SYSTEMS OF STELLAR ASSOCIATIONS IN GALAXIES

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This paper begins with an attempt to examine the problem of identifying stellar associations in galaxies in a consistent way, so that meaningful physical comparisons can be made for the population of stellar associations of different galaxies. A compilation of the existing data on associations in other galaxies is given and their properties compared. Questions relating to star formation in stellar associations are discussed, and then the issue of the initial mass function of core clusters, especially those located in giant HII regions, is briefly examined.

1. IDENTIFYING STELLAR ASSOCIATIONS IN OTHER GALAXIES

Stellar OB associations are not particularly easy to identify in the solar neighborhood without extensive kinematic and spectroscopic data. In other galaxies, where we do not yet have the ability to measure individual candidate stars' proper motions and radial velocities, the problems are severe. Even for the Magellanic Clouds, where we can at least get precise spectral types and colors, it is not yet possible, especially in crowded regions, to be sure that apparent stellar associations are truly physical entities in every case. This question is a key consideration before we can use populations of associations in attacks on such problems as the distance scale or galaxy evolution.

1.1 The Case of the SMC

A good example of some of these concerns is provided by the OB associations of the SMC. In spite of the extensive amount of work that has been done and published about the associations of the LMC, almost nothing has been said about those of the SMC, except for some early pioneering work in the SMC wing by Westerlund (1961, 1964). Considerable spectroscopy of SMC luminous stars has been done, allowing the mapping of OB stars and their use in exploring the structure of the SMC (Azzopardi and Vigneau 1977, Dubois 1980, Florsch, Marcout and Fleck 1981). However, the associations as a

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class of objects have been largely ignored. Azzopardi and Vigneau (1977) divided the surface distribution of O-B2 stars into five relatively large high-density regions, but did not report on the fainter stars in them, which might have helped to distinguish any smaller subdivisions that would have physical meaning. If we interpret their five groupings as the complete sample of OB associations in the SMC, then we find that they are both surprisingly few in number and unusually large in size, compared to the sample in the LMC or in our Galaxy.

To try to understand this situation better, I carried out some experiments in identification of stellar associations for the SMC. Using the published OB surveys as a base, I attempted to see what kind of consistency I could achieve by doing independent searches on a large variety of different kinds of observational material, including large and small scale plates, plates in ultraviolet, blue and visual colors, and with both deep and shallow limiting magnitudes. The result is a list of 70 OB association candidates (Hodge 1985a). But the important point for this review is the fact that many of the possible associations were identified in only one or two of the surveys, especially in the dense core of the Cloud. One might suggest that this means that stellar associations are difficult to find and that all kinds of observational material are needed to rout them out. However, I believe that the experiment has a more discouraging message. I think that the problem of distinguishing real associations in a matrix of irregularly-spaced bright stars is not trivial and that it must be carried out with proper controls and statistical techniques to be sure that we are dealing with physical groupings. For example, one can use pattern-recognition analysis (Feitzinger and Braunsfurth 1984) or other statistical tests for clumping (Hodge 1985b). Therefore, I consider my catalog of objects to be suspect in the SMC core, where at least 16 of the candidates could be asterisms. Good photometry and fainter spectroscopy could help to settle the question of their nature. The point is that even for a galaxy as near as the SMC it is not a simple matter to distinguish stellar associations reliably.

1.2 Existing Samples of Stellar Associations in Resolved Galaxies

Table 1 summarizes the properties of stellar associations in resolved galaxies for which data have been published. Clearly there is a large spread in the properties of the samples. Considering the case of the SMC, however, it is not obvious whether the differences are physical or are the result of different identification criteria and techniques. The rest of this section attempts to answer that question.

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Table 1. Stellar Associations in Resolved Galaxies

	Total No.	No./L_B ($\times 10^8 L_\odot$)	Mean Diam. (pc)	Abs. Mag of Brightest, M_B	Reference
LMC	122	4	78	-11.8[a]	Lucke & Hodge 1970
SMC	70	8	77	---	Hodge 1985a
M31	319	0.5	480[b]	-12.8[c]	van den Bergh 1964; Nikolov and Ivanov 1986
M33	197	2.4	321	-12.4[a]	Humphreys & Sandage 1980; Kunchev & Ivanov 1984
NGC 6822	16	10	163	---	Hodge 1977
IC 1613	20	21	164	---	Hodge 1978
NGC 2403	88	1.0	348	-13.8[d]	Hodge 1985c
NGC 4303	235	0.3	290	-13.9[a]	This paper
NGC 7331	142	0.1	440	---	This paper

[a] From Wray and de Vaucouleurs (1980)
[b] From van den Bergh's data only
[c] From an unpublished paper by Schwartz
[d] From an unpublished paper by Wegner; Wray and de Vaucouleurs (1980) give M = -12.5.

