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Young massive star clusters in nearby spiral galaxies*

III. Correlations between cluster populations and host galaxy properties

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Abstract. We present an analysis of correlations between integrated properties of galaxies and their populations of young massive star clusters. Data for 21 nearby galaxies presented by Larsen & Richtler (1999) are used together with literature data for 10 additional galaxies, spanning a range in specific U-band cluster luminosity $T_L(U)$ from 0 to 15. We find that $T_L(U)$ correlates with several observable host galaxy parameters, in particular the ratio of Far-Infrared (FIR) to B-band flux and the surface brightness. Taking the FIR luminosity as an indicator of the star formation rate (SFR), it is found that $T_L(U)$ correlates very well with the SFR per unit area. A similar correlation is seen between $T_L(U)$ and the atomic hydrogen surface density. The cluster formation efficiency seems to depend on the SFR in a continuous way, rather than being related to any particularly violent mode of star formation. We discuss fundamental features of possible scenarios for cluster formation. One possibility is that the correlation between $T_L(U)$ and SFR is due to a common controlling parameter, most probably the high density of the ISM. Another scenario conceives a high $T_L(U)$ as resulting from the energy input from many massive stars in case of a high SFR.

Key words: galaxies: general – galaxies: spiral – galaxies: starburst – galaxies: star clusters – stars: formation

1. Introduction

A puzzling problem is to understand why different galaxies have such widely different young cluster populations as is observed. The star clusters in the Milky Way clearly do not constitute a representative cluster sample, as is evident already from a superficial comparison with our nearest extragalactic neighbours, the Magellanic Clouds. It was noted early on that the Clouds, in particular the LMC, contain a number of very massive, young clusters that do not have any counterparts in our own galaxy (van den Bergh 1991; Richtler 1993). Many recent studies have shown the presence of such "Young Massive Clusters" (YMCs) also in a number of mergers and starburst galaxies (see e.g. list in Harris 1999) and it is clear that the occurrence of such objects is often associated with violent star formation, leading to the formation of a large number of YMCs within a few times 10^8 years or so. This does not explain, however, why other galaxies like the Magellanic Clouds are able to maintain the formation of YMCs over a much longer time span. YMCs with a broad age distribution have also been found in a few other galaxies, e.g. the blue compact galaxy ESO 338-IG04 (Östlin et al. 1998), and in the Sc spirals M101 and M33 (Bresolin et al. 1996; Christian & Schommer 1988).

In Larsen & Richtler (1999, hereafter Paper1) we carried out a systematic search for YMCs in 21 nearby non-interacting, mildly inclined galaxies, and identified rich populations of YMCs in about a quarter of the galaxies in the sample. Within the range of Hubble types surveyed (Sbc – Irr), no correlation was found between the morphological type of the galaxies and their contents of YMCs. In the present paper we show that the richness of the cluster systems is indeed well correlated with certain other properties of the host galaxies, indicative of a dependence on the star formation rate. We extend our sample relative to Paper1 by also including literature data for a variety of different star-forming galaxies, and show that the correlations inferred from our sample are further strengthened when the additional data are included. Hence, it seems that starburst galaxies with their very rich populations of YMCs represent only an extreme manifestation of the cluster formation process, while the conditions that allow YMCs to be formed can be present also in normal galaxies.

2. Basic definitions

The data reduction procedure and identification of YMCs have been discussed elsewhere (Paper1; Larsen 1999) and we shall not repeat the details here. We just mention that the clusters were

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identified using broad-band photometry, applying a colour criterion of $B-V < 0.45$ (mainly in order to exclude foreground stars) and an absolute visual magnitude limit of $M_V = -8.5$ for objects with $U-B >= -0.4$ and $M_V = -9.5$ for $U-B < -0.4$. The $B-V$ colour cut-off corresponds to an age of about 500 Myr (Girardi et al. 1995) and the lower mass limit is of the order of 3×10^4 $M_\odot$, assuming a Salpeter IMF extending down to 0.1 $M_\odot$ (Bruzual & Charlot 1993). "Fuzzy" objects and HII regions were excluded by a combination of visual inspection and Hα photometry (see Larsen 1999 for details). Hence, we define an object that satisfies these criteria to be a Young Massive Cluster.

Following the definition of the "specific frequency" S_N for old globular cluster systems (Harris & van den Bergh 1981), we defined an equivalent quantity for young clusters in Paper1:

$$T_N = N \times 10^{0.4\times(M_B+15)} \quad (1)$$

Here N is the total number of YMCs in a galaxy, and M_B is the absolute B magnitude of the galaxy. T_N is then a measure of the number of clusters, normalised to the luminosity of the host galaxy. There are, however, several problems in defining a "specific frequency" for young clusters. Since old globular cluster systems have a log-normal like luminosity function (LF), the total number of old clusters belonging to a given galaxy is a well-defined quantity, and can be estimated with good accuracy even if the least luminous clusters cannot be observed directly. Young clusters, on the other hand, usually exhibit a power-law luminosity function of the form

$$N(L)dL \propto L^{-\alpha}dL \quad (2)$$

with an increasing number of clusters at fainter magnitudes. Hence, T_N depends sensitively on the definition one adopts for a YMC, and it is difficult to compare literature data unless the exact selection parameters are known. Moreover, incompleteness effects and errors in the distance modulus always affect the number of clusters in the faintest magnitude bins most severely, and this leads to large uncertainties in T_N.

Another possibility is to consider the total *luminosity* of the cluster system compared to that of the host galaxy. This approach has the advantage of being independent of the distance modulus and interstellar absorption. Following Harris (1991), we define the *specific luminosity*

$$T_L = 100 \cdot \frac{L_{\rm Clusters}}{L_{\rm Galaxy}} \quad (3)$$

where $L_{\rm Clusters}$ and $L_{\rm Galaxy}$ are the total luminosities of the cluster system and of the host galaxy, respectively. It makes no difference if the absolute or apparent luminosities are used in Eq. (3), and corrections for reddening only play a role through the selection criteria for identification of YMCs.

As long as the exponent α in the LF (Eq. (2)) is less than 2, most of the light originates from the *bright* end of the LF. A typical value is $\alpha \approx 1.7$ (Elmegreen & Efremov 1997; Harris & Pudritz 1994), although slopes of $\alpha \sim 2$ have also been reported (e.g. for NGC 3921, Schweizer et al. 1996). In any case, T_L is much less sensitive to incompleteness effects at the lower end of the LF than the specific frequency.

We remark that the brighter end of the LF of old globular cluster systems is also well described by a power-law distribution with an exponent similar to that observed for the young cluster populations. This has stimulated attempts to create a universal theoretical description of the formation of old globular clusters in the halo of the Milky Way and elsewhere as well as the present-day formation of young star clusters (Elmegreen & Efremov 1997; McLaughlin & Pudritz 1996).

3. The data

The basic data related to the cluster systems considered in this paper are given in Table 1. The number of YMCs N and corresponding specific frequencies T_N are taken from Paper1, and in addition we now also list the absolute V-band magnitude of the brightest cluster in each galaxy V_m and the U- and V-band specific luminosities $T_L(U)$ and $T_L(V)$. The T_N values in Tables 1 have not been corrected for completeness effects, which can be quite significant in particular for the more distant galaxies like NGC 2997 (Larsen 1999). However, we are not going to refer much to T_N in this paper for the reasons given in Sect. 2 but will instead use specific luminosities. We remark that the often very luminous clusters found near the centres of certain "hot spot" galaxies (e.g. NGC 2997, Maoz et al. 1996 and NGC 5236, Heap et al. 1993) have not been considered in this study, but only clusters in the disks.

