Young massive star clusters in nearby spiral galaxies

III. Correlations between cluster populations and host galaxy properties

S.S. Larsen\textsuperscript{1,2} and T. Richtler\textsuperscript{3,4}

\textsuperscript{1} Copenhagen University Astronomical Observatory, Juliane Maries Vej 32, 2100 Copenhagen Ø, Denmark
\textsuperscript{2} UCO/Lick Observatories, Kerr Hall, UC Santa Cruz, CA 95064, USA
e-mail: soeren@ucolick.org
\textsuperscript{3} Sternwarte der Universit"{a}t Bonn, Auf dem H"{u}gel 71, D-53121 Bonn, Germany
\textsuperscript{4} Grupo de Astronomía, Departamento de Física, Casilla 160-C, Universidad de Concepción, Concepción, Chile
e-mail: tom@coma.cfm.udec.cl

Received ...; accepted ...

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: individual – spiral – starburst – 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...
Young massive star clusters.

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, Vm is the V magnitude of the brightest cluster, mB is the integrated B magnitude of the galaxy, AB is the galactic foreground reddening, and TN is the “specific frequency”. The two last columns, TL(U) and TL(V) give the specific luminosities of the cluster systems in the U and V bands.

| Name    | m-M | N  | Vm     | mb     | AB    | TN   | TL(U) | TL(V) |
|---------|-----|----|--------|--------|-------|------|-------|-------|
| 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  | 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| 20.5| 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  | 0.00  |
| NGC 7793| 27.6| 20 | -10.4  | 9.63   | 0.02  | 1.21 | 1.15  | 0.51  |

Starbursts / mergers

| Name    | m-M | N  | Vm     | mb     | AB    | TN   | TL(U) | TL(V) |
|---------|-----|----|--------|--------|-------|------|-------|-------|
| NGC 1275 | 34.2| 14 | 12.64  | 0.75   | -     | 2.63 | 1.04  |       |
| NGC 1569 | 27.0| -  | -13.9  | 11.86  | 2.18  | -    | 11.3  | 5.60  |
| NGC 1705 | 28.5| -  | -13.7  | 12.77  | 0.19  | -    | 13.9  | 10.1  |
| NGC 1741 | 33.5| -  | -15    | 13.30  | 0.25  | -    | ~ 10  | ~ 5   |
| NGC 3256 | 32.8| -  | -15    | 12.15  | 0.59  | -    | ~ 15  | ~ 15  |
| NGC 3921 | 36.0| -  | -14    | 13.06  | 0.16  | -    | 0.24  | 0.11  |
| NGC 5253 | 28.0| -  | -11.1  | 10.87  | 0.20  | -    | 1.41  | 0.51  |
| NGC 7252 | 34.9| -  | -17.0  | 12.06  | 0.05  | -    | 2.43  | 1.10  |

Other galaxies

| Name    | m-M | N  | Vm     | mb     | AB    | TN   | TL(U) | TL(V) |
|---------|-----|----|--------|--------|-------|------|-------|-------|
| IC 1613 | 24.3| -  | 9.88   | 0.02   | 0.00  | 0.00 | 0.00  | 0.00  |
| LMC     | 18.5| 8  | -9.4   | 0.91   | 0.27  | 0.57 | 0.12  | 0.11  |

