’s IRAC camera of 2.5″ for a cluster at the same distance as the ONC corresponding to a resolution of 1035 AU $\approx 0.005$ pc. In our diagnostics we scan all particles and mark those which lie in projection within 1000 AU from the current star as not being observable.

Fig 2(b) demonstrates the effects of this observational limitation for the King model cluster with $N = 10^3$ and $N = 10^4$ stars, where grey indicates the case without filter and black the filtered case. Observational limitations lead to the neglect of any stars with local surface densities exceeding roughly ten times the median density of stellar system. In the intermediate density regime a slight increase of the counted number of stars is seen, because in high density areas the local surface density is reduced around those stars remaining observable. Here and in the following the number of stars in the distributions have been normalized to the total number of stars in the sample.

So adopting the Spitzer-like resolution significantly reduces the number of stars at the high-density end. The average number of observed stars in the filtered case reduces for the cluster containing 100 stars to 99, that with 1000 stars to 864 and the one with 10 000 to about 6460. In addition, for the dense clusters the limited resolution renders the existing Gaussian-like shape

**Fig. 1.** Comparison of model clusters with 10 000 stars and a half-mass radius of 1 pc obeying a Plummer distribution (open circles) with those of a King ($W_0 = 12$). Here a) shows the number of stars as a function of the radial distance to the cluster center, whereas b) shows the number of stars of a given surface density and c) the same in cumulative normalized form.
Here we mimic this by excluding all stars closer than 0.5 pc to the cluster centre (Fig. 2). As a consequence, of the observational limitation the median observed density of the densest of our model cluster would be reduced to less than half its real value (see Table 1). The problem of crowding is often circumvented by excluding stars in central high stellar density regions from the sample. We start with two Plummer-type clusters, where one has a ten times higher median density than the other. Fig. 3b) shows the differential local surface density distribution and Fig. 3c) its cumulative form for the case where one cluster corresponds to the 100 and the other to the 1000 star models described in section 3. This illustrates a situation where 10 times as many stars formed in the denser environment than in the less dense one. It can be seen that one would not detect two peaks. Similarly the cumulative surface density distribution increases steadily and does not show any "bumps" although two different cluster modes were present.

In reality sample sizes from different clusters often differ considerably. In many cases only a few tens of data points are available for low-mass clusters but several hundreds to thousand for high-mass clusters like the ONC. Therefore, high-mass clusters might dominate the results. In order to test the limitations we start with a model consisting of two modes of clustered star formation - one compromising a denser and the other a less dense environment.

Combining two Plummer-type clusters, where one has a ten times higher median density than the other, Fig. 3b) shows the differential local surface density distribution and Fig. 3c) its cumulative form for the case where one cluster corresponds to the 100 and the other to the 1000 star models described in section 3. This illustrates a situation where 10 times as many stars formed in the denser environment than in the less dense one. It can be seen that one would not detect two peaks. Similarly the cumulative surface density distribution increases steadily and does not show any "bumps" although two different cluster modes were present.

This demonstrates, that the actual sample-size can mask an existing bi-modal clustered star formation process. We tested the maximum possible difference in sample size that allows the identification of existing cluster modes and find that generally the sample sizes must not differ by less than a factor of five for existing cluster modes to be identifiable.

In reality, one either considers a smooth distribution of young stars throughout a single cloud or one combines the results from multiple distinct clusters. It is obvious that above reservations apply in the first case. In the second case one could argue that there will be many more stars in high-mass clusters than in low-mass clusters, but many more low-mass clusters than high-mass clusters. So in principle one can construct equal-sized samples.

4.4. Two equal modes of clustered star formation

In this section we analyse the case of an idealized sample combining two identical sample sizes of two different cluster modes. So we treat the case where stars form with equal likelihood in one of two clustered modes.

We start with two Plummer-type clusters, where one has a hundred times higher median density than the other. Fig. 4a) shows the surface density on top and its cumulative form underneath for the case where one cluster corresponds to the 100 and...
the other to the 10,000 star models. Scaling is applied to avoid non-detection of cluster modes due to sample size effects.