In addition to the Paper1 sample, we also include literature data for a number of (mostly) starburst and merger galaxies (see references in the caption to Table 1). Since the clusters in these galaxies were not identified according to a homogeneous set of criteria we do not list T_N values, except for the LMC where the published photometry reaches below $M_V = -8.5$. The photometry published for clusters in the remaining galaxies does not go as deep as ours but as we have argued above, the total integrated magnitude of a cluster system is normally dominated by the brighter clusters, so we have calculated $T_L(U)$ and $T_L(V)$ values for all galaxies based on the available data. Not all studies list UBV colours, but these have been estimated from the published cluster ages and the Girardi et al. (1995) "S"-sequence.

Table 2 lists integrated data for the galaxies, mostly taken from the RC3 catalogue, with the exception of the $U-B$ colour which has in a few cases been derived from our own CCD data. T is the revised Hubble type, m_{25} is the B-band surface brightness, m_{21} is a magnitude based on the 21 cm flux (see RC3 for details) and $m_{\rm FIR}$ is a FIR magnitude based on the IRAS fluxes at 60μ and 100μ. $\log D_0$ is the logarithm of the face-on diameter of the galaxy, and the last two columns in Table 2 list the area-normalised star formation rate $\Sigma_{\rm SFR}$ and the HI surface density $\Sigma_{\rm HI}$ derived from $m_{\rm FIR}$ and m_{21} (see Sect. 4.1). The RC3 as well as the IRAS data were retrieved through the NASA/IPAC Extragalactic Database.

Table 1. Basic properties for the galaxies discussed in this paper. The data for galaxies labeled [1] are taken from the literature (NGC 1275: Carlson et al. 1998; NGC 1569 / NGC 1705: O'Connell et al. 1994; NGC 1741: Johnson et al. 1999; NGC 3256: Zepf et al. 1999; NGC 3921: Schweizer et al. 1996; NGC 5253: Gorjian et al. 1996; NGC 7252: Miller et al. 1997; LMC: Bica et al. 1996), while the remaining data are from Paper1. The column labeled m-M is the distance modulus (see Paper1 for references), N is the number of YMCs, V_m is the V magnitude of the brightest cluster, m_B is the integrated B magnitude of the galaxy, A_B is the galactic foreground reddening, and T_N is the "specific frequency". The two last columns, $T_L(U)$ and $T_L(V)$ give the specific luminosities of the cluster systems in the U and V bands.

Name	m-M	N	V_m	m_B	A_B	T_N	$T_L(U)$	$T_L(V)$
				Paper1 sample				
NGC 45	28.4	2	-9.9	11.32	0.06	0.28	0.24	0.11
NGC 247	27.0	3	-10.2	9.67	0.07	0.33	0.30	0.14
NGC 300	26.7	3	-9.9	8.72	0.02	0.18	0.13	0.05
NGC 628	29.6	39	-11.3	9.95	0.13	0.48	0.81	0.29
NGC 1156	29.5	22	-11.1	12.32	0.71	1.61	1.67	1.08
NGC 1313	28.2	46	-12.1	9.20	0.04	1.12	1.47	0.80
NGC 1493	30.4	0	-	11.78	0.00	0.00	0.00	0.00
NGC 2403	27.5	14	-9.9	8.93	0.17	0.45	0.24	0.14
NGC 2835	28.9	12	-10.9	11.01	0.44	0.57	0.55	0.30
NGC 2997	29.9	34	-12.9	10.06	0.54	0.25	1.45	0.99
NGC 3184	29.5	13	-10.6	10.36	0.00	0.28	0.23	0.10
NGC 3621	29.1	51	-11.9	10.18	0.42	0.93	1.33	0.65
NGC 4395	28.1	2	-9.1	10.64	0.01	0.21	0.07	0.05
NGC 5204	28.4	7	-9.6	11.73	0.00	1.49	0.39	0.38
NGC 5236	27.9	153	-11.7	8.20	0.15	1.77	2.33	0.90
NGC 5585	29.2	7	-10.8	11.20	0.00	0.44	0.50	0.31
NGC 6744	28.5	18	-11.0	9.14	0.15	0.28	0.51	0.14
NGC 6946	28.7	107	-13.0	9.61	1.73	0.56	1.44	0.58
NGC 7424	30.5	9	-11.4	10.96	0.00	0.14	0.38	0.19
NGC 7741	30.8	0	-	11.84	0.15	0.00	0.00	0.00
NGC 7793	27.6	20	-10.4	9.63	0.02	1.21	1.15	0.51
				Starbursts / mergers				
NGC 1275[1]	34.2	-	-14	12.64	0.75	-	2.63	1.04
NGC 1569[1]	27.0	-	-13.9	11.86	2.18	-	11.3	5.60
NGC 1705[1]	28.5	-	-13.7	12.77	0.19	-	13.9	10.1
NGC 1741[1]	33.5	-	-15	13.30	0.25	-	~ 10	~ 5
NGC 3256[1]	32.8	-	-15	12.15	0.59	-	~ 15	~ 15
NGC 3921[1]	36.0	-	-14	13.06	0.16	-	0.24	0.11
NGC 5253[1]	28.0	-	-11.1	10.87	0.20	-	1.41	0.51
NGC 7252[1]	34.9	-	-17.0	12.06	0.05	-	2.43	1.10
				Other galaxies				
IC 1613[1]	24.3	-	-	9.88	0.02	0	0	0
LMC[1]	18.5	8	-9.4	0.91	0.27	0.57	0.12	0.11

4. Correlations between host galaxy parameters and cluster systems

In this section we discuss correlations between various host galaxy properties and the specific U-band luminosity $T_L(U)$. We use $T_L(U)$ because the U-band most cleanly samples the *young* stellar populations in a galaxy, and therefore provides the purest measure of *current* cluster formation activity.

4.1. The Paper1 sample

First, we consider only the galaxies studied in Paper1. In Paper1 we showed that there is no evident correlation between T_N and the Hubble type of the host galaxy. In Fig. 1 we show $T_L(U)$ instead of T_N as a function of the Hubble type, but this does not change the conclusion - there is no clear trend in $T_L(U)$ as a function of Hubble type either. The earliest type represented in our sample is Sbc (type 4.0 in the RC3 terminology), and the latest is Im (type 10.0 in RC3). Independently of morphological type, we find a range from galaxies with practically no YMCs to very rich cluster systems in our sample, so even if YMCs might be systematically absent in galaxies of even earlier types, the presence of YMCs cannot be entirely related to morphology. Furthermore, some of the galaxies with high $T_L(U)$ values are grand-design spirals (NGC 5236, NGC 2997), other grand-design spirals are relatively cluster-poor (e.g. NGC 3184,

Table 2. Integrated properties for the galaxies, mostly taken from the RC3 catalogue. T is the revised Hubble type, coded as in RC3. m_{25} is the average B-band surface brightness within an ellipse corresponding to 25 mag / square arc second, and $\log D_0$ is the face-on diameter corrected for galactic extinction. m_{21} is a magnitude derived from the 21-cm flux. $m_{\rm FIR}$ is a Far-Infrared magnitude based on the IRAS 60μ and 100μ fluxes. The IRAS 60 and 100μ fluxes are in units of Jy. $\Sigma_{\rm SFR}$ (given as $10^3 \times$ M$_\odot$ yr^{-1} kpc^{-2}) and $\Sigma_{\rm HI}$ (in units of M$_\odot$ pc^{-2}) are derived from $m_{\rm FIR}$ and m_{21} as described in Sect. 4. [1]: FIR data from Rice et al. (1988) [2]: FIR data from Soifer et al. (1989) [3]: FIR data from IRAS Faint Source Catalog (Moshir et al. 1990) [4]: B-V and U-B from RC3 [5]: U-B measured by us. See the text for further explanation.

