# THE SPATIAL DISTRIBUTION OF STARS IN OPEN CLUSTERS

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## ABSTRACT

We study the internal spatial structure of 16 open clusters in the Milky Way spanning a wide range of ages. For this, we use the minimum spanning tree method (the Q parameter, which enables one to classify the star distribution as either radially or fractally clustered), King profile fitting, and the correlation dimension (Dc) for those clusters with fractal patterns. On average, clusters with fractal-like structure are younger than those exhibiting radial star density profiles. There is a significant correlation between Q and the cluster age measured in crossing time units. For fractal clusters there is a significant correlation between the fractal dimension and age. These results support the idea that stars in new-born clusters likely follow the fractal patterns of their parent molecular clouds, and eventually evolve toward more centrally concentrated structures. However, there can exist stellar clusters as old as 100 Myr that have not totally destroyed their fractal structure. Finally, we have found the intriguing result that the lowest fractal dimensions obtained for the open clusters seem to be considerably smaller than the average value measured in galactic molecular cloud complexes.

## MOTIVATION

The hierarchical structure observed in some open clusters is presumably a consequence of its formation in a medium with an underlying fractal structure. This fractality is considered to be a clear signature of its own turbulent nature. Otherwise, open clusters having central star concentrations with radial star density profiles likely reflect the dominant role of gravity, either on the primordial gas structure or as a result of a rapid evolution from a more structured state. Therefore, the analysis of the distribution of stars may yield information on the formation process and early evolution of open clusters. It is necessary, however, that this kind of analysis is done by measuring the cluster structure in an objective, quantitative, as well as systematic way.

## PROCEDURE

(1) We first used VizieR (Ochsenbein et al. 2000) to search for catalogs containing both positions and proper motions of stars in open cluster regions.

(2) We applied a robust non-parametric method to assign cluster memberships (Cabrera-Caño & Alfaro 1990). This method makes no a priori assumptions about cluster and field star distributions.

(3) We fitted King (1962) profiles to the radial density distribution of cluster members. From these fits we obtained the core radius (Rc) and tidal radius (Rt).

(4) We used the Minimum Spanning Tree technique (see Figure 1) to calculate the dimensionless parameter Q (Cartwright & Whitworth 2004; Schmeja & Klessen 2006). The value Q=0.8 separates radial clustering (Q>0.8) from fractal type clustering (Q<0.8).

(5) We calculated the correlation dimension (Dc) and its associated uncertainty by using an algorithm which gives reliable results (Sanchez et al. 2007; Sanchez & Alfaro 2008).