Consider the contrast between M31 and the LMC. The associations in the former are very large and comparatively few (in terms of the normalized number per unit galaxy luminosity), compared to those in the latter. Is this because M31 is a Sb galaxy and the LMC a Irr? Or is this merely due to different selection criteria? Fig. 1 shows that it is not just the mean sizes that differ, but that the entire size distribution is markedly different.

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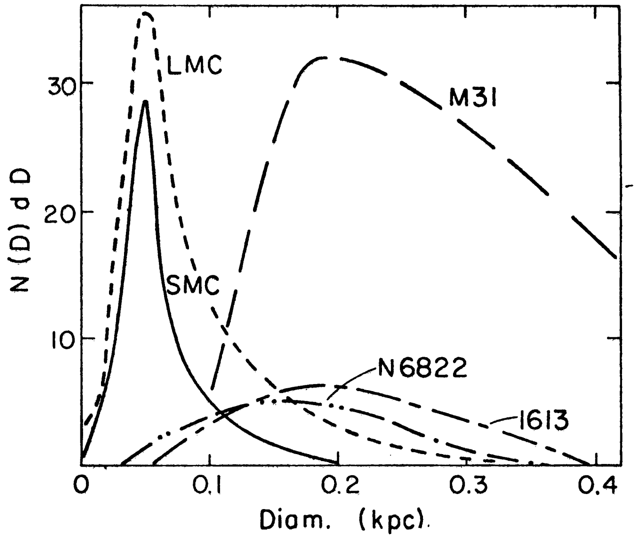

Figure 1. A comparison of the size distributions of OB associations in several local group galaxies.

In an attempt to distinguish between these possibilities, I have examined a series of plates of M31 that have nearly the same linear scale, color, and limiting absolute magnitude as the plates from which the LMC sample was distinguished (Lucke and Hodge 1970), without referring back to the original paper on M31 (van den Bergh 1964). Fig. 2 shows a sample of such a comparison, illustrating the result that the difference is probably not real. At least this particular test provided evidence that the differences in the published characteristics of the samples arise from the use of different observational material and selection criteria.

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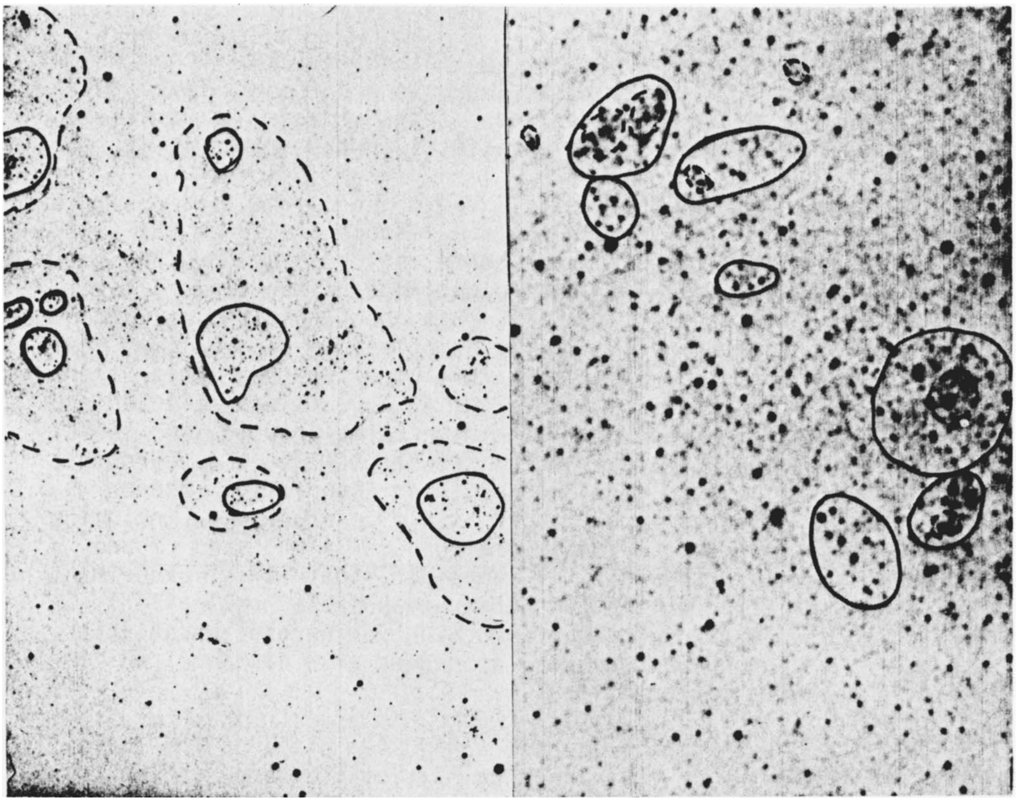

Figure 2. A comparison of photographs of portions of M31 (left) and the LMC (right) from plates that are similar in intrinsic scale and limiting magnitude. Solid lines define the boundaries of associations identified in this experiment, while dashed lines outline those identified in the original publications.

