Indication of Hierarchical Star Formation in Spiral Galaxies

P. Drazinos[1], E. Kontizas[2], I. Bellas-Velidis[2], M. Kontizas[1]

1. *Department of Astrophysics, Astronomy & Mechanics, Faculty of Physics, University of Athens, GR-15783 Athens, Greece*
2. *Institute for Astronomy and Astrophysics, National Observatory of Athens, P.O. Box 20048, GR-11810 Athens, Greece*

Abstract: The presence of small and large scale star formation structures in a sample of six spiral galaxies has been investigated. Our main goal is to identify small structures of young stars known as OB associations and to investigate whether they are formed inside larger stellar structures in a hierarchical form. An automated method was used in order to detect star forming regions. This process was based on a friend of friend (FoF) algorithm applied on bright early type stars above a certain color cutoff limit. A size criterion was introduced at a later stage of the process in order to apply the same process to different types of stellar structures. Depending on their size the structures were divided into four categories, associations, aggregates, complexes and supercomplexes. Catalogues of the four types of star forming structures found in every galaxy has been produced. There is indication of hierarchical structure in the investigated area as the majority of associations and aggregates found are lying inside larger structures like complexes or supercomplexes.

1. Introduction

The study of OB associations is important as it can provide a better understanding of the stellar formation process. Massive young stars are believed to be born mostly inside stellar groupings and not in isolation. Hot massive stars with their UV winds, their short life span and supernova explosions, contribute significantly in the evolution of galaxies. That makes the OB associations an essential part in the process of galaxy evolution and their stellar content. An OB association can be described as a large gravitationally unbound stellar group of O and B stars (Blaauw 1964). The process used to identify an OB association was based mainly to the subjective selection criteria of the observer. As a consequence it was difficult to compare findings between studies and even between observations of different areas made by the same observer.

Battinelli (1991) proposed distance as criterion for a star to be considered as a member of an OB association. His method, the Path Linkage Criterion, provided an objective tool to the identification process. The distance criterion in our study is implemented with the usage of a friend of friend algorithm. The groups in our study were categorized based on their size into associations, aggregates, complexes and supercomplexes (Efremov 1987; Maragoudaki et al. 1998; Livanou et al. 2007). Instead of using one value for the distance parameter or search radius as it was called by Battineli, we selected now four values through the algorithm, one for each group category.

The six galaxies studied were part of the HST Extragalactic Distance Scale Key Project, an effort to study Cepheid variables in order to constrain the Hubble constant (Bresolin et al, 1998; Kennicutt, Freedman & Mould, 1995). All images used for our purpose were taken with the Wide Field and Planetary Camera 2 (WFPC2) with an L-shaped field of view. WFPC2 featured four detectors, three wide-field (WF) cameras which were arranged in an L-shape and the planetary camera (PC) with a higher resolution than the other three. The field of view of the WF cameras covered 1',33×1',33 and of the PC covered 35"×35". The observations were made in two wavelength bands at V (F555W) and at I (F814W).

2. Method

2.1 Path Linkage Criterion

The automated method used in this paper is based on Path Linkage Criterion (PLC) introduced by Battinelli, an objective method to identify OB associations. The main idea is the application of an objective criterion to the identification process. Two stars belong to the same group only if they are at a distance less or equal to a predefined value. In that principle we investigate the whole of our star catalogue in a specific area. One important question needed to be addressed in this method is the value of search radius (Ds) for which our star catalogue will be investigated in order to identify OB associations or any other kind of star forming structures. For each value of Ds that we set as a limit for two stars to be considered members of the same class, a number of groups (n) are found through the algorithm. Battinelli argued that the value of Ds which produces the maximum number of groups is the one that should be used. In order to determine that value, the algorithm will run for a set of Ds values. Details of the technical aspect of the algorithm are given in section 3.2, where the workflow of the process is given.

For each step the process identifies a number of groups and a list of pairs of Ds and n pairs is constructed. If we plot that list of pairs we get a graph like in figure 1.

