Astron. Astrophys. 336, 83–97 (1998)

ASTRONOMY AND ASTROPHYSICS

Young star clusters in the Antennae: a clue to their nature from evolutionary synthesis

Uta Fritze-v. Alvensleben

Universitätssternwarte Göttingen Geismarlandstrasse 11, D-37083 Göttingen, Germany (ufritze@uni-sw.gwdg.de)

Received 12 November 1996 / Accepted 13 May 1998

Abstract. We analyse the population of bright star clusters in the interacting galaxy pair NGC 4038/39 detected with HST WFPC1 by Whitmore & Schweizer (1995). Making use of our spectrophotometric evolutionary synthesis models for various initial metallicities we derive the ages of these star clusters and calculate their future luminosity evolution. This allows us to compare their luminosity function (**LF**), evolved over a Hubble time, to globular cluster (**GC**) LFs. Since effective radii are difficult to determine due to crowding of the clusters, the shape of the LF after a Hubble time may help decide whether the young clusters are young GCs or rather open clusters/OB associations. We subdivide the cluster population into subsamples with small and large effective radii. While the LF for the extended clusters looks exponential, that for clusters with small effective radii clearly shows a turn-over brighter than the completeness limit. For other possible subdivisions as to luminosity or colour no comparable differences are found. Evolving, in a first step, the LF from a common mean age of the young clusters of 0.2 Gyr to an assumed age of 12 Gyr, the LF for the subsample of clusters with small effective radii seems compatible with a Gaussian GCLF with typical parameters $\mathrm{M_{V_0}} = -7.1$ mag and $\sigma(\mathrm{M_{V_0}}) = 1.3$ mag, except for some overpopulation of the faint bins. These faintest bins, however, might be suspected to be subject to the strongest depopulation through effects of dynamical evolution not included in our models. We also follow the colour evolution of the young star clusters over a Hubble time and compare to observations on the Milky Way and other galaxies' GC systems.

For an ongoing starburst like the one in the NGC 4038/39 system age spread effects among the young star cluster population may not be negligible. In a second step, we therefore account for age spread effects by individually age-dating every cluster on the basis of its observed colours. This drastically changes the time evolution of the LF, confirming Meurer's (1995) conjecture. We find that $-$ if age spread effects are properly accounted for $-$ the LF of the entire young star cluster population, and in particular that of the brighter subsample, is in good agreement with an average Gaussian GCLF after a Hubble time. It shows a turn-over at $\langle \mathrm{M_{V_0}} \rangle = -7.1$ mag with $\sigma(\mathrm{M_{V_0}}) = 1.3$ mag.

The age distribution reveals that the brightest GCs from the interacting galaxies' original population are also observed. They make up the bulk of the red subpopulation with $\mathrm{(V-I)_0} > 0.95$. Their effective radii do not significantly differ from those of the young star cluster population, neither on average nor in their distribution.

We discuss the influence of metallicity, a possibly inhomogeneous internal dust distribution, as well as of internal $-$ through stellar mass loss $-$ and external dynamical effects on the secular evolution of the LF.

Referring YSC luminosities to a uniform age and combining with model M/L, we recover the intrinsic mass distribution of the YSC system. Its shape is compatible with a Gaussian which $-$ according to Vesperini's (1997) dynamical modelling for the Milky Way GC system $-$ represents a quasi-equilibrium distribution and will **not** be altered over a Hubble time of dynamical evolution, allthough a substantial number of clusters will be destroyed.

We briefly compare the young star cluster population of the Antennae to the older one in the merger remnant NGC 7252 and point out that the intercomparison of young cluster populations in an age sequence of interacting and merged galaxies may become an interesting approach to study in detail the role of external dynamical effects.