The data in Table 1 show that the normalized numbers of associations in galaxies might be a function of the distances to the galaxies. In each distance realm galaxies have a nearly constant relative population of associations, except for M31 and NGC 7331, and the smaller numbers for them can be interpreted as the result of their earlier Hubble type and consequent smaller content of extreme Population I objects. Although the sample is inadequately small to generalize reliably, the more distant galaxies have decidedly fewer associations per unit galaxy luminosity. I believe that this fact can be understood as a result of their greater distance, which makes the recognition of small associations more difficult, and which leads, as Figure 2 illustrates, to preferentially interpreting complexes of associations as single objects.

1.3 Unresolved Associations in More Distant Galaxies

Identifying OB associations in more distant galaxies, in which the individual stars are not even resolved, is a difficult task. With only the integrated color and patchiness of the images as criteria, the danger of having severe selection effects in the sample is acute.

To test for these problems, I have conducted two simple experiments. In the first I used two small-scale plates of M31 (in B and V), chosen to match in scale and degree of resolution the best available plates of galaxies at the distance of the Virgo cluster. Individual stars, for the most part, are not resolved. Without reference to the existing maps of associations in M31, I then attempted to identify the population of blue patches that might correspond to OB associations. A total of 42 objects was selected and their diameters were measured, with the mean calculated to be 300pc. When I compared my map with that of van den Bergh (1964), I found that every one of the 42 objects corresponded to an association chosen by him. However, using much larger scale plates and including ultraviolet plates, he located many more objects (188) and found a larger mean diameter (480pc). I consider that this experiment provides a demonstration of the fact that reasonable reliability in identifying such objects can be achieved even for unresolved galaxies. The efficiency of detection, however, decreases with distance and the sizes may be measured differently.

In the second experiment, I chose a KPNO 4-m plate of the galaxy NGC 7331, very similar in appearance to M31, of the same Hubble type, similar though somewhat brighter in absolute magnitude, and with a nearly identical inclination angle. Its distance is approximately 20 Mpc. Attempting to duplicate the procedures I used for the M31 experiment, I produced a catalog of candidate OB associations in NGC 7331. Table 2 shows the result. The total number of associations, 142, when normalized by the galaxy's luminosity, compares well with the number found in M31. They are somewhat larger than those in M31, however; this may be due to the greater intrinsic scale of NGC 7331. The experiment appears to confirm the fact that Sb galaxies have intrinsically larger OB associations than later Hubble types and that a reasonable fraction of the population of a galaxy's associations can be distinguished out to 20 Mpc.

Table 2. M31 versus NGC 7331

Associations	NGC 7331	M31 (small scale plates)
No. detected	142	42
No./L_B ($\times 10^8 L_\odot$)	0.09	0.07
Size range (pc)	100-950	100-500
Mean diameter (pc)	440	300

Beyond these distances, however, it is expected that problems can arise. For example, while the stellar associations in nearby galaxies are measured to have absolute magnitudes in B that reach a maximum at about -12 (see Tables 1 and 3 for several values), Shakhbazyan (1968) describes more distant galaxies that have stellar complexes with absolute magnitudes of -16.

Wray and de Vaucouleurs (1980), who attempted to identify the brightest blue patches in galaxies for their use as distance indicators, apparently found that they could compensate for any selection effects. On the other hand, various other studies of associations (e.g., Humphreys 1977 and Efremov 1982) show us that difficulties remain in finding consistent criteria that will allow unbiased comparisons of associations in different galaxies.

Table 3. Photoelectric Measures of Integrated Light from the Brightest Stellar Associations in M101

Association*	V	B-V	U-B
A1	13.70	0.79	-0.80
A2	15.92	0.36	-0.83
A3	14.65	0.62	-0.83
A4	14.85	0.52	-1.01
A5A	15.87	0.17	-0.88
A5B	15.83	0.22	-0.89

* All measures were made with a 20 arcsec diaphragm with the KPNO 0.9m telescope.

In concluding this section of the paper, I will summarize the various possible conclusions, which can be made with different levels of confidence. First, it can be said with certainty that the derived characteristics of a sample of extragalactic OB associations can depend on various selection effects, including the distance of the galaxy, the resolution of the images, the depth of exposure, and the identification criteria adopted. With considerable confidence we can say that their properties also depend somewhat on the total luminosity of the host galaxy, especially the total number of associations, which averages approximately 10 per 10^8 solar luminosities for late type galaxies. We conclude tentatively that the characteristics also depend on the Hubble type of the galaxies, with Sb galaxies having fewer (for a given total luminosity) OB associations than Sc and Irr galaxies.