The function's maximum is the value of Ds at which we get the maximum number of groups in the investigated area. In some cases (Battinelli et al, 1996) as the distance value increases and we move farther away from the maximum point, some of the smaller formations are starting to merge hence we detect less groups than we did before. A secondary maximum or a plateau in the graph is an indication of the existence of larger formations along with associations. With a further increase in Ds the larger groups merge and the number of groups decreases again. As a result we can use both maxima in order to find small (maximum point of the plot) and larger formations (secondary maximum).

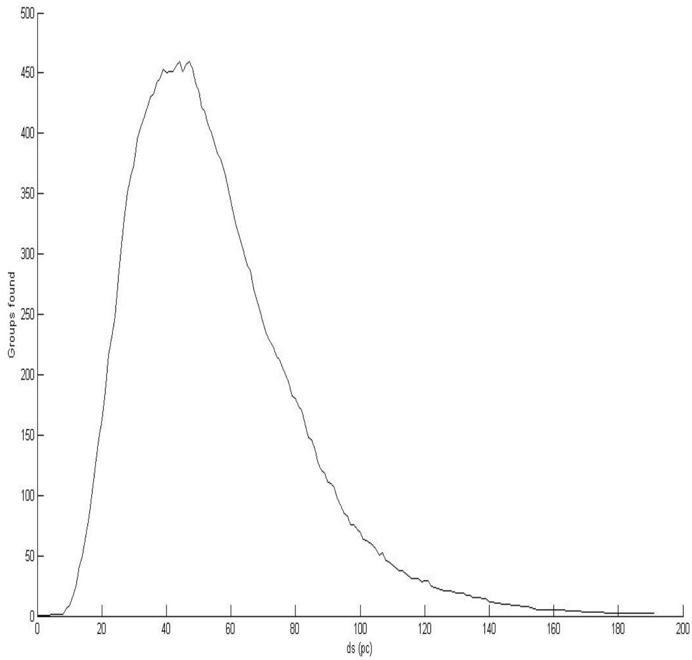

Figure 1. The number of groups found in NGC3621 versus the distance used.

The problem lies on the physical parameters of the field in study. If the field is relatively small or it is chosen to be small then the plot can indicate the value of Ds order to identify formations larger than associations. Else if the the field is large, the application of PLC produces a smooth plot where the only point relatively easy to identify is the function's maximum and larger formations like complexes remain mostly undetected.

2.2 Friends of Friends algorithm

For each galaxy of our sample the same process described above was applied. A code based on Friends of Friends algorithm was constructed for the application of the distance criterion. The Friends of Friends algorithm was invented by Huchra and Geller (1982) and is a cluster finding technique. The algorithm searches for pairs of objects that they are closer than a cut off distance limit. The original algorithm was used in finding groups and clusters of galaxies. In our case we not only need to identify small scale stellar formations but larger as well in order to study their distribution and to assess if they represent a hierarchy of scales. The field of each galaxy studied was large enough to produce a smooth plot of Ds and n values. That made the identification of larger scale structures almost impossible.

One possible approach is to divide the large area into smaller subsections and hence to apply the identification process into each subsection. The problem here is that by dividing the area we will lose some larger formations that could be laying on the borderlines between our subsections. Also if we end up with a significant number of smaller areas the process becomes more time consuming and the number of large structure that we lose increases. Another possible approach is to target a specific area of the field which is small enough to produce the graph that is useful to the identification process or an area that is optically rich in stellar formations. That approach is susceptible to the subjective selection of the researcher and lacks the information of hierarchy in large scales. What we can do in order to apply our code in a large area without worrying about identifying the secondary maximum is to introduce another criterion into the process, the size of the formations found. We divide the stellar structures into four main types, associations (from 30 to 100 pc in size), aggregates (from 100 to 300 pc), complexes (from 300 to 1000 pc) and supercomplexes (from 1000 pc and above). That way the code produces four graphs similar to figure 1, one for each formation type. Each plot shows the population of groups found against the Ds value but only for a specific group type. The plot of the total number of groups found is still. So in essence the second criterion, group size, creates four subplots under the one proposed by Battineli (Fig.2).