The combined surface density shows a strong double peak and the cumulative distribution a saddle point. These features are still visible if the density in one cluster is only 10 times that of the other cluster (see Fig. 3b). These multiple peaks in the surface density distribution and the “bumpy” nature of the cumulative distribution is what is expected for multi-modal clustered star formation. Conversely, the absence of these features is often taken as proof of continuous star formation ranging from low to high density regions (see, for example, Bressert et al. 2010). It is argued that the peaks are so densely packed that the result is a continuous function. We will show that this argument is only valid under very specific conditions which are usually not fulfilled in young cluster environments.

As mentioned above Plummer profiles are widely used in theoretical investigations due to the existence of an analytical solution. However, they seem less suitable for modelling young clusters. King profiles with high $W_0$ are regarded as a better choice. So performing the same investigation as above but now for two of the King-type clusters deviating by a factor of 10 in density, we obtained results quite different from the Plummer case. Instead of two peaks a single one appears in the surface density distribution (Fig. 3b) which is no longer "M"-shaped but nearly Gaussian and wider than in case of a single King-shaped cluster.

As a result the cumulative surface distribution (Fig. 3b) looks very much like that of a single cluster with only a slightly different slope. So despite being the result of two distinct modes of clustered star formation with a factor of 10 difference in mean cluster density, this fact would neither be inferred from the differential nor the cumulative local surface density distribution in this case.

The reason that the two different modes of clustered star formation are detectable for Plummer-type but not for King-type clusters is the different shape of the surface distribution of each individual cluster at the high-density end. For King-type clusters the high-density tail of the lower-density cluster overlaps with the low-density end of the high-density cluster, creating a peak in the middle between the two mean cluster densities. As there is no high-density tail in Plummer-type clusters the steep drop leads to two clearly distinct peaks. Consequently, the threshold for identifying distinct peaks in superpositions of King-type cluster modes is much higher and requires a ratio of the median densities of ~65.

The result that the shape of the distribution is relevant for the detectability of different cluster modes, does not only hold for the cases of Plummer and King models, but applies to other distributions as well: distinct cluster modes are easily detectable for narrow distribution whereas concentrated but broader distributions can hide such modes. In the following we will continue to speak of King-type clusters, but the reader should keep in mind that this is valid for any type of broader distribution.

For concentrated King-type clusters the absence of peaks in the surface density distribution therefore neither allows the conclusion that there are not multiple modes of star formation present nor that star formation is continuous over all cluster densities. At the same time a smooth surface distribution does not allow one to draw the conclusion that no distinct scale for YSO clustering within nearby star-forming regions exists as, for example, recently stated by Bressert et al. (2010).

In view of the above findings local surface density distributions are limited in their informative value concerning existing modes of clustered star formation.

4.3. Observational biases

We just showed that for two King-type clusters, which differ in density by a factor 10, only a single peak appears in the surface density profile. How far do observational limitations affect above result? Fig. 5 shows the surface density distribution that results from two observationally limited King model clusters as shown in Fig. 2. It can be seen that observational limitations lead to a non-physical cut-off at the high-density end of the surface density distribution. Although the observational limitations lead to an under-representation of high-density areas, the two underlying cluster modes are still not detected. Different cluster modes are only revealed if the peak densities of the two modes differ by more than a factor ~ 65.

4.4. Multiple modes of clustered star formation

If there are more than two modes of clustered star formation, the surface density distribution as diagnostic of multiple modes becomes increasingly unreliable. Fig. 6 shows the combination of three model King-type clusters (non-detection limited cluster
Fig. 4. Differential and cumulative local surface density distribution for stars from two Plummer-shaped (a and b) and two King-shaped (c) model clusters. The approximate mean densities of each individual cluster is 10 stars pc$^{-3}$ and 1000 stars pc$^{-3}$ in a) and 100 stars pc$^{-3}$ and 1000 stars pc$^{-3}$ in b) and c). For each cluster mode 10 000 stars were considered.