Key words: galaxies: star clusters – galaxies: individual: NGC 4038/39, – galaxies: interactions – galaxies: starburst

1. Introduction

When normalised to the stellar mass of a galaxy, the specific globular cluster (**GC**) frequency $T_{GC} := \frac{N_{GC}}{M_*/10^9\ M_\odot}$ is a factor of ~ 2 higher, on average, in ellipticals than in spirals. Therefore, Zepf & Ashman (1993) predict that if elliptical galaxies are formed from one major spiral $-$ spiral merger the number of GCs formed during the merger- induced starburst should be of the same order of magnitude as the number of GCs present in the progenitor galaxies.

The high burst strengths and star formation (**SF**) efficiencies in massive gas-rich spiral $-$ spiral mergers and in IR-ultraluminous galaxies lead us to expect the formation of star clusters so tightly bound that they are able to survive as GCs (Fritze $-$ v. Alvensleben & Gerhard 1994).

Fritze − v. Alvensleben & Gerhard (1994) predicted the metallicity range of stars and star clusters formed in massive gas-rich (i.e. late type) spiral−spiral mergers on the basis of the ISM abundances of the progenitor galaxies to be $\frac{1}{3}\ \mathrm{Z}_\odot \lesssim \mathrm{Z} \lesssim \mathrm{Z}_\odot$ or $-0.8 \lesssim [\mathrm{Fe/H}] \lesssim -0.2$.

In many interacting galaxies and merger remnants, bright blue knots are observed (cf. e.g. Lutz 1991, Holtzman et al. 1992, 1996, Whitmore et al. 1993, Hunter et al. 1994, Conti & Vacca 1994, O'Connell et al. 1994, 1995, Meurer et al. 1995, Whitmore & Schweizer 1995, Schweizer et al. 1996, Östlin et al. 1998). These bright blue knots, of course, immediately raised the question as to their identity: are these Young Star Clusters (**YSC**) − or, at least, some of them − the progenitors of GCs? And, if the latter were true, how many of them are typically formed in a merger? How many will be able to survive in the tidal field of two massive interacting spirals? Can such a higher metallicity subpopulation be identified in GC systems (hereafter **GCS**) around merger remnants and perhaps even around normal ellipticals? Could the metallicity distribution of a GCS give information about the origin of its parent galaxy (cf. Zepf & Ashman 1993)? Or should all of these bright blue knots be open clusters/OB associations (van den Bergh 1995) most of which will disperse within few Gyr? The discussion of the nature of these YSCs is focussed on two aspects, their effective radii $\mathrm{R_{eff}}$ and their luminosity function. In mergers at distances of the Antennae or NGC 7252, effective radii as measured on WFPC1 images are clearly overestimated. However, it has been shown that for nearby YSC systems the mean effective radii do readily fall within the range of GC radii (Meurer et al. 1995). Our focus in this paper is the luminosity and colour evolution of the YSC population in the Antennae and, in particular, the future evolution of the YSC's LF.

In a previous paper, we modelled the evolution of star clusters for different initial metallicities in terms of broad band colours and stellar metallicity indices. We find important colour differences for clusters of various metallicities, already at young ages, and showed that once the stellar metallicity is known, rather precise age dating becomes possible. Comparison with young star clusters in NGC 7252 (Whitmore et al. 1993), the two brightest of which have spectroscopy available (Schweizer & Seitzer 1993), confirmed a metallicity of $\mathrm{Z} \sim \frac{1}{2}\mathrm{Z}_\odot$ predicted from our global starburst modelling in this Sc − Sc merger remnant. The mean age of the young star cluster population was shown to agree well with the global burst age of ~ 1.3 Gyr, and ages derived from solar metallicity models would differ by a factor ~ 2 (see Fritze − v. Alvensleben & Burkert 1995 for details).