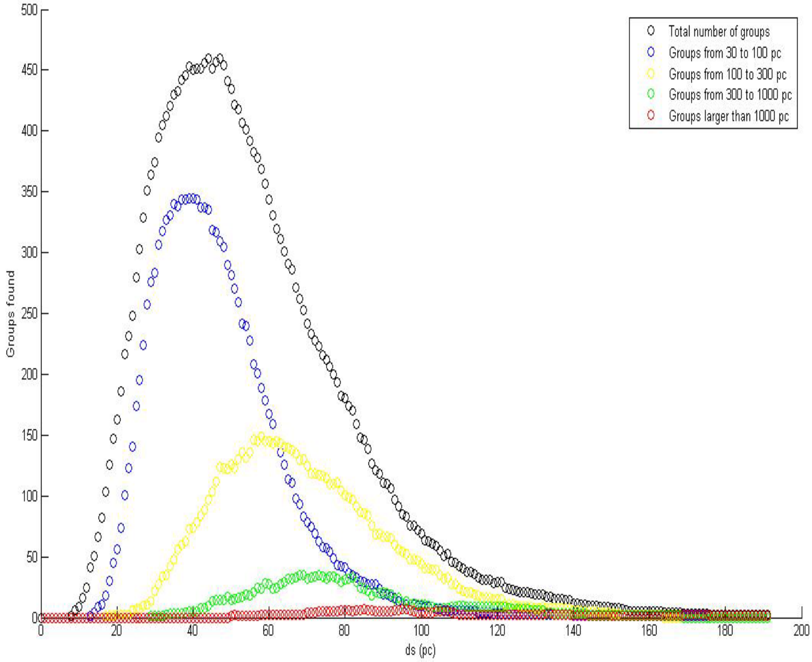

Figure 2. f(Ds) and four subplots for NGC3621

The code is first run applying the distance criterion, identifying groups, estimating the size of each group in order their type to be assessed as mentioned above. Then all the needed plots are drawn. Instead of using one or two distance values for group as in 2.1 for identification we now have four, the maximum point of each subplot. The code is run again for each specific Ds value and all groups found are mapped and catalogued. In that approach we can target a specific type of stellar formation independent of size and search specifically for that type however large that area can be. We can combine our search for other types of structures, smaller or larger in order to evaluate their spatial distribution in accordance to each other and for large scale fields.

3. Six Hubble Space Telescope Galaxies

3.1 Observational Data

NGC925 is classified as SBcII-III galaxy by Sandage and Tammann (1981) and as an SBS3 galaxy by de Vaucouleurs et al. (1991). It is a member of the NGC1023 galaxy group (Tully 1980). The NGC1023 group is a bound association of about 30 galaxies, at a distance of about 10 Mpc, with an estimated radius of about 0.8 Mpc. The inclination angle of NGC925 is 57^{o}. After the photometry for the field of view of WFPC2 a catalog of stars was produced with 25584 members. In order to ensure that we will obtain a sample of early type stars a color cutoff limit (V-I < 0.23) was imposed and the original sample was limited to 3930 members.

NGC2541 belongs to the NGC2841 group near the border of Ursa Major and Lynx. The distance of the NGC2541 was estimated by HST Key Project to be 12.4Mpc. The sample of bright stars after the photometry contained 4356 members.

NGC3351, at a distance 10.05 Mpc, is a bright barred spiral galaxy. It was classified by Sandage and Tammann (1981) as SBb(r)II and is a member of the Leo I group of galaxies. The FoF algorithm was applied to a bright early type star catalog after the phototmetry to 2420 members.

NGC3621 is a relatively isolated spiral, classified as Sc II.8 (Sandage and Tamman 1981) and lies at a distance of 6.3 Mpc and the photometry produced a smaple of 5329 bright stars.