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 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 MV = −8.5 for objects with U − B > −0.4 and MV = −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 3×10^5 M⊙, assuming a Salpeter IMF extending down to 0.1 M⊙ (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.
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. $m_{FIR}$ is a Far-Infrared magnitude based on the IRAS $60 \mu$ and $100 \mu$ fluxes. The IRAS 60 and 100 $\mu$ fluxes are in units of Jy. $\Sigma_{SFR}$ (given as $10^3 \times M_\odot$ yr$^{-1}$ kpc$^{-2}$) and $\Sigma_{HI}$ (in units of $M_\odot$ pc$^{-2}$) are derived from $m_{FIR}$ and $m_{21}$ as described in Sect. [1]; FIR data from Rice et al. (1988) [2]; FIR data from Soifer et al. (1989) [3]; FIR data from IRAS Faint Source Catalog (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 | $m_{25}$ | $m_{21}$ | $m_{FIR}$ | $f(60\mu)$ | $f(100\mu)$ | log $D_0$ | $\Sigma_{SFR}$ | $\Sigma_{HI}$ |
|---------------|----|-----|-----|----------|----------|-----------|-------------|-------------|-----------|---------------|--------------|
| 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 2403 [4,6] | 6.0 | -0.10 | 0.50 | 14.95 | 10.27 | 10.55 | 7.93 | 27.3 | 2.34 | 0.18 | 5.3 |
| NGC 3091 [4]  | 7.0 | 0.11 | 0.59 | 14.91 | 9.15 | 9.43 | 23.1 | 74.4 | 2.10 | 0.50 | 14.3 |
| NGC 2997 [4]  | 7.0 | 0.00 | 0.56 | 14.79 | 10.77 | 9.56 | 20.9 | 65.6 | 2.03 | 1.88 | 14.0 |
| NGC 1159 [4,5] | 10.0 | -0.19 | 0.58 | 14.43 | 12.72 | 11.28 | 5.71 | 9.20 | 1.58 | 3.07 | 18.4 |
| NGC 1313 [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 [4,5] | 6.0 | -0.06 | 0.52 | 14.27 | 13.38 | 11.89 | 2.33 | 8.19 | 1.54 | 2.10 | 12.1 |
| NGC 4031 [4]  | 9.0 | 0.10 | 0.47 | 14.88 | 9.58 | 8.63 | 51.6 | 148 | 2.36 | 0.97 | 9.2 |
| Other galaxies |    |     |     |        |        |        |      |      |      |      |      |
| NGC 5204 [4,4] | 9.0 | -0.33 | 0.41 | 14.55 | 12.35 | 12.10 | 2.32 | 5.35 | 1.70 | 0.83 | 14.9 |
| NGC 5236 [4,4] | 5.0 | 0.03 | 0.66 | 13.48 | 9.60 | 6.95 | 266 | 693 | 2.12 | 13.8 | 27.2 |
| NGC 5585 [4,4] | 7.0 | -0.22 | 0.46 | 14.35 | 12.10 | 12.82 | 0.99 | 3.65 | 1.76 | 0.33 | 14.3 |
| NGC 6744 [4,5] | 4.0 | 0.13 | 0.75 | 15.00 | 9.55 | 9.36 | 22.2 | 85.8 | 2.31 | 0.62 | 11.9 |
| NGC 6960 [4,5] | 6.0 | 0.20 | 0.80 | 14.58 | 10.09 | 7.64 | 137 | 344 | 2.22 | 4.60 | 10.9 |
| NGC 7421 [4,3] | 6.0 | -0.15 | 0.48 | 15.52 | 11.27 | 12.36 | 1.22 | 7.83 | 1.98 | 0.18 | 11.1 |
| NGC 7793 [4,4] | 6.0 | -0.14 | 0.53 | 14.45 | 13.15 | 12.00 | 2.27 | 6.98 | 1.65 | 1.14 | 9.0 |
| Other galaxies |    |     |     |        |        |        |      |      |      |      |      |
| IC 1613 [4,4] | 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 |

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:

$$T_N = N \times 10^{0.4(T_B+15)}$$  \hspace{1cm} (1)

Here $N$ is the total number of YMCs in a galaxy, and $T_B$ 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

$$N(L)dL \propto L^{-\alpha}dL$$  \hspace{1cm} (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 (1993), we define the specific luminosity

$$T_L = 100 \cdot \frac{L_{\text{Clusters}}}{L_{\text{Galaxy}}}$$

(3)

where $L_{\text{Clusters}}$ and $L_{\text{Galaxy}}$ 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 $\alpha$ 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 $M_V$, 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 $M_V = -5.5$. 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. (1997) “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 $m_{\text{FIR}}$ is a FIR magnitude based on the IRAS fluxes at 60$\mu$m and 100$\mu$m. $\log D_0$ 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 $S_{\text{FIR}}$ and the HI surface density $\Sigma_{\text{HI}}$ derived from $m_{\text{FIR}}$ and $m_{21}$ (see Sect. 4.1). The RC3 as well as the IRAS data were retrieved through the NASA/IPAC Extragalactic Database.

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.
other grand-design spirals are relatively cluster-poor (e.g. NGC 3184, 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. [1997]), 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 $m_{\text{FIR-B}} = m(\text{FIR}) - m(B)$.