Observationally, the best case for studying the LF of YSCs are the Antennae with more than 700 young star clusters detected by Whitmore & Schweizer (1995, hereafter **WS95**), a number large enough to allow for a statistical analysis. In this paper, we will examine the LF of the young star cluster system in the Antennae. It seems clear that not all bright knots in the NGC 4038/39 system with its still ongoing starburst will probably be GCs, in particular those with large effective radii $\mathrm{R_{eff}}$ might rather be open clusters or associations. Therefore, after age dating the clusters in Sect. 2., we subdivide Whitmore & Schweizer's young star cluster sample into two subsamples containing the small knots and the more extended systems, respectively (Sect. 3.). In a first step, we assume a uniform age for the YSC population and we model the evolution of the YSCs' LF over a Hubble time and compare to LFs of the Milky Way's and other nearby galaxies' GCSs (Sect. 4.). In an ongoing starburst like in the Antennae, the age spread among the YSCs may not be negligible (see also Meurer 1995). To examine the age spread effects on the LF we determine individual ages for all star clusters from their observed colours and discuss the star clusters' age distribution in Sect. 5. We calculate the resulting individual fading for all clusters in Sect. 6. Alternative possibilities to subdivide the YSC sample and their consequences are discussed in Sect. 7. The luminosity of a young GCS may not only change by fading but also by dynamical effects as e.g. stellar mass loss within the cluster and/or tidal interaction of a cluster with the galactic potential. For GC populations in non-interacting galaxies, these effects were studied by Chernoff & Weinberg (1990), their results are largely confirmed by the independent and more realistic approach of Fukushige & Heggie (1995). In a recent paper Vesperini (1997) shows that in the Milky Way potential an initial log-normal mass distribution represents a quasi-equilibrium state that preserves both its shape and parameters during a Hubble time of dynamical evolution, even though up to 70 % of the initial cluster population get disrupted. In case of the Antennae, i.e. in a still uncompleted merger with its gravitational potential being highly variable both in space and in time, however, external dynamical effects seem extremely difficult to model. Referring YSC luminosities to a common age allows the mass function of the YSC system to be recovered when combined with model M/L. We discuss the possible influence of dynamical effects in Sect. 8. and point out the possibility to observationally approach these dynamical effects by intercomparing star cluster populations in interacting galaxies and merger remnants of various ages. Sect. 9. summarizes our conclusions. The spatial distribution of the YSCs − and of their properties as derived here − will be discussed in a forthcoming paper.

2. Age dating of the star clusters in the Antennae

Details of our photometric evolutionary model can be found in Fritze − v. Alvensleben & Burkert (1995, hereafter **FB95**), where it has been used to age-date the young star clusters in NGC 7252. Similar to NGC 7252, though less advanced, NGC 4038/39 seems to be a merger of two gas-rich spirals of comparable mass. Though not known very accurately, the progenitor spirals of the Antennae may probably have been of type Sc − Sc as in NGC 7252 on a similar kind of reasoning as in that case. Observations of large amounts of HI within the body of NGC 4038/39 and along its tidal tails are from van der Hulst (1979), Stanford et al. (1990) report on molecular gas observations. Thus, from the progenitor spiral's ISM abundances a metallicity of $\sim \frac{1}{2}\ \mathrm{Z}_\odot$ is estimated for the stars and star clusters formed during the interaction triggered starburst in the Antennae. This estimate would not change by much, if e.g. one of the progenitor spirals were of type Sb or Sd. As long as no spectroscopic abundance determination is available for young star clusters in NGC 4038/39, we will have to rely on this rough metallicity estimate. While a certain metallicity spread among young star clusters formed in the burst cannot be excluded, in a first step we will – for lack of better knowledge – assume that all young clusters have this same metallicity of $\frac{1}{2}$ $Z_\odot$ and we will derive a mean age of the YSC population from their mean $(V-I)$ colour.

In a second step, we release the simplifying assumption that all YSCs have the same age and we will derive ages for individual clusters from their $(V-I)$ to discuss the effect of an age spread among the very young star clusters.

For a mean dereddened $\langle (V-I)_0 \rangle_{\rm (all\ clusters)} \sim 0.5$ (cf. WS95), our models give a mean cluster age of $\sim 2 \cdot 10^8$ yr (cf. FB95). If the metallicity were as low (as high) as $1 \cdot 10^{-3}$ (as $2 \cdot Z_\odot$) the clusters would have ages of $\sim 4 \cdot 10^8$ yr ($\sim 1 \cdot 10^8$ yr). These mean ages of the YSC population seem quite compatible with Barnes' (1988) dynamical time of $2 \cdot 10^8$ yr since the last (=first) pericenter.