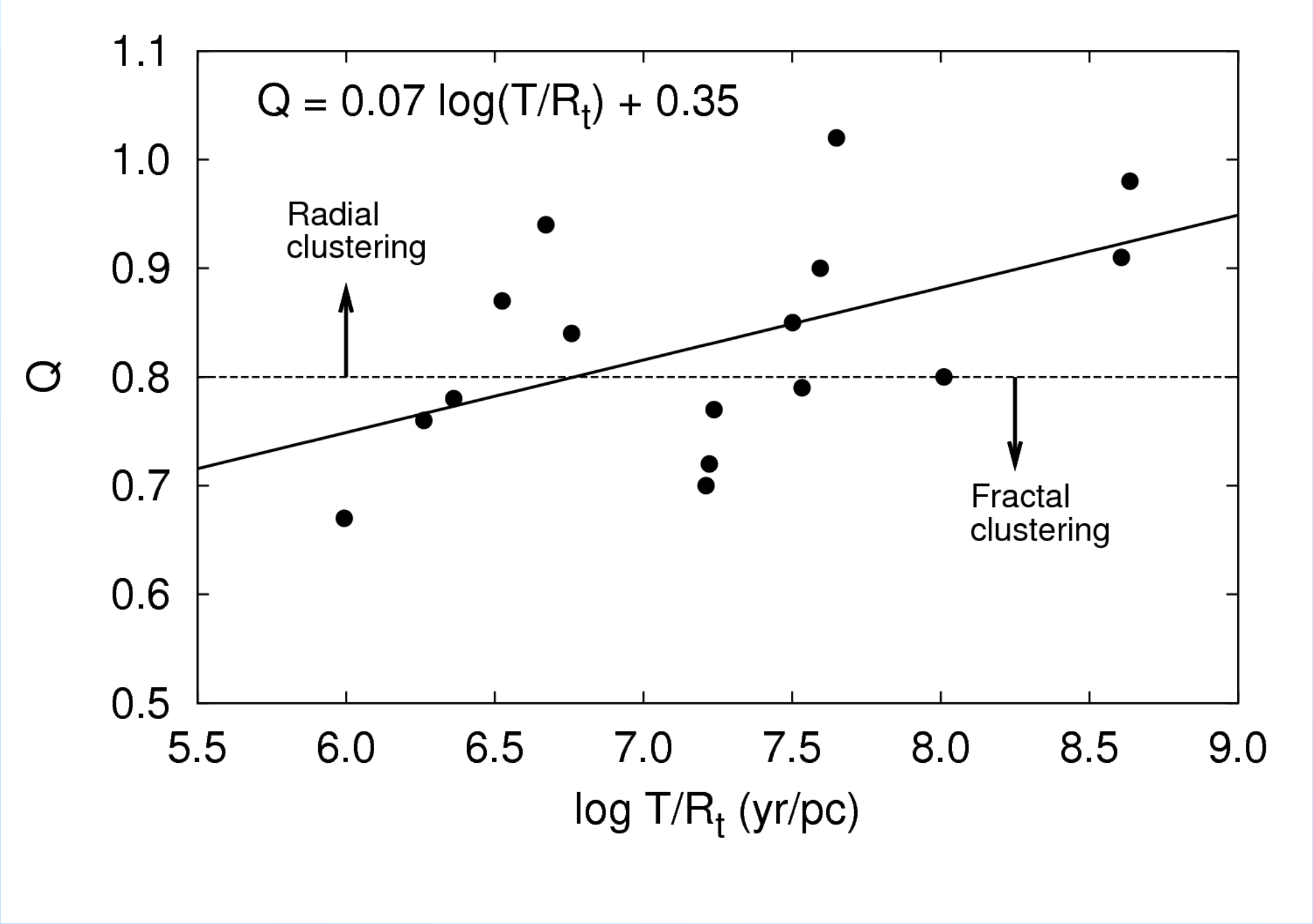

Figure 2: Structure parameter Q as a function of the logarithm of age divided by the tidal radius, which is nearly proportional to age in crossing times units. The dashed line at Q=0.8 roughly separates radial from fractal clustering. The best linear fit (equation at the top) is represented by a solid line.