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2. STAR FORMATION IN STELLAR ASSOCIATIONS

The surveys listed in Table 1 provide a useful pool of data for looking at certain questions regarding star formation in OB associations. This is not the right place for an exhaustive review of this important topic, but it might be appropriate to point out a few facts that emerge and that seem to relate to the basic questions of how star formation is triggered and how it proceeds, once begun.

First, we can compare the positions of the recognized associations with the locations of HII regions, which represent the loci of (visible only) massive star formation processes. Table 4 summarizes the statistics for several galaxies. On the average, only about 50% of stellar associations contain HII regions, but the dispersion in this figure is surprisingly large. The LMC's have 79%, while those in the SMC and IC 1613 have only a little over 30%. These two latter galaxies are in a relatively quiescent phase, as far as star formation is concerned, but their numbers of stellar associations are not especially small. The fact that they have small numbers of HII regions imbedded in them may reflect the possibilty that the associations are relatively old compared to those of the LMC and NGC 6822. This fact may also explain the observation that the SMC associations, although the same size as those of the LMC, possess notably fewer supergiants (Hodge 1985a).

Table 4. HII Regions and Core Star Clusters in Associations

	LMC	SMC	NGC 6822	IC 1613
No. Associations	122	70	16	20
No. containing bright HII regions	96	22	10	7
Percent with bright HII regions	79	31	62	35
Percent bright HII regions not in associations	79	79	62	12
No. young star clusters in associations	14	21	0	4
Percent with core star clusters	11	30	0	20
Percent of young star clusters not in associations	91	70:	100	0

[a] With $M < -4.5$ for their brightest stars
[b] Several clusters included with unknown ages

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It is also of interest to note that, on the average, about 60% of the bright HII regions do not occur in stellar associations. IC 1613, with 12%, is an exception to this rule, but the general trend seems to indicate clearly that massive star formation in irregular galaxies can occur on a sufficiently small temporal or spatial scale that it need not involve a large complex, as represented by a stellar association.

Core clusters are fairly rare in stellar associations. The exact figures are difficult to obtain because of the difficulty of knowing whether coincidences are physical or accidental (a real problem for clusters, especially in the MC's, where clusters are extremely abundant). I have attempted to limit consideration to only very young clusters, those with brightest stars brighter than -4 in absolute blue magnitude, in order to avoid chance coincidences with the large numbers of older clusters. On the average, only 15% of the associations contain possible core clusters, without any correction made for chance superpositions. This implies that there will be no stable star concentration left at the position of the association after it disperses, in most cases.

For three of the galaxies, the overwhelming majority of young clusters are found outside of stellar associations. Does this mean that they formed as small-scale, dense objects without a large-scale star formation region around them? Conceivably each cluster once belonged to a giant gas cloud in which star formation went on at the 100pc scale level, and subsequent events have caused the surrounding, less dense group to disperse. Ages of the clusters in question, however, are on the order of 10-20 million years. To disperse in that time, a surrounding association would have to have had a high velocity dispersion. One might instead suggest that dense clusters can form in these galaxies independently of large-scale associations. The large number of isolated HII regions and lone O and B stars seem to substantiate this hypothesis.

2.1 The Mass Function of Young Clusters in HII Regions

In this brief section of the paper, I report on a somewhat related result of our study of the core clusters in giant HII regions. Measurement of the H-alpha luminosities of complete samples of HII region populations in several galaxies has now been complete and we find that the form of the luminosity function seems to be nearly universal. The universality of this shape implies a common cluster formation function (the exciting stars must be in the form of a cluster, because the models indicate that the brighter HII regions require hundreds of O and B stars). This somewhat surprising result seems to indicate that, whatever causes star formation to occur, the mass function of condensing regions is (or becomes) always the same. Can this really be true for all star-forming complexes, whether they are triggered by the passage of a density wave, started by the compression of gas from a supernova, or somehow otherwise involved in a GMC? The further detailed study of OB associations, star clusters, and populations of HII regions in different parts of galaxies and in galaxies of different types should eventually help answer this important question.

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Discussion : HODGE.

KAUFMAN :

1) Is the turnover in the M101 luminosity function just the effect of incompleteness?

2) Do your luminosity functions for the 3 galaxies shown include only giant HII regions?

3) How do you explain the high percentages of bright HII regions not in associations - are these just one or two O stars?

HODGE :

1) Yes.

2) They extend down to 3 orders of magnitude below the brigthest in the case of M101.

3) Yes, or a compact cluster.

ZINNECKER :

Have you made a comparison between your (universal) luminosity function with van den Bergh's cluster luminosity function (van den Bergh and Lafontaine 1985, PASP 96, 880) i.e. the frequency distribution of star clusters as a function of their integrated light?

HODGE :

No.

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