Name	T	U-B	B-V	m_{25}	m_{21}	$m_{\rm FIR}$	$f(60\mu)$	$f(100\mu)$	$\log D_0$	$\Sigma_{\rm SFR}\times 10^3$	$\Sigma_{\rm HI}$
Paper1 sample											
NGC 45[1,4]	8.0	−0.05	0.71	15.39	11.43	12.34	1.62	4.99	1.93	0.23	12.1
NGC 247[1,5]	7.0	−0.10	0.56	14.95	10.27	10.55	7.93	27.3	2.34	0.18	5.3
NGC 300[1,4]	7.0	0.11	0.59	14.91	9.15	9.43	23.1	74.4	2.35	0.49	14.3
NGC 628[1,5]	5.0	0.00	0.56	14.79	10.77	9.56	20.9	65.6	2.03	1.88	14.0
NGC 1156[3,4]	10.0	−0.19	0.58	14.43	12.72	11.28	5.71	9.20	1.58	3.07	18.4
NGC 1313[1,4]	7.0	−0.24	0.49	13.52	10.54	9.08	36.0	92.0	1.96	4.04	23.9
NGC 1493[3,5]	6.0	−0.06	0.52	14.27	13.38	11.89	2.33	8.19	1.54	2.10	12.1
NGC 2403[1,5]	6.0	−0.10	0.47	14.88	9.58	8.63	51.6	148	2.36	0.97	9.2
NGC 2835[3,4]	5.0	−0.12	0.49	14.51	11.98	11.44	3.25	16.0	1.86	0.73	10.0
NGC 2997[1,5]	5.0	0.10	0.00	14.33	11.50	9.18	32.3	85.1	2.00	3.07	8.2
NGC 3184[2,4]	6.0	−0.03	0.58	14.49	12.18	10.46	8.92	29.0	1.87	1.72	8.0
NGC 3621[1,4]	7.0	−0.08	0.62	14.90	10.20	9.19	29.6	90.1	2.13	1.67	14.9
NGC 4395[1,5]	9.0	0.10	0.46	15.86	11.11	11.31	4.21	12.9	2.12	0.25	6.8
NGC 5204[3,4]	9.0	−0.33	0.41	14.55	12.35	12.10	2.32	5.35	1.70	0.83	14.9
NGC 5236[1,4]	5.0	0.03	0.66	13.48	9.60	6.95	266	639	2.12	13.8	27.2
NGC 5585[3,4]	7.0	−0.22	0.46	14.35	12.10	12.82	0.99	3.65	1.76	0.33	14.3
NGC 6744[1,5]	4.0	0.13	0.75	15.00	9.55	9.36	22.2	85.8	2.31	0.62	11.9
NGC 6946[1,5]	6.0	0.20	0.80	14.58	10.09	7.64	137	344	2.22	4.60	10.9
NGC 7424[1,3]	6.0	−0.15	0.48	15.52	11.27	12.36	1.22	7.83	1.98	0.18	11.1
NGC 7741[3,4]	6.0	−0.14	0.53	14.45	13.15	12.00	2.27	6.98	1.65	1.14	9.0
NGC 7793[3,4]	7.0	−0.09	0.54	13.91	11.21	9.68	19.6	56.3	1.98	2.12	11.7
Starbursts / mergers											
NGC 1275[3,4]	-	0.07	0.76	-	-	11.24	7.15	6.98	1.41	6.96	-
NGC 1569[3,4]	10.0	−0.14	0.83	13.71	12.43	9.16	45.4	47.3	1.76	9.43	10.5
NGC 1705[3,4]	−3.0	−0.45	0.38	13.70	-	13.16	0.87	1.82	1.28	2.16	-
NGC 1741[3,−]	10	-	-	-	14.03	11.73	3.92	5.84	1.18	12.8	34.8
NGC 3256[3,4]	-	−0.08	0.64	-	-	8.34	88.3	115	1.63	36.5	-
NGC 3921[3,4]	2	0.25	0.68	14.04	15.51	13.29	0.83	0.0	1.32	1.59	4.7
NGC 5253[3,4]	10	−0.24	0.43	13.18	13.00	9.64	30.5	29.4	1.72	7.29	7.5
NGC 7252[3,4]	-	0.20	0.66	13.83	-	11.60	3.98	7.02	1.28	9.09	-
Other galaxies											
IC 1613[3,4]	10.0	-	0.67	15.68	10.73	12.58	0.98	2.67	2.22	0.05	6.1
LMC[2,4]	9.0	0.00	0.51	14.64	2.75	0.74	82900	185000	3.84	1.51	5.4

NGC 7424), while the flocculent galaxy NGC 7793 also has a high $T_L(U)$ value, so the presence of a spiral density wave is apparently not a discriminating factor either. No galaxies of types Sa and Sb were included in our sample, primarily because of a general lack of sufficiently nearby galaxies of these types (see Paper1 for a more detailed discussion of the selection criteria).

We therefore continue to look for other host galaxy parameters that could correlate with $T_L(U)$. Even for the relatively nearby galaxies in our sample, it is not an easy task to find homogeneous sets of observations of integrated properties that allow a comparison of all galaxies, mainly because the most complete data exist for the northern hemisphere while many of our galaxies are in the southern sky. For example, existing CO surveys have included only few of our galaxies (Elfhag et al. 1996; Young et al. 1995), We are therefore largely limited to discussing optical data, HI data and Far-Infrared data from the IRAS survey.

In order to reach independence of distance and absolute galaxy luminosity, we normalise the FIR flux to the B-band magnitude of a galaxy by using the "FIR – B" index $m_{\rm FIR-B}$ = $m({\rm FIR}) - m(B)$.

Fig. 2 shows $T_L(U)$ as a function of various integrated host galaxy parameters: The $m_{\rm FIR-B}$ index, the B-band surface brightness, the integrated $U-B$ colour and the IRAS $f(60\mu)/f(100\mu)$ flux ratio. The $U-B$ and the B band data have been corrected for Galactic foreground extinction (as given in Table 1), but not for internal absorption in the galaxies. The latter correction would move the points around slightly, but nei-

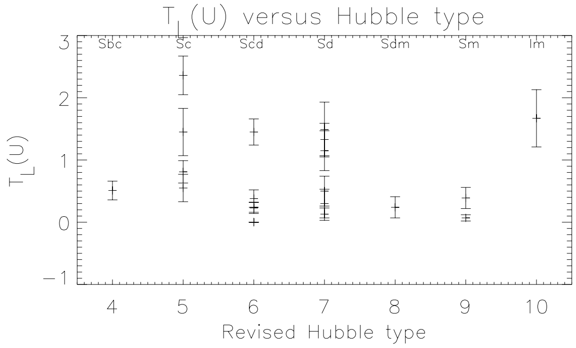

Fig. 1. The specific U-band luminosity $T_L(U)$ as a function of revised Hubble type.

ther reduce the scatter significantly nor change the conclusions. We have therefore avoided to apply this anyway quite uncertain correction.