$(U-V)$ colours are available for 48 YSCs only. Their mean dereddened $\langle (V-I)_0 \rangle \sim -1.0$ would lead to a mean age of $\sim 1 \cdot 10^7$ yr for $Z \sim \frac{1}{2}$ $Z_\odot$. This younger age is not in conflict with our $\langle {\rm age} \rangle \sim 2 \cdot 10^8$ yr from $(V-I)$ since only the very brightest YSC in U are detected which – of course – are expected to be the bluest and youngest.

Both nuclei of NGC 4038 and 4039 are sites of ongoing or recent strongly enhanced star formation (e.g. Rubin et al. 1970, Keel et al. 1985) and contain sufficient reservoirs of molecular gas (Stanford et al. 1990) to sustain their starbursts for a while. A typical burst duration in this kind of gas-rich spiral – spiral merger is of the order of $\sim 4 \cdot 10^8$ yr (Fritze – v. Alvensleben & Gerhard 1994, Bernlöhr 1990, Carico et al. 1990).

3. Subdivision of the Antennae's YSC sample with respect to $R_{\rm eff}$

In the course of mass loss through any mechanism whatsoever during secular evolution, the effective radius of a star cluster can only grow (cf. Sect. 8). From the observed range of effective radii $R_{\rm eff} = 0 \ldots 50$ pc (we use $H_0 = 75$ throughout) it seems clear that not all bright knots in the Antennae may be GCs, the more extended ones having a higher probability of being open clusters or associations. Here, we are facing a significant difference to the case of NGC 7252 where from the larger mean age of ~ 1.3 Gyr alone, most objects can be expected to be GCs. And indeed, the mean effective radius of the NGC 7252 clusters is ~ 7 pc, significantly smaller than the $\langle R_{\rm eff} \rangle = 13$ pc of all the Antennae's clusters, despite the considerably larger distance to NGC 7252.

Meurer (1995) argues that – due to severe crowding on a bright and spatially variable galaxy background – YSC effective radii in distant galaxies may be strongly overestimated. Effective radii are generally determined from the luminosity difference in a small and a larger aperture centered on a YSC, where the large aperture in some cases might be contaminated by light from neighbouring star clusters. The observed clustering of YSCs – typically a dozen within one giant HII region (WS95) – tends to increase this overestimation of effective radii. Meurer et al. (1995) estimate the distance out to which this two aperture method should be expected to yield reliable $R_{\rm eff}$ to be 9 Mpc and emphasise that the mean $R_{\rm eff}$ of YSCs in all three starburst galaxies observed to date within this distance is indeed ~ 1.3 pc, i.e. even smaller than the median $R_{\rm eff} \sim 3$ pc of Galactic GCs as given by Djorgovski & Meylan (1994).

Table 1. Comparison of young star cluster subsamples.

	$R_{\rm eff} \leq 10$ pc	$R_{\rm eff} > 10$ pc
$N_{\rm obj}$	242	472
$\langle R_{\rm gc} \rangle$	$3.65 \pm .11$ kpc	$3.49 \pm .07$ kpc
$\langle V \rangle$	$21.57 \pm .08$ mag	$21.73 \pm .05$ mag
$\langle V-I \rangle$	$0.75 \pm .03$	$0.73 \pm .03$
$\langle U-V \rangle$	$-0.66 \pm .05$	$-0.74 \pm .05$
$\langle R_{\rm eff} \rangle$	$6.92 \pm .14$ pc	$16.60 \pm .29$ pc

Tidal radii R_T or core radii R_C could not be determined for clusters in the Antennae, so no information is available about their concentration parameters
$c := {\rm Log} R_T/R_C$ ($= \log R_T/R_{\rm eff}$ before core collapse)
which are crucial for the question of survival or destruction (Chernoff & Weinberg 1990). Thus, we are left with effective radii as the only discriminating quantity between probable GCs and suspected open clusters (but see also Sects. 4 and 5).