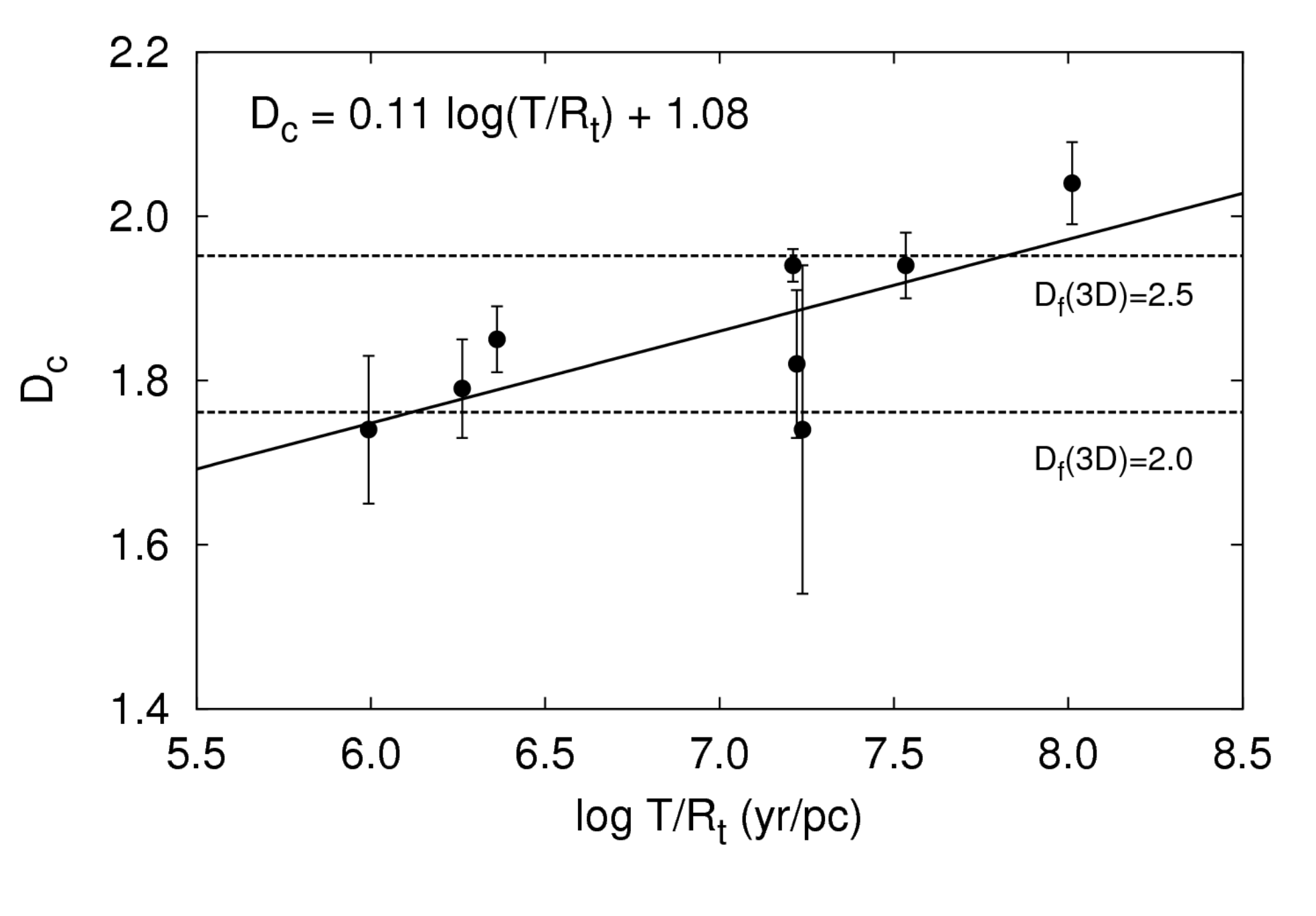

Figure 3: Calculated correlation dimension as a function of age (in crossing time units). The best linear fit (equation at the top) is represented by a solid line. As a reference, horizontal dashed lines indicate the values corresponding to three-dimensional distributions with fractal dimension values of 2.0 and 2.5.

## MAIN RESULTS

- Table 1 summarizes the open clusters data (ages and distances were taken from Webda).
- On average, stars in young clusters tend to be distributed following clustered, fractal-like patterns (Q<0.8), whereas older clusters tend to exhibit radial star density profiles (Q>0.8). This result supports the idea that stars in new-born cluster likely follow the fractal patterns of their parent molecular clouds, and that eventually evolve toward more centrally concentrated structures (see Schemja & Klessen 2006; Schmeja et al. 2008, 2009; Sanchez et al. 2007, 2009). However, the statistical analysis indicates that there is no significant correlation between Q and log(T).
- If instead we consider the variable T/Rt which is proportional to the cluster age measured in crossing time units (assuming nearly the same typical velocity dispersion for the open clusters), then a significant correlation is observed (Figure 2).
- There can exist open clusters as old as 100 Myr that have not totally destroyed their clumpy structure (for example, NGC 1513 and NGC 1647).
- We observe significant correlations (confidence levels above 96 %) between Dc and T (cluster age) and also between Dc and T/Rt (age in crossing time units) for those clusters with internal substructure (Figure 3).