From Fig. 2 we first note the striking correlations between $T_L(U)$ and $m_{\rm FIR-B}$ and the surface brightness m_{25}. This is of great interest because both these parameters can be taken as indicators for the star formation rate in the host galaxy (Kennicutt 1998b). We stress that, because we are operating with specific luminosities this is not just a sampling effect - Fig. 2 shows that the *relative* amount of light that originates from clusters, relative to the general field population, increases as a function of m_{25} and $m_{\rm FIR-B}$. A similar result regarding surface brightness and the fraction of UV light in clusters was also noted by Meurer et al. (1995) for a number of starburst galaxies, but over a smaller range in surface brightness.

No correlation between $T_L(U)$ and the $U-B$ colour is seen, but this may not be quite as surprising since the $U-B$ colour index has a less clear physical interpretation and is, in any case, severely affected by absorption effects.

There is also some correlation between $T_L(U)$ and the $f(60\mu)/f(100\mu)$ flux ratio, which measures the dust temperature and can therefore be taken as a measure of the intensity of the radiation field in a galaxy (Soifer et al. 1989). The radiation field might play a role for the formation of bound clusters by keeping proto-cluster clouds in thermal equilibrium and delaying thermal instabilities, thereby preventing star formation from setting in too early and disrupting the clouds (Murray & Lin 1992). However, a high $f(60\mu)/f(100\mu)$ ratio follows naturally from a high global FIR luminosity (Soifer et al. 1989), and the correlation between $T_L(U)$ and $f(60\mu)/f(100\mu)$ does not by itself provide any evidence that the radiation field is a dominating factor in determining whether YMCs can form in a galaxy. Thermal instabilities might be prevented in other ways, particularly by magnetic pressure support (see e.g. Mouschovias 1991).

The FIR luminosity itself is an indicator of the current SFR through heating of dust grains by young stars (Kennicutt 1998b). The uncertainties on the exact relation are, however, considerable and a single calibration is unlikely to apply to all galaxies over a wide range in morphological type. This is mainly because older stellar populations also contribute to dust heating, and the ratio of current to past star formation varies along the Hubble sequence. Of course, the FIR luminosity also suffers the same IMF dependence as any other SFR indicator. Here we will use the calibration by Buat & Xu (1996) which is claimed to be reasonably accurate for galaxies later than type Sab, noting that it may overestimate the SFR in starburst galaxies by about a factor of 2 (Kennicutt 1998b):

$$\mathrm{SFR}(\mathrm{M}_\odot\,\mathrm{yr}^{-1}) = 8^{+8}_{-3} \times 10^{-37} L_{\rm FIR} \quad (4)$$

where $L_{\rm FIR}$ is the far-infrared luminosity (in J/sec). We obtain $L_{\rm FIR}$ from the $m_{\rm FIR}$ magnitudes in Table 2 and the distance moduli, using the relation

$$m_{\rm FIR} = -20 - 2.5\log(S_{\rm FIR}) \quad (5)$$

with $S_{\rm FIR}$ being the far-infrared flux density, based on IRAS 60μ and 100μ flux densities (see RC3 for details). From (4) and (5),

$$\mathrm{SFR}(\mathrm{M}_\odot\,\mathrm{yr}^{-1}) = 0.0096^{+0.0096}_{-0.0036} D^2 10^{-0.4\times(m_{\rm FIR}+20)} \quad (6)$$

where D is the distance in pc.

However, the global SFR is not likely to tell us much because of the large range in galaxy size and total luminosity. We therefore normalise the SFR to the area of each galaxy based on the *optical* diameter (using $\log D_0$ from RC3), defining $\Sigma_{\rm SFR}$ as the SFR per kpc^2:

$$\Sigma_{\rm SFR}(\mathrm{M}_\odot\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2}) = 144000 \times 10^{-0.4\,m_{\rm FIR} - 2\,\log D_0} \quad (7)$$

It might seem more reasonable to normalise to some area traced by the FIR luminosity, but the resolution of the IRAS data does not allow this in all cases. Another possibility would be to normalise to the optical luminosity rather than the area, but in this way some information might be lost because the optical luminosity is also correlated with the SFR, and because of the contribution from the bulge/halo components.

Fig. 3 displays $T_L(U)$ as a function of the host galaxy SFR according to Eq. 4 (top panel) and $\Sigma_{\rm SFR}$ (bottom panel). A correlation is evident in both cases, but the scatter clearly decreases when plotting $T_L(U)$ as a function of $\Sigma_{\rm SFR}$ rather than the global SFR.

The SFR in galaxies is generally assumed to be proportional to some power of the gas density (Schmidt 1959), and it has recently been shown that the Schmidt law can also be formulated in terms of surface densities with $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$ (Kennicutt 1998a). It would therefore be of interest to look for a corresponding relation between $T_L(U)$ and the gas surface density ($\Sigma_{\rm gas}$). Lacking a homogeneous set of data on total gas masses, we will here consider the atomic hydrogen mass $M_{\rm HI}$ which may be derived from the 21-cm flux density (Roberts 1975):

$$M_{\rm HI}(\mathrm{M}_\odot) \;=\; 2.356 \times 10^{19} D^2 \int_{-\infty}^{\infty} S_\nu dV_r \quad (8)$$

where D is the distance in pc and $\int_{-\infty}^{\infty} S_\nu dV_r$ is the flux density integrated over the line profile. Here S_ν is in units of

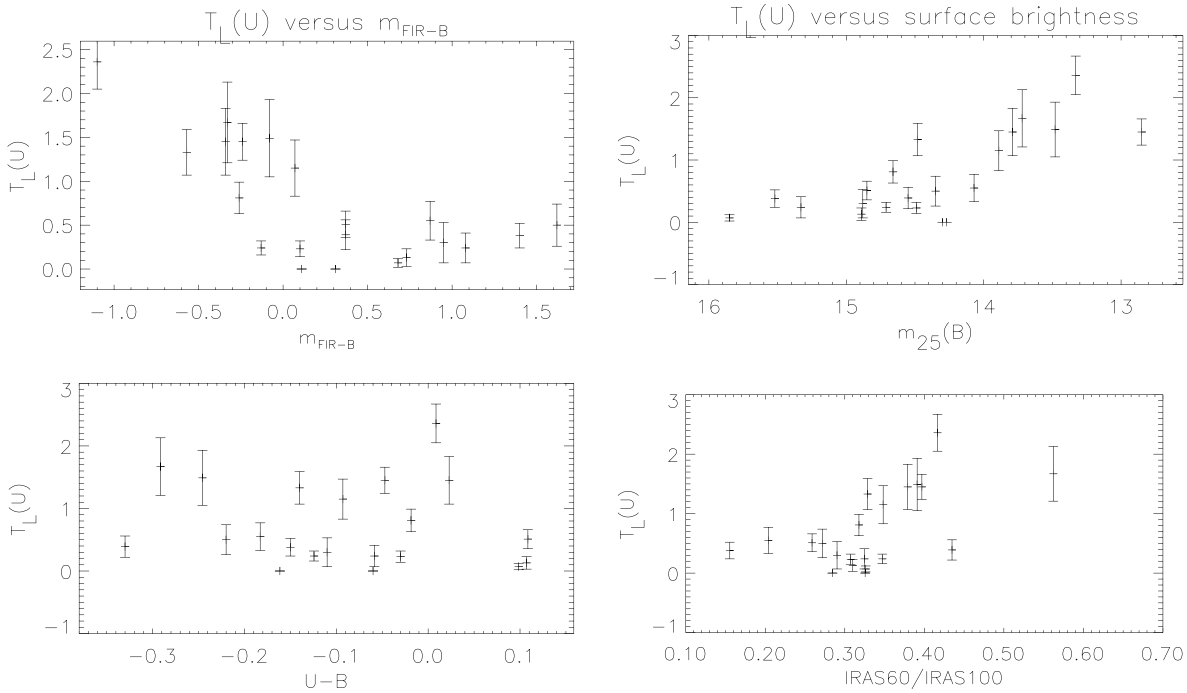

Fig. 2. The correlation between various integrated galaxy properties and $T_L(U)$.