In the following, we devide WS95's original YSC sample into two subsamples of clusters with $R_{\rm eff} \leq 10$ pc, which probably will contain young GCs, and of clusters with $R_{\rm eff} > 10$ pc, which may contain open clusters or OB associations, but possibly young GCs, too. Galactic GCs have effective radii in the range of $1-25$ pc (Djorgovski & Meylan 1994). We chose a delimiting $R_{\rm eff}$ of 10 pc in order not to have too low a number of objects in the small $R_{\rm eff}$ subsample.

Table 1 compares the mean properties of the two subsamples. All throughout this paper, numbers after the $\pm$ sign are standard errors. It is seen that the subsample with $R_{\rm eff} \leq 10$ pc has $\langle R_{\rm eff} \rangle = 6.9 \pm .1$ pc as compared to the mean effective radius of Galactic GCs of ~ 3 pc, while the subsample with $R_{\rm eff} > 10$ pc has $\langle R_{\rm eff} \rangle = 16.6 \pm .3$ pc.

Furthermore, Table 1 shows that clusters with $R_{\rm eff} \leq 10$ pc, as compared to clusters with larger $R_{\rm eff}$, have slightly larger mean galactocentric distances $R_{\rm gc}$, a marginally higher $V-$luminosity (by 0.16 mag), are redder in $(V-I)$ by 0.02 and in $(U-V)$ by 0.08 mag with a smaller scatter in their colours. It is worth noting that if the observed colour difference is interpreted in terms of an age difference, our evolutionary model for $Z = 0.01$ indeed indicates a luminosity difference compatible with the one observed. WS95 give an average correction for internal reddening of the YSCs of $\Delta(\mathrm{V}-\mathrm{I}) = 0.3$ mag. When compared to our $\mathrm{Z} = \frac{1}{2}\,\mathrm{Z}_\odot$ models, the dereddened $\langle \mathrm{V}-\mathrm{I}\rangle_0 = 0.45 \pm .03$ of the YSCs with $\mathrm{R_{eff}} \leq 10$ pc corresponds to a mean age of $(2 \pm 1) \cdot 10^8$ yr with a full dispersion in age ranging from $1 \cdot 10^7$ to $2 \cdot 10^9$ yr, while with $\langle \mathrm{V}-\mathrm{I}\rangle_0 = 0.43 \pm .03$ the clusters with $\mathrm{R_{eff}} > 10$ pc have a mean age of $(1.6 \pm 0.8) \cdot 10^8$ yr with an even larger dispersion ranging from $6 \cdot 10^6$ to $2.5 \cdot 10^9$ yr.

With this mean age and the assumed metallicity the YSCs with $\mathrm{R_{eff}} \leq 10$ pc will redden until an age of 12 Gyr (15 Gyr) to a $\langle \mathrm{B}-\mathrm{V}\rangle_0 \sim 0.85$ (~ 0.88, respectively). This is significantly redder than the observed $\langle \mathrm{B}-\mathrm{V}\rangle_0$ of the Milky Way, Andromeda, LMC or SMC GCs which are in the range 0.67 − 0.74 (Harris & Racine 1979). The red $\langle \mathrm{B}-\mathrm{V}\rangle_0$ is due to the higher mean metallicity of these secondary generation clusters. GC systems in ellipticals have a mean metallicity typically higher by 0.5 dex than that of spiral galaxy GC systems and are therefore expected to have $\langle \mathrm{B}-\mathrm{V}\rangle_0 \sim 0.93$ (Ashman et al. 1995). The reddest GC system known is that of the Hydra cD NGC 3311 with $\langle[\mathrm{Fe/H}]\rangle = -0.31$ dex (Secker et al. 1995). Ashman et al. 's analysis using Worthey's (1994) models as well as our own models (FB95) suggest a $\langle \mathrm{B}-\mathrm{V}\rangle_0 \sim 1.0$ for this extreme GC system, while for the metallicity we assume for the young Antennae clusters a $\langle \mathrm{B}-\mathrm{V}\rangle_0 \sim 0.9$ is predicted by Ashman et al. , close to the 15 Gyr value we obtain.