Fig. 2 shows $T_L(U)$ as a function of various integrated host galaxy parameters: The $m_{\text{FIR-B}}$ index, the $B$-band surface brightness, the integrated $U - B$ colour and the IRAS $f(60\mu m)/f(100\mu m)$ flux ratio.

From Fig. 2 we first note the striking correlations between $T_L(U)$ and $m_{\text{FIR-B}}$ 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 [1988]). 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 $m_{FIR-B}$. 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 1998). 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 1998):

$$SFR(M_\odot \text{ yr}^{-1}) = 8.0 \times 10^{-37} L_{FIR}$$  \hspace{1cm} (4)

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

$$m_{FIR} = -20 - 2.5 \log(S_{FIR})$$  \hspace{1cm} (5)

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

From (4) and (5),

$$SFR(M_\odot \text{ yr}^{-1}) = 0.0096 - 0.0006 D^2 10^{-0.4(m_{FIR}+20)}$$  \hspace{1cm} (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 $D_o$ from RC3), defining $\Sigma_{SFR}$ as the SFR per kpc$^2$:

$$\Sigma_{SFR} = \frac{SFR}{D_o^2} = 144000 \times 10^{-0.4m_{FIR}-2} \log D_o$$  \hspace{1cm} (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 pos-
sibility 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. 3 (top panel) and $\Sigma_{SFR}$ (bottom panel). A correlation is evident in both cases, but the scatter clearly decreases when plotting $T_L(U)$ as a function of $\Sigma_{SFR}$ 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 $\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$ (Kennicutt 1998a). It would therefore be of interest to look for a corresponding relation between $T_L(U)$ and the gas surface density ($\Sigma_{gas}$). Lacking a homogeneous set of data on total gas masses, we will here consider the atomic hydrogen mass $M_{HI}$ which may be derived from the 21-cm flux density (Roberts 1976):

$$M_{HI}(M_\odot) = 2.356 \times 10^{19} D^2 \int_{-\infty}^{\infty} S_{\nu} dV_r$$

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 $S_{\nu}$ is in units of $W \text{ m}^{-2} \text{ Hz}^{-1}$ and $V_r$ is in km/sec. The total integrated flux density $S_{HI}$ can be obtained from the $m_{21}$ values given in Table 3 using the expression

$$m_{21} = 21.6 - 2.5 \log(S_{HI})$$

with $S_{HI}$ in units of $10^{-24} W \text{ m}^{-2}$ (RC3). Combining (3) and (4) we obtain

$$M_{HI}(M_\odot) = 4.97 \times 10^{-9} D^2 10^{0.4 \times (21.6 - m_{21})}$$

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 $\Sigma_{HI}$:

$$\Sigma_{HI}(M_\odot \text{ pc}^{-2}) = 3.26 \times 10^9 \times 10^{-0.4 m_{21} - 2} \log D_0$$

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

4.2. Including literature data

It is of interest to see if the $T_L(U)$ vs. $\Sigma_{SFR}$ 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 4 and 5 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 1983). 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 ($\sim 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
Young massive star clusters.

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 $0.7 \pm 0.3$ 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 $\Sigma_{SFR}$ 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 $\Sigma_{SFR}$ 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. 1, $T_L(U)$ correlates significantly better with $\Sigma_{SFR}$ 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 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 $\Sigma_{SFR}$ and $T_L(U)$, though a least-squares fit formally yields a power-law dependence of the form $T_L(U) \sim \Sigma_{SFR}^{0.87\pm0.15}$. This
is seen somewhat more clearly on a double-logarithmic plot (Fig. 5).

The $T_L(U)$ vs. $\Sigma_{\text{HI}}$ diagram for all galaxies with 21-cm data in RC3 is shown in Fig. 6. 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.

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 $T_L(U) - \Sigma_{\text{SFR}}$ 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. $\Sigma_{\text{SFR}}$ 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 $\Sigma_{\text{SFR}}$ (that is, higher than about $10^{-3}$ M$_\odot$ yr$^{-1}$ kpc$^{-2}$, Fig. 7). 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 $\Sigma_{\text{SFR}}$, 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 2 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. 1998) 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 \( T_L(U) - \Sigma_{SFR} \) 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 \( \Sigma_{gas} \), the Schmidt (1959) law may be written as \( \Sigma_{SFR} \propto \Sigma_{gas}^N \), where the exponent \( N \) has a value close to 1.4 (Kennicutt 1998a).