A, B and C in Table 1) of different average density but with an equal number of stars in each mode. As in the case of two cluster modes, here again the underlying three cluster modes would not show up as separate peaks but one obtains a more or less Gaussian-shaped smooth distribution with a single (although this time broader) peak. In the cumulative surface plot this is represented by a smooth but somewhat flatter curve than the ones for the single clusters. This might possibly open up a way to detect the underlying cluster modes.

We want to emphasize that we do not advocate that all star formation happens in two, three or more modes but that surface density distributions are of limited use in inferring underlying modes of clustered star formation. Especially in the solar neighbourhood there are so far no indications for different modes of star formation. However, on Galactic scales that might, at least for massive clusters, be different [Hunted 1998; Maiz-Apellániz 2001; Pfalzner 2009].

5. Influence on star and planetary system formation

Observations often apply the technique of surface density plots to find out to what degree the cluster environment influences planet and star formation. These studies presume a density limit above which they assume that the interactions between the stars become important. Determining the relative proportion of stars that reside in areas with stellar densities above and below that limit, this is then used as argument for or against the importance of the environment for star and planet formation.

Often the value of $10^4$ stars pc$^{-3}$ (see Gutermuth et al. 2005) is quoted as threshold for the cluster environment playing a role or not. Gutermuth et al. (2005) translated this into a local surface density exceeding 200 star pc$^{-2}$ (see Bressert et al. 2010). These values are just rough estimates and it should be kept in mind that this value of the local surface density limit at which environmental effects play a role depends strongly on the actual aspect of star and planet formation one considers. Stellar mergers, disc destruction or modifications of the disc structure will correspond to very different local surface density limit.

For the moment we take the estimated local surface density threshold – 200 stars pc$^{-2}$ – at face value to investigate how the cluster profile, sample and incompleteness effects influence the estimate of the relative importance of the cluster environment on star and planet formation. Returning to Fig. ?? For the three cluster modes of different densities Table 1 provides – in dependence of observational limitations – the number of observed stars, the resulting change in average and median surface density, and the number of stars detectable above the local surface density threshold of 200 stars pc$^{-2}$.

The values in our model clusters are scaled in such a way that all three clusters contain 10 000 stars but their densities differ by a factor 10 and 100, respectively. In the least dense cluster no stars are located in regions above the local surface density threshold, whereas 80% of stars in the densest cluster encounter...
higher local densities and are thus potentially affected by the cluster environment.

For a Spitzer resolution-limited sample obviously the densest cluster has the largest number of undetected stars in high-density regions. However, in relative terms it is the same in intermediate- and high-density clusters - in both cases observational limitations result in missing ~45% of the stars potentially affected by the environment.

Excluding the central area of the cluster from the study (see Bressert et al. 2010) again lowers the number of detected stars in high-density regions. If such a cut-off is applied in our high-density and even intermediate density clusters the mean and average surface density are underestimated. However, whereas in high-density clusters resolution limitations already eliminate most of the stars affected by the high stellar density, in intermediate density clusters stars that would normally be resolved are heavily affected by excluding the central area. Bressert et al. state that excluding the central areas would at most effect the number of detected stars by a factor of 2. For our model cluster B the cut-off procedure and the Spitzer limitations would reduce the number of stars above the threshold to less than a tenth of its real value.