Table 1. Galaxy distance and bright star number after photometry

Galaxies	Distance (Mpc)	Number of blue stars
NGC925	9.30	3930
NGC2541	12.40	4356
NGC3351	10.05	2420
NGC3621	6.30	5329
NGC4548	15.90	3697
NGC5457	7.40	4052

NGC4548 belongs to the Virgo Cluster, a well resolved spiral with galaxy type SBb(rs)I-II and lies at a distance of 15.9 Mpc. The bright star sample for NGC4548 consisted of 3697 members.

NGC5457 of M101 is a luminous spiral with morphological type SAB(rs)cd and estimated distance 7.4 Mpc and the bright star catalogue after photometry had 4052 stars.

3.2 Application of the friend of friend algorithm

The distances between all stars for each one sample were calculated in order to be used later in the application of the algorithm. The range of Ds was set from 1 pc to 200 pc and the step between Ds values to 1pc. For each value of Ds the algorithm was applied to the sample producing a list of groups and for each group found its size was calculated. After the completion of the process for the whole Ds range, graphs as in Figure 3 were plotted for each one of the galaxies. This kind of graph was created by plotting pairs of Ds value and the number of groups found for that specific value. For each category of group, depending on its size, the same process was followed, essentially producing five plots, four for each size category and one for all groups found as described in section 2. The maximum point of each of the four plots is identified and the FoF algorithm is applied again, now only for the four specific values, producing for each one a catalog of the identified groups. The center of each group is calculated as, the mean Right Ascension and Declination of their star members. Subsequently these groups are plotted as seen in Figure 4.

4. Discussion

The method used in this study is a variation of the PLC method described in section 2 by Battineli. It provides the advantage of searching for a specific formation structure. The search radius in this case is determined by the structure to be identified, the FoF algorithm searches through a range of distance values to find the one presenting the maximum population number of that particular structure instead of searching for the maximum number of all groups and then searching among that sample for a specific type of group.

In the case of associations, the point of maximum of the plot of the total number of groups found in all galaxies, presented a reduced number of associations and an increased number of aggregates than the maximum point of the curve plotted using the size criterion for associations. It should be noted that the other group types, complexes and supercomplexes were limited to a very small number or they were not detected at all, thus the need to introduce to the FoF algorithm the parameter of group size. Essentially the plot for all groups can be analyzed into multiple subplots. At every search radius value (Ds), the observer can analyze the total number of groups to the size types defined earlier. The sum of the intersection points of all