W m^{-2} Hz^{-1} and V_r is in km/sec. The total integrated flux density $S_{\rm HI}$ can be obtained from the m_{21} values given in Table 2 using the expression

$$m_{21} \;=\; 21.6 - 2.5\log(S_{\rm HI}) \tag{9}$$

with $S_{\rm HI}$ in units of 10^{-24} W m^{-2} (RC3). Combining (8) and (9) we obtain

$$M_{\rm HI}({\rm M}_\odot) \;=\; 4.97\times10^{-9}\,D^2\,10^{0.4\times(21.6-m_{21})} \tag{10}$$

We ignore corrections for self-absorption since most of the galaxies are seen nearly face-on. No homogeneous set of data is available on the HI sizes so we use again the optical sizes to derive the HI surface density $\Sigma_{\rm HI}$:

$$\Sigma_{\rm HI}({\rm M}_\odot\,{\rm pc}^{-2}) = 3.26\times10^9\;\times\;10^{-0.4\,m_{21}-2\,\log D_0} \tag{11}$$

This is somewhat problematic since HI disks often extend beyond the optical disk size. However, as long as the same procedure is applied to all galaxies in the sample the results should at least be comparable, although we stress that the absolute values of the HI surface density ($\Sigma_{\rm HI}$) should probably not be given too much weight. The uncertainties on m_{21} quoted in RC3 are typically of the order of 0.1 mag or about 10%, so errors in $\Sigma_{\rm HI}$ are more likely to arise from the area normalisation because of differences in the scale length of the HI disks relative to the optical sizes.

Fig. 4 shows $T_L(U)$ vs. $\Sigma_{\rm HI}$. The plot clearly shows a correlation, although not as nice as between $T_L(U)$ and $\Sigma_{\rm SFR}$. This may not be surprising, considering the relatively small range in $\Sigma_{\rm HI}$ compared to $\Sigma_{\rm SFR}$, which makes the result much more sensitive to errors in the area normalisation. Also, $\Sigma_{\rm SFR}$ (and thus $T_L(U)$) is expected to depend on the *total* gas surface density $\Sigma_{\rm gas}$ of which $\Sigma_{\rm HI}$ constitutes only a fraction, which is not necessarily the same from galaxy to galaxy. However, we note that Kennicutt (1998a) finds that $\Sigma_{\rm SFR}$ correlates nearly

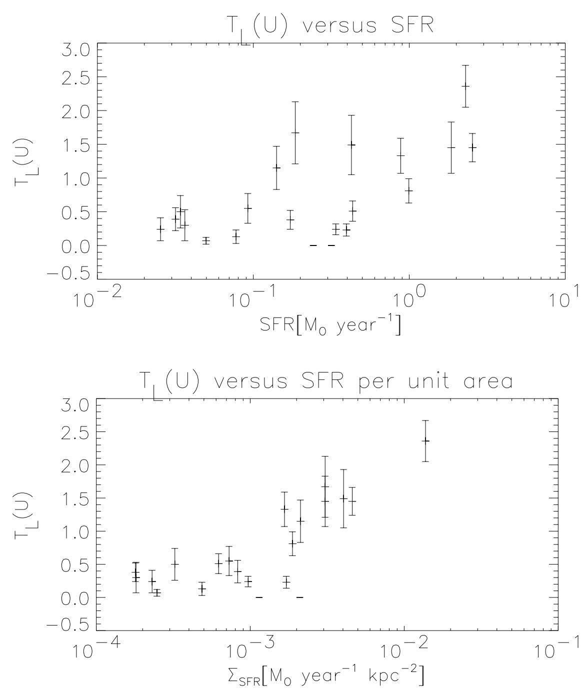

Fig. 3. $T_L(U)$ vs. Star Formation Rate as derived from the FIR luminosities for galaxies in the Paper1 sample. The upper panel shows $T_L(U)$ as a function of the global SFR, while the lower panel shows $T_L(U)$ vs. $\Sigma_{\rm SFR}$, the SFR per unit area.

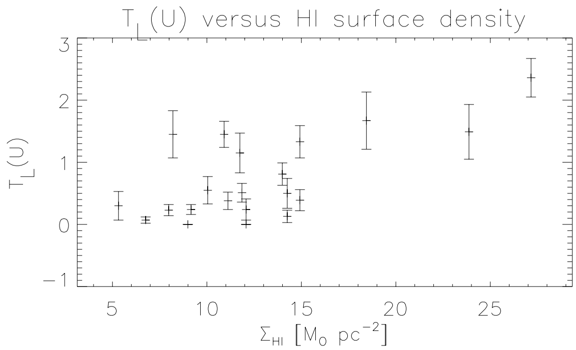

Fig. 4. $T_L(U)$ as a function of the HI surface density $\Sigma_{\rm HI}$.

as well with $\Sigma_{\rm HI}$ as with $\Sigma_{\rm gas}$ though the physical interpretation of the correlation between $\Sigma_{\rm SFR}$ and $\Sigma_{\rm HI}$ is not entirely clear, because of the complicated interplay between the different phases of the interstellar medium and young stars. Somewhat surprisingly, Kennicutt (1998a) finds no significant correlation between $\Sigma_{\rm SFR}$ and the surface density of *molecular* gas.

4.2. Including literature data

It is of interest to see if the $T_L(U)$ vs. $\Sigma_{\rm SFR}$ relation holds also when including other types of galaxies than those from Paper1. In particular, a comparison with the many studies of starburst galaxies that exist in the literature is tempting. In Tables 1 and 2 we have included literature data for a number of different galaxies, briefly discussed in the following. These galaxies have been chosen mainly so that a number of different cluster-forming environments are represented, with the additional criterion that some photometry was available for individual clusters so that (at least approximate) $T_L(U)$ values could be estimated.

We first give a few comments on each galaxy:

NGC 5253: A dwarf galaxy, located at a projected distance of about 130 kpc from NGC 5236. It is possible that the starburst currently going on in this galaxy could have been triggered by interaction with its larger neighbour, though no obvious indications of direct interaction between the two galaxies are evident. Several massive clusters exist in NGC 5253, but the absolute magnitudes are somewhat uncertain because of heavy extinction (Gorjian 1996).

NGC 1569 and NGC 1705: These were two of the first galaxies in which the existence of "super star clusters" was suspected (Arp & Sandage 1985). Their $T_L(U)$ values are dominated by 2 bright clusters in NGC 1569 and by a single cluster in NGC 1705, each with $M_V \approx -13$. Both galaxies are gas-rich amorphous dwarfs, but none of them have high enough star formation rates to qualify as real starburst galaxies (O'Connell et al. 1994) although NGC 1569 may be in a post-starburst phase (Waller 1991).