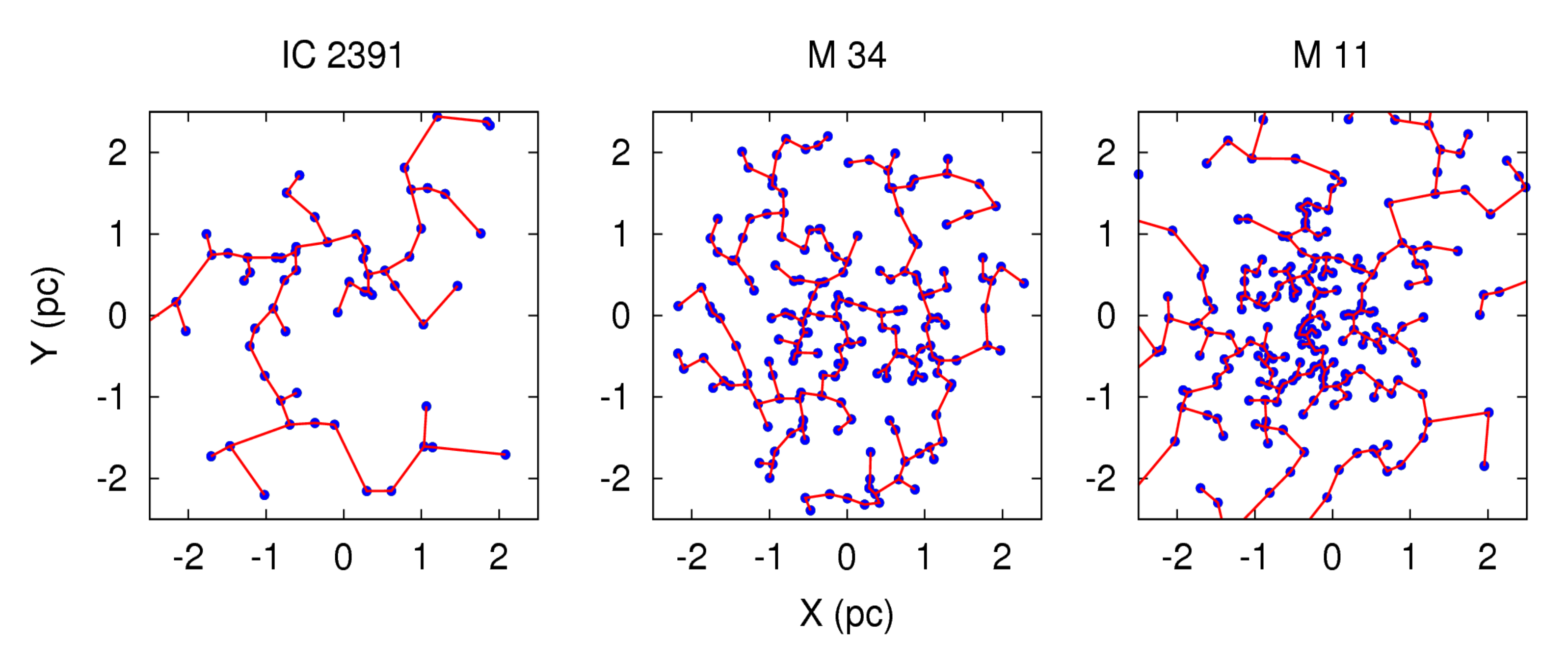

Figure 1: Minimum Spanning Trees for three open clusters, from which we can calculate the structure parameter Q. Star positions are indicated with blue circles and red lines represent the tree. The value of Q quantifies the spatial distribution of stars. For IC 2391 the stars are distributed following an irregular fractal pattern (Q=0.77<0.8), for M 34 the stars are distributed roughly homogeneously (Q=0.8), and for M 11 the stars follow a radial density profile (Q=1.02>0.8).