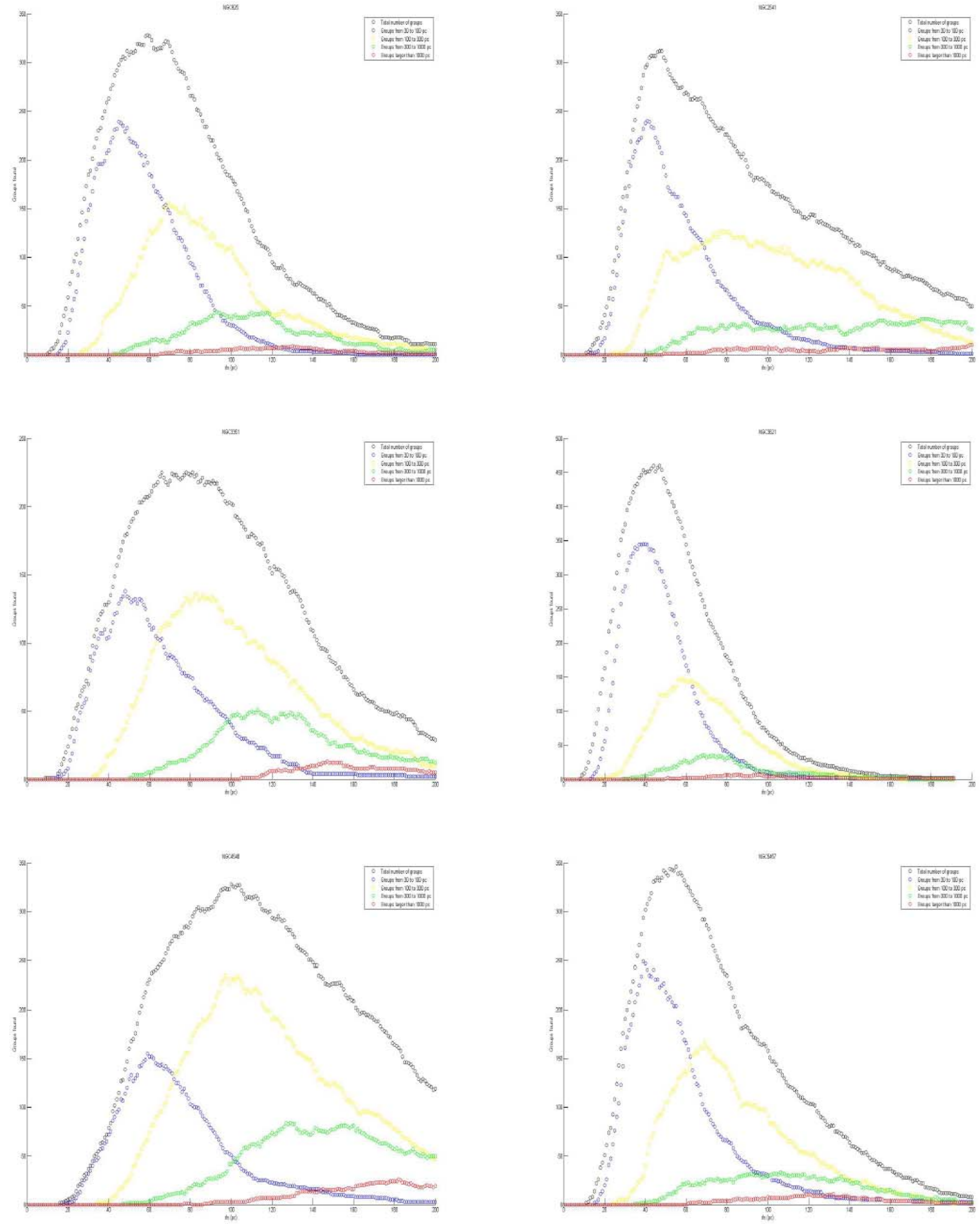

Figure 3. Plots of number of groups found and search radius for all galaxies.

subplots at a specific Ds value is equal to the intersection point of the total groups plot at the same Ds.