To conclude, all the differences between the two YSC subsamples do not prove but are consistent with a scenario of a global starburst contracting in time. On average, YSCs now observed with $\mathrm{R_{eff}} \leq 10$ pc formed in a slightly earlier and spatially somewhat more extended stage of the starburst. Their age spread is slightly smaller than that of the clusters with $\mathrm{R_{eff}} > 10$ pc which might still be forming now.

4. Evolution of the YSC luminosity functions over a Hubble time

In Fig. 1, we present the LFs of the star cluster subsamples with $\mathrm{R_{eff}} \leq 10$ pc (Fig. 1a) and with $\mathrm{R_{eff}} > 10$ pc (Fig. 1b). We have transformed apparent to absolute luminosities by using a distance modulus of 31.42 corresponding to a distance of 19.2 Mpc ($\mathrm{H_0} = 75$) to NGC 4038/39.

Assuming an initial metallicity of $\frac{1}{2}\,\mathrm{Z}_\odot$ and an average age of the young star clusters of 0.2 Gyr as derived in Sects. 1. and 2., our models give the (purely photometric) luminosity evolution in various passbands allowing us to calculate the LF at any time from the presently observed one. In Fig. 2., we show the LF at a time of 12 Gyr for the subsamples of clusters with $\mathrm{R_{eff}} \leq 10$ pc (Fig. 2a), and for clusters with $\mathrm{R_{eff}} > 10$ pc (Fig. 2b). Dereddened luminosities are obtained by applying a constant internal dust extinction correction of $\mathrm{A_V} = 0.5$ mag (cf. WS95) for all YSCs. Going to a later time of 15 Gyr would simply shift the LF to the fainter side by 0.3 mag in Figs 2a, b. For comparison, we also depict in Fig. 2a. a Gaussian type LF with $\langle \mathrm{M_{V_0}}\rangle = -7.1$ mag and $\sigma(\mathrm{M_V}) = 1.3$, the average values given by Harris (1991) for the GCSs of 16 galaxies, normalised to twice the number of clusters with $\mathrm{R_{eff}} \leq 10$ pc and