Table 1. PROPERTIES OF THE CLUSTERS IN THE SAMPLE

| Name | log $T$ | $D$ | $N_s$ | $R_c$ | $R_t$ | $Q$ | $D_c$ |
|---|---|---|---|---|---|---|---|
| IC 2391 | 7.661 | 175 | 62 | 1.46 | 2.65 | 0.77 | $1.74 \pm 0.20$ |
| M 11 | 8.302 | 1877 | 289 | 1.98 | 4.49 | 1.02 | ⋯ |
| M 34 | 8.249 | 499 | 181 | 0.11 | 1.73 | 0.80 | $2.04 \pm 0.05$ |
| M 67 | 9.409 | 908 | 354 | 2.21 | 5.92 | 0.98 | ⋯ |
| NGC 188 | 9.632 | 2047 | 1459 | 2.90 | 10.57 | 0.91 | ⋯ |
| NGC 581 | 7.336 | 2194 | 526 | 1.38 | 11.86 | 0.76 | $1.79 \pm 0.06$ |
| NGC 1513 | 8.110 | 1320 | 156 | 1.55 | 7.73 | 0.72 | $1.82 \pm 0.09$ |
| NGC 1647 | 8.158 | 540 | 683 | 1.23 | 8.86 | 0.70 | $1.94 \pm 0.02$ |
| NGC 1817 | 8.612 | 1972 | 277 | 3.39 | 11.97 | 0.79 | $1.94 \pm 0.04$ |
| NGC 1960 | 7.468 | 1318 | 311 | 2.96 | 8.77 | 0.87 | ⋯ |
| NGC 2194 | 8.515 | 3781 | 228 | 3.17 | 10.31 | 0.85 | ⋯ |
| NGC 2548 | 8.557 | 769 | 168 | 2.61 | 9.16 | 0.90 | ⋯ |
| NGC 4103 | 7.393 | 1632 | 799 | 0.72 | 10.74 | 0.78 | $1.85 \pm 0.04$ |
| NGC 4755 | 7.216 | 1976 | 196 | 1.11 | 3.50 | 0.94 | ⋯ |
| NGC 5281 | 7.146 | 1108 | 80 | 0.62 | 2.44 | 0.84 | ⋯ |
| NGC 6530 | 6.867 | 1330 | 145 | 1.43 | 7.47 | 0.67 | $1.74 \pm 0.09$ |

Note. — $T$: cluster age ($Myr$); $D$: distance ($pc$); $N_s$: number of members; $R_c$ core radius ($pc$); $R_t$: tidal radius ($pc$); $Q$: structure parameter; $D_c$: correlation dimension.

## DISCUSSION

From Figure 2, we can see that clusters with the smallest correlation dimensions (Dc = 1.74) would have three-dimensional fractal dimensions around Df ~ 2.0. This is a very interesting result because this value is considerably smaller than the average value estimated for galactic molecular clouds in recent studies, which is Df ~ 2.6-2.7 (Sanchez et al. 2005, 2007). If the fractal dimension of the interstellar medium has a nearly universal value around 2.6-2.7, and if newborn stars in this fractal medium follow similar fractal patterns (Elmegreen & Elmegreen 2001), then some further explanation is required for this difference. There are several possibilities that should be explored:

- Perhaps some clusters may develop some kind of substructure starting from an initially more homogeneous state (Goodwin & Whitworth 2004).
- This difference could be a consequence of a more clustered distribution of the densest gas from which stars form at the smallest spatial scales in the molecular cloud complexes, according to a multifractal scenario (Chappell & Scalo 2001).
- Another explanation is that the fractal dimension in the Galaxy does not have a universal value and therefore some regions form stars distributed following more clustered patterns.
- Finally, maybe the star formation process itself modifies in some (unknown) way the underlying geometry generating distributions of stars that can be very different from the distribution of gas in the parental clouds.

These points clearly require more investigation. High-precision positions, parallaxes, proper motion and photometry to be obtained by Gaia will yield reliable membership determinations that will allow a better understanding of this subject.