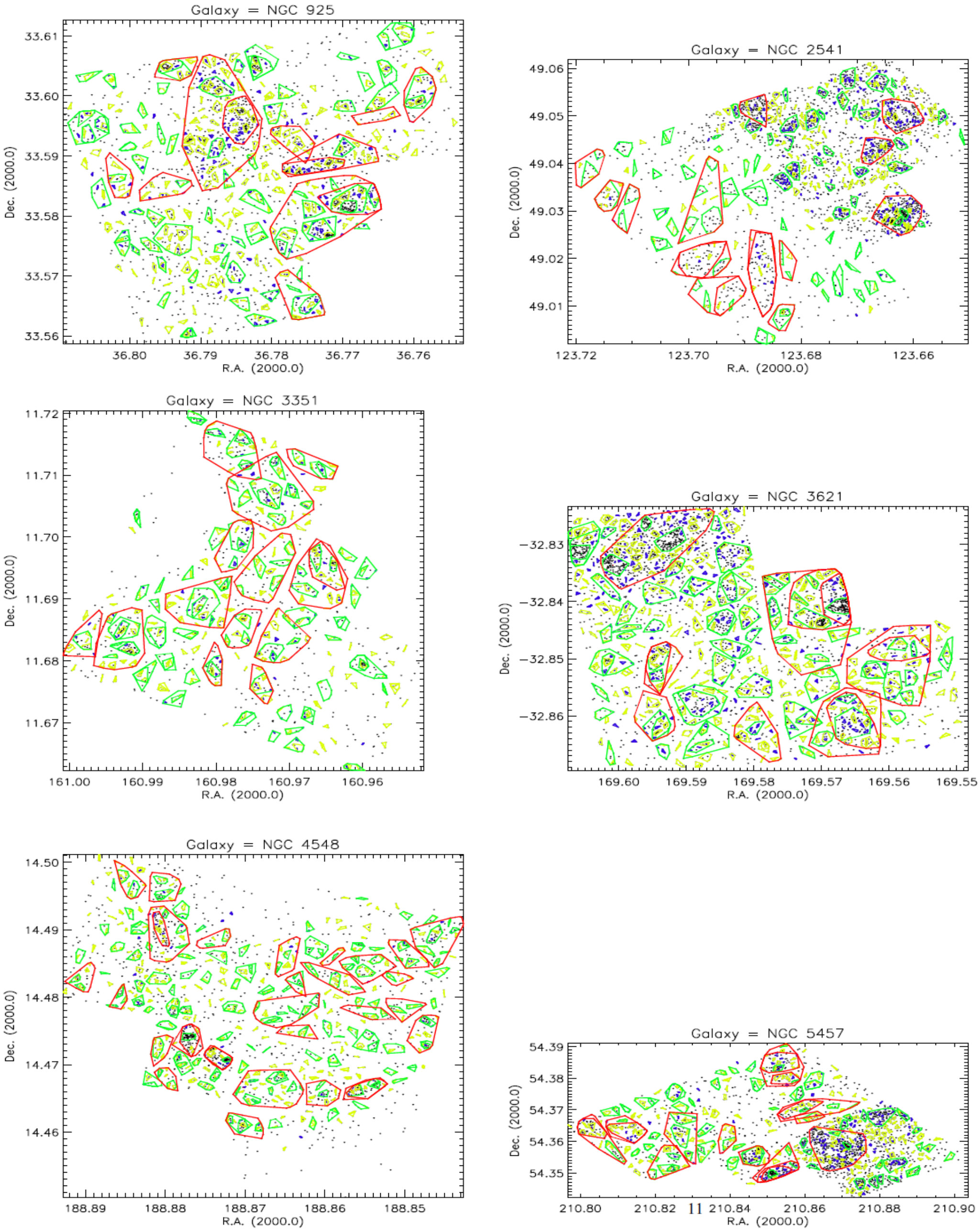

Figure 4. Plots of all groups found for each galaxy (b=associations, y=aggregates, g=complexes,red=scomplexes)

The final graph, as in figure 4, is the result of running the FoF algorithm at the same time using four different size criteria, removing any duplicate findings.

Setting a size limit for each group type can affect the Ds value determination by the algorithm. The Ds value is actually the distance radius at which the algorithm searches around each star of the catalog, in order to find if any other star lies in that area. If that is the case, both of them, will be considered members of the same group. When the algorithm moves to the next star follows the same process and adds to the group any other star that lies within a distance defined by the Ds value. It is almost impossible to detect large structures using small Ds values. At some point there will be no stars within that distance, unless the local star density is high, to continue adding members into the group. Even if the algorithm runs through a dense area, it is unlikely, for Ds values around the associations' maximum, to detect structures larger than aggregates. Hence the large scale structures are found in higher Ds values than small structures (associations). In that sense the type of structure that we are looking for, indicates a range of Ds values at which it is possible to be found, and affects the resulting average sizes. The selection of that Ds value though is not arbitrary as the algorithm seeks the maximum point in each plot. Not all of these groups identified by the algorithm are 100% real, as we may see projections of stars actually lying further away.