6. Summary and Conclusions

We investigated under which circumstances categorical distributions of local surface densities of young stellar objects – here

| Property                  | Cluster A | Cluster B | Cluster C |
|---------------------------|-----------|-----------|-----------|
| No. stars                 | 10 000    | 10 000    | 10 000    |
| median density            | 12.6      | 126       | 1260      |
| average density           | 21.2      | 530       | 11000     |
| above threshold           | 0         | 3300      | 8000      |
| Spitzer resolution sample |           |           |           |
| No. stars                 | 9923      | 8638      | 6458      |
| median density            | 12.6      | 79.4      | 501       |
| average density           | 21.2      | 151       | 668       |
| above threshold           | 0         | 1813      | 4327      |
| Radial cut-off and Spitzer resolution sample |           |           |           |
| No. stars                 | 8476      | 7246      | 5990      |
| median density            | 7.9       | 50.1      | 501       |
| average density           | 11.7      | 77.1      | 518       |
| above threshold           | 0         | 290       | 3893      |

Table 1. Properties of the King-type cluster models used in Section 4. The “above the threshold”-lines denote the “detectable” number of stars in an environment where the stellar density exceeds 200 stars pc$^{-2}$. The densities are median and average surface densities and are given in units of pc$^{-2}$. 
shortly referred to as surface density plots – are suitable tools for investigating modes of clustered star formation and the dynamical influence of the star cluster environment on star and planet formation. Using different types of model star clusters we demonstrate how sensitive the results depend on the actual cluster density profile. Whereas for narrow (for example Plummer-shaped) density distributions discrete cluster modes are easily identified as multiple peaks in the surface density plot; this is often not the case for distributions that span over a wider density range - for, example, concentrated King-type density distributions. Our findings imply that surface density plots of star-forming regions will not show multiple peaks unless the median density of the individual cluster modes differs by more than a factor of ~65.

The relative population size plays as well a role. Only if they do not differ by more than a factor of 5 the detection of discrete modes in the surface density plot is possible. Even, if one constructs equal sized samples, there might arise difficulties. If one combines different low-mass clusters to a single sample, it is very difficult to guarantee that they are in the same evolutionary stage. The cluster age is at least for embedded clusters not a reliable indicator for their dynamical stage. The reason is that if star formation is ongoing and accelerated then averaging will not lead to approximately the same mean cluster age of ~1-2Myr. So a cluster just starting to form stars and one that has nearly finished the star formation process will both be attributed the same age. However, during that phase the cluster size, profile and surface density evolves considerably. Including such different clusters in the same sample would lead to erroneous results. This means that the right sample choice is vital to determine whether a dominant mode of clustered star formation exists.

This means that although one can conclude from multiple peaks in the surface density plot on the existence of discrete modes of clustered star formation, the reverse is not possible. We point out that unlike assumed in recent publications (e.g. Bressert et al. 2013) a smooth surface density plot does not rule out the existence of dominant modes of clustered star formation. We thus caution against the use of surface density plots to determine whether dominant modes of clustered star formation exist.

However, surface density plots are potentially very useful in determining the dynamical influence of the cluster environment on star and planet formation. Yet a robust estimate requires high-resolution observations of rich star clusters to map the entire stellar population. Here we demonstrated that excluding regions of high local surface density in rich star clusters (like in Bressert et al. 2010) leads to underestimating the average local surface density not as estimated in their study by at most a factor of two but by up to more than an order of magnitude. Observations with instruments other than Spitzer (such as HST) are important for determining high surface density regions in such clusters.

Another limitation that biases our understanding of star formation modes arises from restrictions of observational samples to the solar neighbourhood. Although there are good reasons for this approach such as sample completeness, one has to be aware that these results cannot be generalized to the Galaxy as for example, starburst clusters with their mostly much higher local surface densities are excluded.

Similarly, the age of the clusters included in the sample is an important factor. Dynamical interactions and stellar evolution in star clusters induce cluster expansion and hence act to lower their median local surface density with time. This effect becomes even more pronounced if gas expulsion is taken into account (see e.g. the review of Vesperini 2010). Hence using a sample with a spread of cluster ages leads to an underestimate of the median local surface density of a given mode. This is of particular relevance for low-mass clusters that are expected to dissolve faster due to their short relaxation time.

In summary, a consistent analysis of the modes of clustered star formation requires a sample of isochronal clusters unlimited in mass and the development of a tool suitable to reveal potential discrete modes.

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