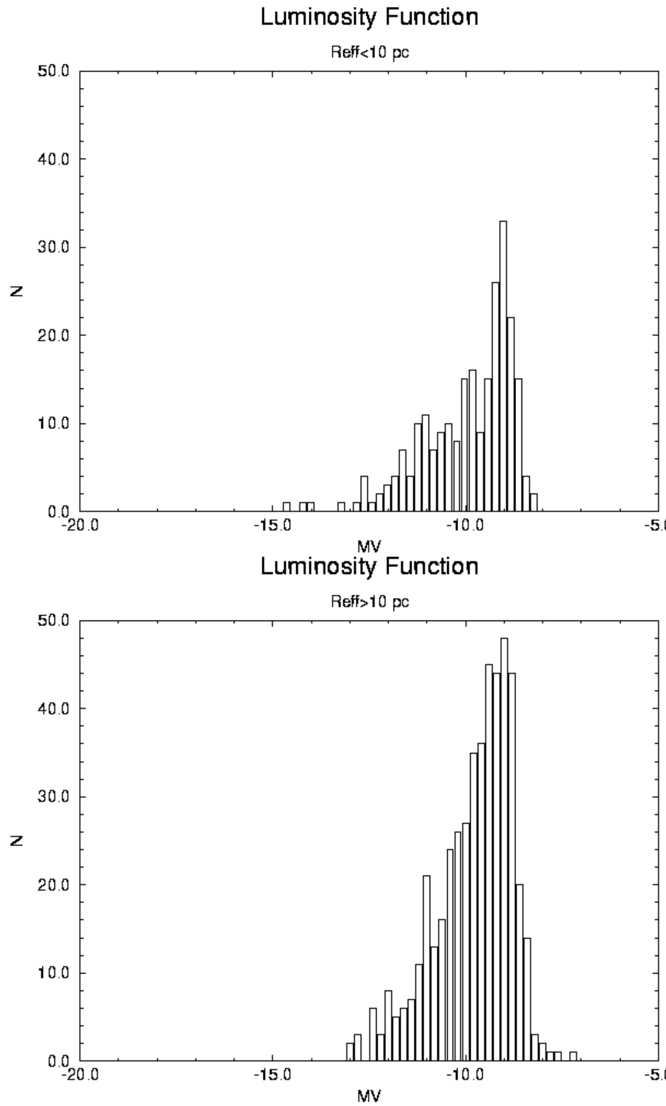

Fig. 1a and b. LFs for star clusters with $\mathrm{R_{eff}} \leq 10$ pc (**a**) and for star clusters with $\mathrm{R_{eff}} > 10$ pc (**b**) in the Antennae as observed by WS95.

$\mathrm{M_{V_0}} \leq -7.1$ mag. It is seen that the LFs for the subsamples of clusters with small and large effective radii look intriguingly different. The LF for YSCs with $\mathrm{R_{eff}} > 10$ pc indeed looks exponential like the open cluster LF in the Milky Way or the Magellanic Clouds. The LF of YSCs with $\mathrm{R_{eff}} \leq 10$ pc does not show a turnover up to the completeness limit, which has evolved to $\mathrm{M_{V_0}} = -5.7$ mag at 12 Gyr. Yet one may argue that to some degree it resembles the GC LF in the Milky Way and other galaxies with a strong overpopulation of the faint magnitude bins. It is, however, the faintest bins that may be expected to be most severely depopulated in the course of dynamical evolution (cf. Sect. 8.). Moreover, in an ongoing starburst as in the NGC 4038/39 system, our simplifying assumption that the YSCs are coeval clearly is a poor approximation and age spread effects will redistribute the final luminosities of star clusters as shown in Sect. 6. A Kolmogorov-Smirnov (**KS**) test shows that the probability for the LFs of both subsamples of clusters