4.1 Star forming structure properties

The average size of associations for our galaxy sample is in the area of 60-75 pc. Five of them are between 61 and 67 pc, except for NGC4548 where the average value is 75 pc. The average of the medians of all galaxies is at 66 pc. The size distribution of the associations (In figure 5, the size distribution of groups from 30 pc to 300 pc, for NGC2541 is given as an example indicative of all galaxies) presents a peak for associations from 50 to 80 pc. The average number of members for associations is fairly constant for all galaxies, varying from 3.35 to 3.95 stars per group.

We compare our findings with a number of studies of other galaxies, M101 and LMC (Bresolin,Kennicut,Stetson 1996, BKS), LMC (Gouliermis et al 2003), M33, M31, SMC (Battineli 1991), NGC6822 (Karampelas et al 2009, Gouliermis et al 2010), HST galaxies (Bresolin et al 1998).

Bresolin et al studied the same sample of HST galaxies, using a FoF algorithm based on the PLC method of Battineli. They selected a different value for the minimum number of stars for each group (Nmin) and search radius for each galaxy. They found a scale length for the associations around 80 pc, using the median values of each galaxy, for identified groups with sizes up to 200 pc. That can be explained by the criteria used in order to approach the term associations. Groups with upper size limit 200 pc contributed to the increased average value. If in our group

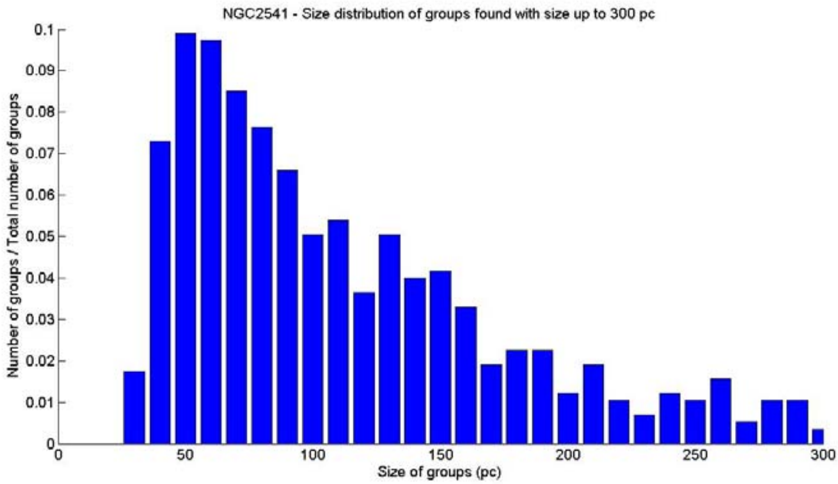

Figure 5. NGC2541 – Size distribution for groups with size up to 300 pc.

findings the same criterion was applied, the average value per galaxy would be close to that found by Bresolin et al. The size distribution though for both studies peaked at the same range, 40-80 pc for Bresolin et al and 50-80 pc for this study.

The scale length of ~80 pc was reported as well by BKS comparing groups found in six galaxies, M101(=NGC5457), M31, M33, NGC6822, LMC and SMC, where the median value varied from 60 to 100 pc for a varying value of Nmin from 3 to 10. The size distribution of all galaxies presented a peak at the 40-80 pc range except M31 were it was ~110 pc.

Gouliermis et al (2003) reported for LMC an average size of associations of 86 pc, and a peak in the size distribution at 70 pc and a number of studies for different galaxies was presented as well where the average size of the associations varied from 65-93 pc. For NGC6822 Gouliermis (2010) gives a lower average of 68 pc. Most of the studies mentioned above reported average size and distributions peaked in the same range, 60-100 for average and 40-80 for distribution. These values were found at different galaxies and using different selection criteria as to what is considered an association and various techniques were used.

Stellar formation structures larger than associations were also detected by our algorithm. Aggregates with average values varying, from 162-175 pc for size and 5-9 stars per group. Complexes with an average size from 500 to 517 pc and average number of members from 15-48, five of the six galaxies though presented an average number of stars from 15-26. The final category, supercomplexes, was detected to have an average size from 1200-1600 pc and 74-311 members, where five of the six were in the range of 75-200.