NGC 1741: A merger/starburst galaxy with a large number of very young (~ 10 Myr) YMCs. Johnson et al. (1999) found that YMCs contribute with 5.1% of the B-band luminosity in NGC 1741, and since the YMCs are generally bluer than the host galaxy we have crudely adopted $T_L(U) \sim 10$ for Table 1.

NGC 1275: This is the central galaxy in the Perseus cluster. It is sitting at the centre of a cooling flow, and exhibits a number of structural peculiarities (Nørgaard-Nielsen et al. 1993). Most recently, the cluster system in NGC 1275 was studied by Carlson et al. (1998) who identified a population of 1180 YMCs. It has been proposed that the clusters could have condensed out of the cooling flow, but it seems more likely that they are due to a merger event (Holtzman et al. 1992).

NGC 3256: This is one of the classical recent merger galaxies. Zepf et al. (1999) identified more than 1000 YMCs on HST / WFPC2 images, and estimated that the clusters contribute with about 15–20% of the total B-band luminosity in the starburst region. Thus, we adopt $T_L(U)$ = 15.

NGC 3921: NGC 3921 is the remnant of two disk galaxies which merged 0.7±0.3 Gyr ago, and contains about 100 YMC candidates with $V - I$ colours consistent with this age (Schweizer et al. 1996). We have calculated $T_L(U)$ using the objects classified as types 1 or 2 by Schweizer et al. (1996).

NGC 7252: Another famous example of a merger galaxy, although dynamically more evolved than NGC 3256 and the Antennae. The merger age has been estimated to be about 1 Gyr (Schweizer 1982), and the 140 YMCs that have been identified in the galaxy have colours roughly compatible with this age (Whitmore et al. 1993; Miller et al. 1997).

IC 1613: IC 1613 stands out by containing very few star clusters at all, even when counting "normal" open clusters (van den Bergh 1979). Indeed, it has the lowest star formation rate among all the galaxies discussed in this paper and thus fits nicely into the $T_L(U)$ vs. SFR relation.

The conclusion that $\Sigma_{\rm SFR}$ may be one of the dominating parameters in determining the properties of the young cluster systems in galaxies is further strengthened by including the literature data for a variety of star forming environments. Fig. 5 shows $T_L(U)$ as a function of the global SFR and $\Sigma_{\rm SFR}$ once again, but now with all galaxies in Table 1 included. $T_L(U)$ now ranges from 0 – 15, and the galaxies span 5 decades in global SFR. Like in Fig. 3, $T_L(U)$ correlates significantly better with $\Sigma_{\rm SFR}$ than with the global SFR. The two dwarf galaxies NGC 1569 and NGC 1705, especially the latter, deviate somewhat from the general pattern, but because the cluster light in both these galaxies is dominated by only a few bright clusters, the statistical significance of their high $T_L(U)$ values is

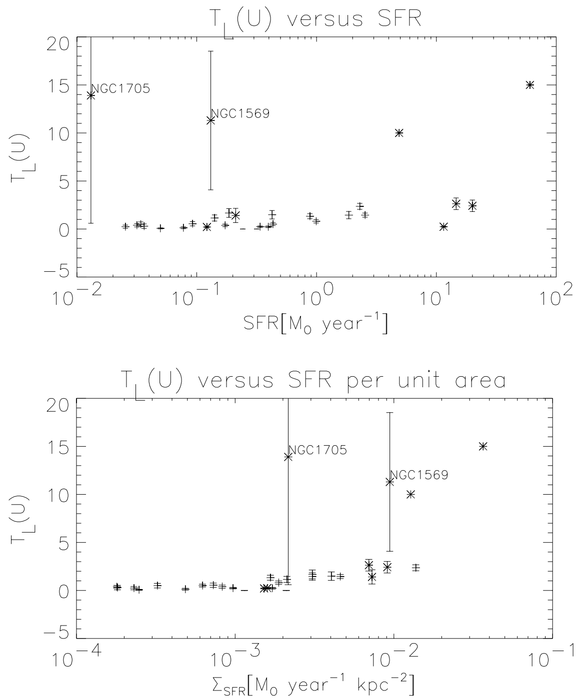

Fig. 5. $T_L(U)$ vs. Star Formation Rate and $\Sigma_{\rm SFR}$ as derived from the FIR luminosities for all galaxies in Table 1. Data from Paper1 are shown with $+$ markers while literature data are plotted with $*$ markers. See caption to Fig. 3 for further details.

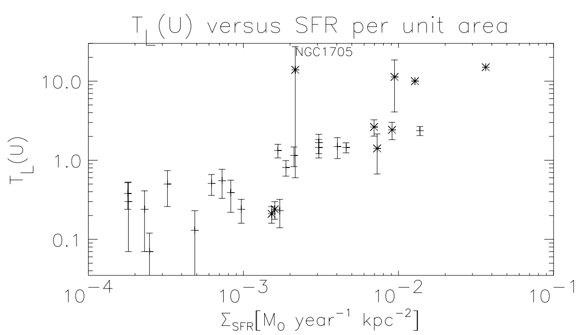

Fig. 6. Same as Fig. 5, lower panel, but with logarithmic y-axis. Galaxies with $T_L(U) = 0$ have arbitrarily been assigned $T_L(U) = 10^{-3}$.

low. Furthermore, the area normalisation is obviously uncertain and could easily shift the data points horizontally in the diagram by large amounts. The data presented here are compatible with a linear relation between $\Sigma_{\rm SFR}$ and $T_L(U)$, though a least-squares fit formally yields a power-law dependence of the form $T_L(U) \sim \Sigma_{\rm SFR}{}^{0.87 \pm 0.15}$. This is seen somewhat more clearly on a double-logarithmic plot (Fig. 6).

The $T_L(U)$ vs. $\Sigma_{\rm HI}$ diagram for all galaxies with 21 cm data in RC3 is shown in Fig. 7. Note that m_{21} data are lacking for many of the starburst and merger galaxies in Table 2. Thus, the only galaxies in Fig. 7 with a significantly higher $T_L(U)$ value than those from the Paper1 sample are NGC 1569 and NGC 1741. Again we see the poor fit of NGC 1569 into an otherwise quite good correlation, while NGC 1741 is located to the far right in the diagram, as expected from its high $T_L(U)$ value.

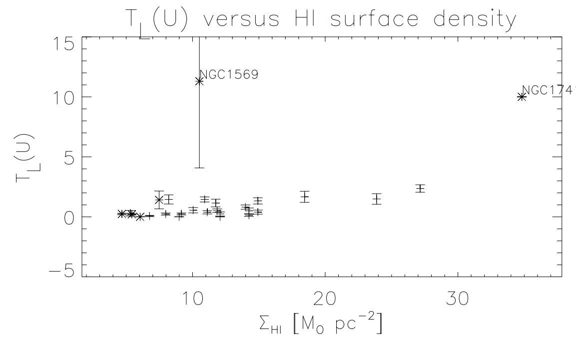

Fig. 7. $T_L(U)$ as a function of neutral hydrogen surface density $\Sigma_{\rm HI}$ for all galaxies with 21-cm data.