As shown by Kennicutt (1998b), the Schmidt law provides a surprisingly good description of the SFR in galaxies in terms of a global \( \Sigma_{gas} \) 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 \( T_L(U) - \Sigma_{SFR} \) relation in combination with the Schmidt law implies that \( T_L(U) \) should scale with \( \Sigma_{gas} \) as well. This is at least partly confirmed by the observed correlation between \( T_L(U) \) and the HI gas surface density, \( \Sigma_{HI} \) (Figs. 4 and 5). A \( T_L(U) - \Sigma_{gas} \) relation may follow from the fact that a higher gas density leads to a generally higher ISM pressure \( P \approx \Sigma_{gas}^2 \) 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 \( T_L(U) - \Sigma_{gas} \) 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 \( \Sigma_{gas} \) 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 \( \Sigma_{gas} \) 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, \( \tau_{cc} \), and the time scale for (high-mass) star formation in the cloud core, \( \tau_{sf} \).

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)

\[
\rho \approx 1.3 \times 10^{-20} \left( \frac{M}{10^8 M_\odot} \right) \left( \frac{R}{5 \text{ pc}} \right)^{-3} \text{ g cm}^{-3}
\]

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 \( 3 \times 10^{-19} \text{ g cm}^{-3} \). If such a critical density exists, one could understand \( \tau_{sf} \) 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 \( \tau_{sf} \ll \tau_{cc} \), the result might be a low mass cluster.

In addition, \( \tau_{sf} \) 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 $\tau_{sf} > \tau_{cc}$, 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 ($\gtrsim 10^5 \text{cm}^{-3}$) the thermal pressure may become able to compete with or even dominate over magnetic pressure (Pringle 1983), so an energy input may also prevent premature star formation by Jeans or thermal instability (Murray & Lin 1999).

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 $\Sigma_{SFR}$.

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 ($m_{B25}$) and IRAS far-infrared fluxes. Using the FIR fluxes to derive star formation rates (SFR) and obtaining the area-normalised SFR ($\Sigma_{SFR}$), 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 $\Sigma_{SFR}$ 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 ($\Sigma_{HI}$) and find a correlation here as well. Since $T_L(U)$ and $\Sigma_{SFR}$ are correlated, this is an expected consequence of the fact that $\Sigma_{SFR}$ scales with some power of the gas surface density $\Sigma_{gas}$ (Kennicutt 1998).

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 $\Sigma_{SFR}$. In other words, a galaxy contains large numbers of YMCs whenever $\Sigma_{SFR}$ 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 la-
beled “the less disturbed galaxy in the Local Universe” (Karachentsev et al. 1999), 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 10^3 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).

Acknowledgements. This research was supported by the Danish Natural Science Research Council through its Centre for Ground-Based Observational Astronomy. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We would like to thank B. Elmegreen for interesting discussions.