The average size for each group category seems to agree with previously reported typical sizes of structures larger than associations. For M31 van den Bergh (1964) identified groups of blue stars with average size ~500 pc. Efremov et al. (1987) identified star complexes ~600 pc average size. Magnier et al. (1993) found a large number of groups with sizes from 50-150, roughly the averages of associations and aggregates in our study and a few larger structures ~400 pc in size. For the same galaxy Battineli, Efremov and Magnier (1996) found hierarchical structures in two levels, the first with size ~100 pc and the second with a distribution of sizes from ~100 to ~800 pc with maximum at ~200 pc, in the middle of our aggregates range and an indication of a peak at ~400 pc (complexes).

Similar were the findings for LMC (Livanou et al 2007) and NGC6822 (Karampelas et al 2009) were star complexes were detected in two ranges, from 150-400 pc, roughly what we considered as aggregates and the second from 400-800 pc, in the complexes range.

It seems that surface density is correlated with the group size. The density of the structures seems to increase as the size decreases; most of the associations are denser than any other group except a small part of aggregates with size around the lower limit, 100 pc. Complexes and supercomplexes have the lowest surface density values. In Figure 6, the surface density – group size plot is presented for NGC2541 which is indicative of what was described above. The same applies for all other galaxies studied.

Hierarchical structure (Elmegreen & Efremov 1996; Maragoudaki et al. 2001; Livanou et al. 2006; Karampelas et al. 2009) is indicated in all six galaxies, as it can be seen in Figure 5. Most of the associations and aggregates, the smaller and denser groups, are found to be lying inside larger groups, complexes and supercomplexes, which present the lower density values of all groups. The average sizes is another indication of hierarchical star formation, since groups with sizes ~65 pc and ~160 pc are engulfed by structures ~500 pc and even larger ones ~ 1400 pc.

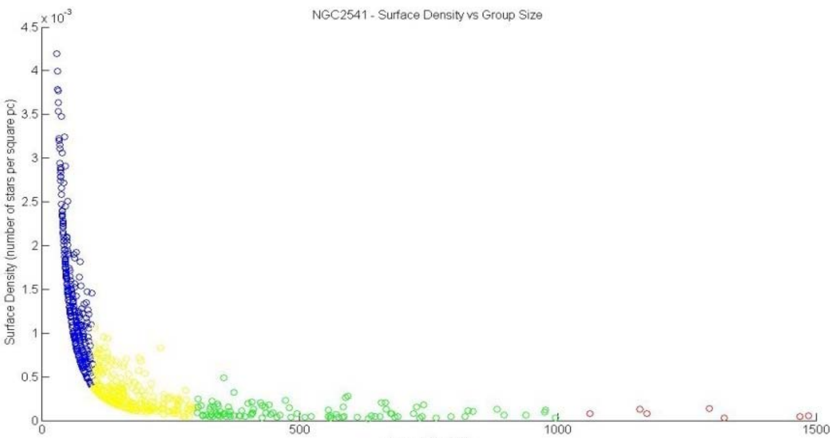

Figure 6. NGC2541 – Plot of surface density and group size.

5. Summary

A friend of friend algorithm was used to identify star forming structures in six galaxies of the HST Key Project. Groups were divided into specific size ranges as was suggested in the literature (associations, aggregates, complexes and supercomplexes) and the FoF algorithm searched for four kinds of structures. This method provides better detection of small groups, smaller than the typical size of 80 pc for associations, reported in the literature. It is also capable to detect larger structures as well in a large area, where previously the PLC was unable to identify complexes or supercomplexes. The detected groups were within the reported ranges of hierarchical star formation in the literature.

The associations found to have an average of ~65 pc and ~4 members, the aggregates ~165 pc and ~8 stars per group, complexes were found to have an average of ~500pc and ~22 members and finally supercomplexes to be around ~1400 pc and to have ~150 stars.

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