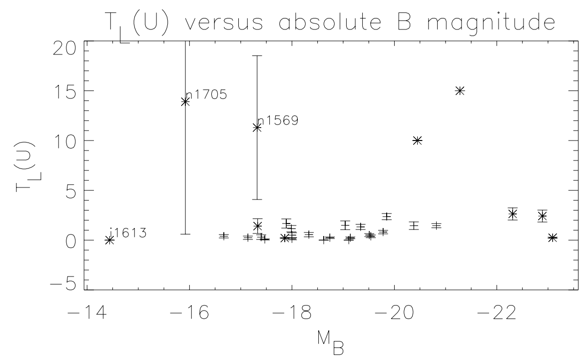

Fig. 8. $T_L(U)$ as a function of the absolute host galaxy B magnitude.

NGC 1569 and NGC 1705 differ from the other cluster-rich galaxies by their relatively low absolute luminosities, and one could speculate that YMC formation might be due to a different physical mechanism in these galaxies. In Fig. 8 we show $T_L(U)$ as a function of the absolute B magnitude of the host galaxy (derived from m_B and the distance moduli and A_B values in Table 1). Although NGC 1569 and NGC 1705 are among the least luminous galaxies in our sample, there are in fact even less luminous galaxies with ongoing star formation, but without rich cluster populations (notably IC 1613). Thus the main cause for the high $T_L(U)$ values of NGC 1705 and NGC 1569 still appears to be their relatively high level of star formation activity, and the poor fit of these two galaxies into the $T_L(U)$ – $\Sigma_{\rm SFR}$ relation may be ascribed primarily to the small number statistics of their cluster systems.

5. Discussion

Our data apparently indicate that the formation efficiency of YMCs in galaxies is closely linked to the star formation activity. By using U-band luminosities, the derived specific luminosities are dominated by the youngest stars, effectively making $T_L(U)$ a measure of the relative fraction of stars that currently form in massive clusters. $T_L(U)$ increases from about 0.1 in the most cluster-poor galaxies to 15 or more in merger galaxies like NGC 3256. We can, of course, not exclude the possibility that some of the very youngest objects are unbound associations that will not survive for long, rather than bound clusters. However, as shown in Paper1, the age distributions of the clusters are generally quite smooth, indicating that at least some fraction of the objects are indeed gravitationally bound star clusters, orders of magnitudes older than their crossing times (Larsen 1999).

The $T_L(U)$ vs. $\Sigma_{\rm SFR}$ correlation may explain why YMCs have, so far, been noticed predominantly in late-type galaxies (Kennicutt & Chu 1988). Apart from the small number of nearby, early-type spirals, this may just be an effect of the general increase in SFR along the Hubble sequence. However, there is a large scatter in SFR at any given morphological type (Kennicutt 1998b), which is presumably also the reason for the corresponding scatter in $T_L(U)$, and we would expect YMCs to be abundant also in Sa and Sb galaxies with a sufficiently high $\Sigma_{\rm SFR}$ (that is, higher than about 10^{-3} $M_\odot$ yr^{-1} kpc^{-2}, Fig. 3). The main point here is that $T_L(U)$ correlates with the SFR, rather than that formation of YMCs is generally favoured in late-type galaxies.

Our data imply a continuum of $T_L(U)$ values, varying smoothly with $\Sigma_{\rm SFR}$, rather than a division of galaxies into those that contain YMCs and those that do not. That YMCs have often been considered as a special class of objects which only exist in certain galaxies, probably arises from the fact that most efforts to detect them have focused on starburst galaxies, where they are much more numerous. Table 1 also shows that the M_V of the brightest cluster in each galaxy varies significantly. Recent, deep studies of young clusters in NGC 3256 (Zepf et al. 1999), NGC 1275 (Carlson et al. 1998) and other galaxies have not revealed any clear indications of a turn-over in the cluster luminosity function down to $M_V \sim -8.5$ or so, so the fact that these galaxies contain brighter clusters than less cluster-rich systems may just be a statistical effect.

There does not seem to be any SFR threshold for formation of YMCs. Instead, the number of YMCs formed and the efficiency of YMC formation appear to increase steadily with the star formation rate. This also raises the question whether massive star clusters are good tracers of the star formation history in a galaxy, as they have often been used in the Magellanic Clouds. For example, the apparent lack of massive star clusters in the LMC in the age range 4 – 10 Gyr (Girardi et al. 1995) has been seen as an indication that the LMC was in a sort of "hibernating" state during this period. However, if the cluster formation efficiency depends upon the star formation rate as suggested by this paper, then the "gap" in the LMC cluster age distribution could merely represent an epoch where star formation proceeded at a somewhat slower, but not necessarily vanishing rate. Indeed, this has been recently demonstrated from field star studies by Dirsch et al. (1999).

It still remains to be explained *why* the formation of YMCs is correlated with the star formation rate. It is not even clear if YMCs form because there is a high SFR, or if the $T_L(U) - \Sigma_{\rm SFR}$ correlation is a consequence of some underlying mechanism that regulates both the SFR and the formation of YMCs. Here we briefly discuss both possibilities in a speculative manner, and consider how they may complement each other.

5.1. SFR and cluster formation as resulting from a high gas density

An underlying parameter controlling both the star formation rate and the ability to form bound, massive clusters could be the *mean* gas density. It is well established that the SFR in a galaxy scales with some power of the gas density. Denoting the total gas surface density $\Sigma_{\rm gas}$, the Schmidt (1959) law may be written as $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^N$, where the exponent N has a value close to 1.4 (Kennicutt 1998a). As shown by Kennicutt (1998a), the Schmidt law provides a surprisingly good description of the SFR in galaxies in terms of a global $\Sigma_{\rm gas}$ over a wide range of surface gas density, so there is hope that cluster formation may depend on similar global galaxy properties, at least to a first approximation.

The $T_L(U) - \Sigma_{\rm SFR}$ relation in combination with the Schmidt law implies that $T_L(U)$ should scale with $\Sigma_{\rm gas}$ as well. This is at least partly confirmed by the observed correlation between $T_L(U)$ and the HI gas surface density, $\Sigma_{\rm HI}$ (Figs. 4 and 7). A $T_L(U)$ – $\Sigma_{\rm gas}$ relation may follow from the fact that a higher gas density leads to a generally higher ISM pressure ($P \sim \Sigma_{\rm gas}^2$ where P is the pressure, Elmegreen 1999). The ISM pressure has been suggested to be one of the dominant parameters governing the formation of strongly bound clusters (Elmegreen & Efremov 1997) and acts by producing proto-cluster clouds with higher binding energies, thus preventing them from dispersing too easily once star formation sets in. The clouds will have higher densities so that recombination rates are higher, and smaller fractions of the gas will be ionized by massive stars. Also the dispersive power of stellar winds and supernovae will be lower in a high density environment. All these effects promote a high star formation efficiency, one of the necessary conditions to produce a bound cluster.

A $T_L(U)$ – $\Sigma_{\rm gas}$ relation may thus be explained by saying that the high gas density delivers the required high pressure to form massive clusters. As local fluctuations are always important, we do not expect an overall "threshold" gas density when averaging over a whole galaxy, but as $\Sigma_{\rm gas}$ increases, the number of regions with the required high density will gradually increase too and naturally lead to the formation of more strongly bound clusters. With a high $\Sigma_{\rm gas}$ one also expects a fast growth of the protocluster so that higher masses become plausible.

5.2. A high SFR as a precondition to form massive clusters

The main effect of a high SFR is to pump energy into the ISM. Can this energy be responsible of creating suitable conditions for globular clusters? According to Elmegreen & Efremov (1997), globular cluster formation needs highly efficient star formation in a high pressure environment.