References

Arp H., Sandage A. 1985, AJ 90, 24
Bica E., Claris J.J., Dottori H. et al. 1996, ApJS 102, 57
Bresolin F., Kennicutt R.C., Stetson P.B., 1996, AJ 112, 1009
Bruzual G.A., Charlot S. 1993, ApJ 405, 538
Buat v., Xu C. 1996, A&A 306, 61
Carlson M.N., Holtzman J.A., Watson A.M. et al. 1998, AJ 115, 1778
Christian C.A. & Schommer R.A. 1988, AJ 95, 704
Dirsch B., Richtler T., Gieren W. 1999, submitted to A&A
Elmegreen B.G., Booth R.S., Heisler B., Johansson L.E.B. and Sandqvist Aa. 1996, A&A 115, 439
Elmegreen B.G. 1983, MNRAS 203, 1011
Elmegreen B.G. 1993, in “Protostars and Planets III”, eds. E.H. Levy, J.I. Lunine, University of Arizona Press, p.97
Elmegreen B.G. 1999, in “The Physics and Chemistry of the Interstellar Medium” eds. G. Winnewisser, J. Stutzki and V. Ossenkopf, Shaker-Verlag
Elmegreen B.G., Efremov Y.N. 1997, ApJ 480, 235, EE97
Girardi L., Chiosi C., Bertelli G., Bressan A. 1995, A&A 298, 87
Gorsian V. 1996, AJ 112, 1886
Harris W.E. 1991, ARA&A 29, 543
Harris W.E. 1999, 28th Saas-Fee Advanced Course for Astrophysics and Astronomy, “Star Clusters”
Harris W.E. and van den Bergh S. 1981, AJ 86, 1627
Harris W.E. and Pudritz R.E. 1994, ApJ 429, 177
Heap S.R., Holbrook J., Mulmuth E. et al. 1993, BAAS 182
Hilker M., Infante L., Richtler T. 1999, A&A 138, 55
Holtzmann J.A., Faber S.M., Shaya E.J. et al. 1992, AJ 130, 691
Johnson K.E., Vacca W.D., Leitherer C. et al. 1999, AJ 117, 1708
Karachentsev I., Musella I., Grimaldi A. 1996, A& A 310, 722
Kennicutt R.C. 1998a, ApJ 498, 541
Kennicutt R.C. 1998b, ARA&A 36, 189
Kennicutt R.C., Chu Y-H. 1988, AJ 95, 720
Lada E.A., Evans II, M.J., Falgarone E. 1997, ApJ 488, 286
Larsen S.S., Richtler T. 1999, A& A 345, 59
Larsen S.S. 1999, A&AS 139, 393
Larson R.B. 1993, in: “The Globular Cluster-Galaxy Connection”, eds. G.H. Smith and J.P. Brodie
Maoz D., Barth A.J., Sternberg A. et al. 1996, AJ 111, 2248
McKee C.F. 1999, ApJ 457, 578
McLaughlin D.E. and Pudritz R.E. 1996, ApJ 457, 578
Meurer G.R., Heckman T.M., Leitherer C. et al. 1995, AJ 110, 2665
Miller B.W., Whitmore B.C., Schweizer F., Fall S.M. 1997, AJ 114, 2381
Moshir M., Kopan G., Conrow T., McCaill H., Hacking P., Gregorich D., Melnyk M., Rice W., Fullmer L. et al. 1990, Infrared Astronomical Satellite Catalogs, The Faint Source Catalog v. 2.0
Mouschovias T. Ch. 1991, In: “The Physics of Star Formation and Early Stellar Evolution”, eds. C.J. Lada and N. D. Kylafis, Kluwer Academic Press
Murray S.D., Lin D.N.C. 1989, ApJ 339, 933
Murray S.D., Lin D.N.C. 1992, ApJ 400, 265
Norgaard-Nielsen H.U., Goudfrooij P., Jørgensen H.E., Hansen L. 1993, A&A 279, 61
O’Connell R.W., Gallagher III J.S., Hunter D.A. 1994, AJ 433, 65
Pringle J.E. 1989, MNRAS 239, 361
Rice W., Lonsdale C.J., Soifer B.T., Neugebauer G. et al. 1988, ApJS 68, 91
Richtler T. 1993, “The Globular Cluster-Galaxy Connection” eds. G.H. Smith & J.P. Brodie, ASP p. 375
Roberts M.S. 1975, in “Galaxies and the Universe”, eds. Sandage A., Sandage M. and Kristian J., Univ. Chicago Press
Schmidt M. 1959, ApJ 129, 243
Schweizer F. 1982, ApJ 252, 455
Schweizer F., Miller B.W., Whitmore B.C., Fall M.S. 1996, AJ 112, 1839
Soifer B.T., Boehmer L., Neugebauer G., Sanders D.B. 1989, AJ 98, 766
Tan J.C. 1999, preprint astro-ph/9906355
van den Bergh S. 1979, ApJ 230, 95
van den Bergh S. 1991, ApJ 369, 1
de Vaucouleurs G., de Vaucouleurs A., Corwin H.G., Buta R.J., Paturel G., Fouqué P. 1991, “Third Reference Catalogue of Bright Galaxies”, Springer-Verlag New York
Waller W. 1991, ApJ 370, 144
West, M.J. 1993, MNRAS 265, 755
Whitmore B.C., Schweizer F., Leitherer C., Borne K., Robert C., 1993, AJ 106, 1354
Young J.S., Xie S., Tacconi L. et al. 1995, ApJS 98, 219
Zepf S.E., Ashman K.M., English J. et al. 1999, AJ 118, 752
Östlin G., Bergvall N., Römbach J. 1998, A&A 335, 85