In order to form a massive, bound cluster two timescales apparently are of importance: The timescale for formation of a cloud core, which is massive enough to host a massive cluster, $\tau_{\rm cc}$, and the time scale for (high-mass) star formation in the cloud core, $\tau_{\rm sf}$.

It is interesting to note that the *average* density of a proto-YMC cloud prior to the onset of star formation (if the radius of the cluster equals the radius of the proto-cluster cloud)

$$\rho \approx 1.3 \times 10^{-20} \left(\frac{M}{10^5\,\mathrm{M}_\odot} \right) \left(\frac{R}{5\,\mathrm{pc}} \right)^{-3} \mathrm{g\,cm}^{-3} \quad (12)$$

must be quite similar to that observed in cluster-forming clumps in Galactic giant molecular clouds (Lada et al. 1997), although the total mass is much larger. In the Milky Way, efficient cluster formation appears to take place only in massive, high-density cloud cores, but not in *all* such cores (Lada et al. 1997). A discriminating factor appears to be the degree of fragmentation within the core, presumably because star formation takes place only in regions with a density higher than 10^5 molecules per cm^3, or about $3 \times 10^{-19}\,\mathrm{g\,cm}^{-3}$. If such a critical density exists, one could understand $\tau_{\rm sf}$ as the timescale which is needed for the gas to reach this density.

Whatever the formation mechanism of the cloud core is (Elmegreen 1993), star formation may not commence early, because the returned energy from massive stars by radiation, outflows and stellar winds presumably will terminate the growth of the cloud core and moreover is a threat to its dynamic stability. If $\tau_{\rm sf} \ll \tau_{\rm cc}$, the result might be a low mass cluster.

In addition, $\tau_{\rm sf}$ may not vary strongly in the cloud core. If it did so, one expects the outcome again to be not a globular cluster, but a star forming region with many dynamically distinct smaller clusters. i.e. a configuration resembling an association. However, if $\tau_{\rm sf} > \tau_{\rm cc}$, the cloud core can grow undisturbed by star formation and develop towards a strongly bound state. This may be the case either if the onset of star formation is somehow delayed, or if the formation of the proto-cluster cloud proceeds rapidly.

Any attempt to construct a scenario is hampered by the fact that even the physical cause for the onset of star formation (e.g. ambipolar diffusion, Jeans instabilities, thermal instabilities) is not yet clearly identified. However, star formation in general means to put matter into a state of strongly negative potential energy, so there is demand for an external energy input to delay star formation, even if the exact process is not known.

Part of the required energy may come from early low-mass star formation within the cloud (Tan 1999), but in order to maintain energy equilibrium in a large, massive cloud, external heat sources might also be necessary. At the highest densities ($\gtrsim 10^5\,\mathrm{cm}^{-3}$) the thermal pressure may become able to compete with or even dominate over magnetic pressure (Pringle 1989), so an energy input may also prevent premature star formation by Jeans or thermal instability (Murray & Lin 1989).

A high overall star formation rate naturally provides a number of energy sources, not only in the form of radiation from massive stars. Other possibilities are supersonic motions in the gas, induced by supernova shells or stellar winds. These may also help to compress proto-cluster clouds, so that large amounts of gas can be collected at high densities more easily, and fast enough to form a bound cluster. There is, in fact, some evidence that the formation of massive clusters marks the culmination of episodes of vivid star formation (Larson 1993).

These arguments apply not exclusively to massive clusters, but it is conceivable that more extreme external conditions can lead to denser, more massive clusters. This is in good agreement with the observed continuous dependence of $T_L(U)$ on $\Sigma_{\rm SFR}$.

5.3. The relation to old globular clusters

Within the scenarios described above, some findings regarding the systematics of globular clusters in early-type galaxies become understandable. The relevant labels can be called "hot" and "cold" dynamical environments. Cluster formation in orderly rotating gaseous disks, a "cold" dynamical environment, may not be supported without the impact of a high star formation rate. In the dynamically "hot" bulges and halos, the external energy supply comes from turbulent motions in the ambient medium which acts as a reservoir.

A striking feature regarding cluster populations in elliptical galaxies is the high specific frequency of central galaxies in clusters like M87 and NGC 1399. At least in the case of NGC 1399, these can be understood by the early infall of a population of dwarf galaxies into the Fornax cluster (Hilker et al. 1999). The infall velocities are of the order hundreds of km/s and the kinematic situation is similar to those in starburst galaxies. A lot of energy can by dissipated and very suitable conditions for cluster formation are provided.

The same interpretation may be valid for the relation between the specific frequency of globular cluster systems and the environmental galaxy density of the host galaxies (West 1993): The higher the galaxy density, the more frequent galaxy interaction with violent star formation must have been, leading to higher cluster formation efficiencies.

This might have been generally the case in the very early Universe, when the average star formation rates were much higher than nowadays. The old halo globular cluster systems of "normal" galaxies, which belong to the oldest stellar populations in galaxies, have been formed during this period, which quite naturally provided suitable conditions for massive cluster formation.

6. Conclusions

We have studied the cluster systems of the 21 galaxies in the sample of Larsen & Richtler (1999) together with literature data for some additional galaxies. It has been demonstrated that the specific U-band luminosity of the cluster systems, $T_L(U)$ (Eq. (3)) correlates with host galaxy parameters indicative of the star formation rate, in particular the B-band surface brightness (m_{25}) and IRAS far-infrared fluxes. Using the FIR fluxes to derive star formation rates (SFR) and obtaining the area-normalised SFR ($\Sigma_{\rm SFR}$), we find an even stronger correlation with $T_L(U)$, which seems to indicate that the formation of YMCs is favoured in environments with active star formation. However, this does not imply that YMCs form only in bona-fide starbursts, but rather that the cluster formation efficiency as measured by $T_L(U)$ increases steadily with $\Sigma_{\rm SFR}$ and that the formation of YMCs in starbursts and mergers may just be extreme cases of a more general phenomenon.

We have also compared the $T_L(U)$ values with integrated HI gas surface densities ($\Sigma_{\rm HI}$) and find a correlation here as well. Since $T_L(U)$ and $\Sigma_{\rm SFR}$ are correlated, this is an expected consequence of the fact that $\Sigma_{\rm SFR}$ scales with some power of the gas surface density $\Sigma_{\rm gas}$ (Kennicutt 1998a).

Although the two amorphous dwarfs NGC 1569 and NGC 1705 have rather high $T_L(U)$ values for their star formation rates, we do not see any examples of *cluster-poor* galaxies with a *high* $\Sigma_{\rm SFR}$. In other words, a galaxy contains large numbers of YMCs whenever $\Sigma_{\rm SFR}$ is high enough, although the physical relation is not yet well understood. Formation of a rich cluster system does not require a strong spiral density wave, for example, since the flocculent galaxy NGC 7793 has a high $T_L(U)$. Interaction with nearby neighbours does not appear to be necessary either, as illustrated by NGC 1156 which has been labeled "the less disturbed galaxy in the Local Universe" (Karachentsev et al. 1996), but nevertheless contains a rich population of YMCs.

Some mechanisms were outlined which may explain why massive star clusters form at a high efficiency in environments with a high SFR: A generally high SFR acts as an energy source that keeps molecular clouds in an equilibrium state and allows massive clouds to contract to a high density before high-mass star formation sets in. Once the required high average density to form a YMC is reached (about 10^4 cm^{-3}), star formation proceeds rapidly and at a high efficiency within the clouds, because the high pressure in the ambient medium keeps the proto-cluster clouds from dispersing (Elmegreen & Efremov 1997).

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