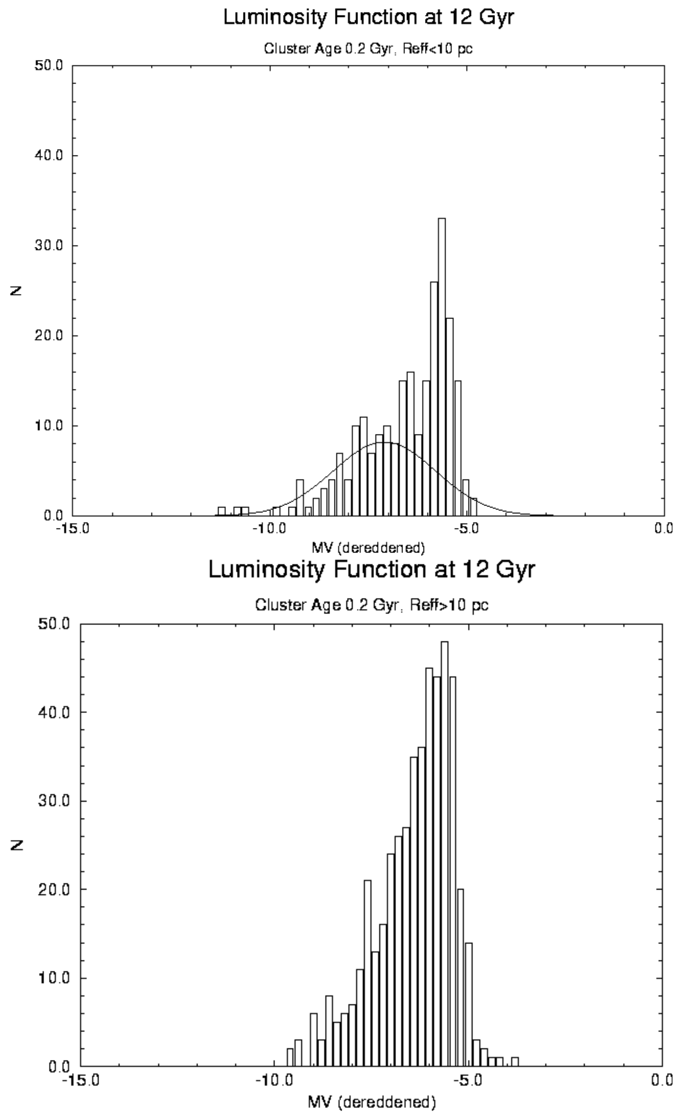

Fig. 2a and b. Dereddened LFs for star clusters with $\mathrm{R_{eff}} \leq 10$ pc (**a**) and for star clusters with $\mathrm{R_{eff}} > 10$ pc (**b**) at a cluster age of 12 Gyr as given by our models. Superimposed in **a** is a Gaussian with $\langle \mathrm{M_{V_0}} \rangle = -7.1$ mag and $\sigma_{\mathrm{M_V}} = 1.3$ mag, scaled to the total number of YSCs with $\mathrm{R_{eff}} \leq 10$ pc in the Antennae.

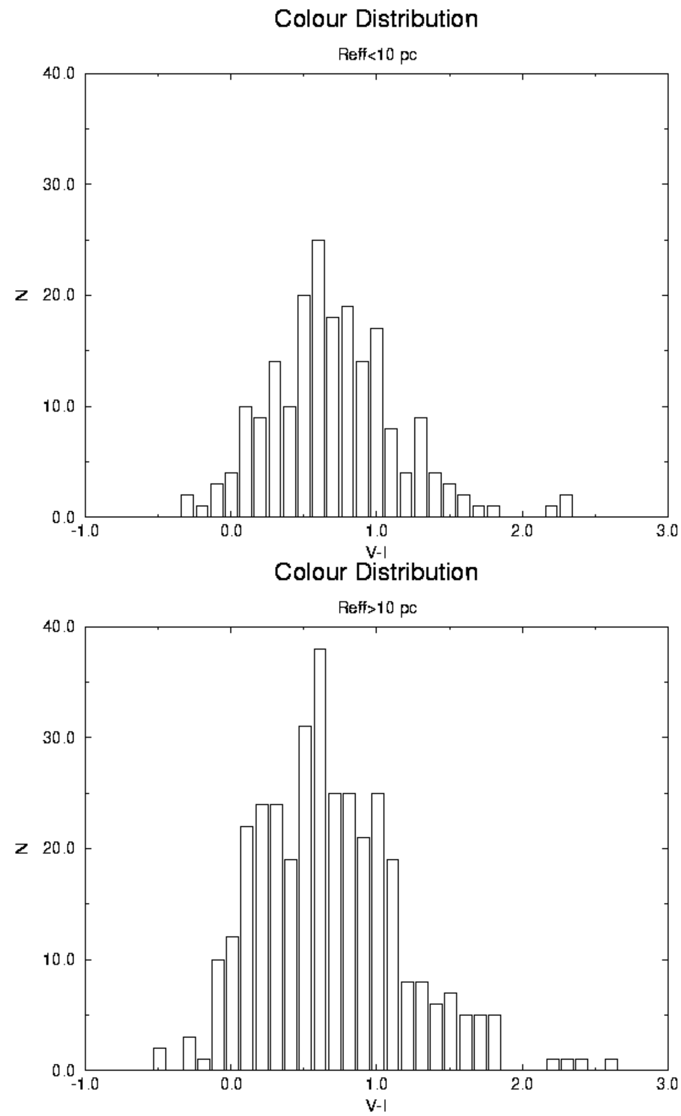

Fig. 3a and b. $\mathrm{V - I}$ colour distribution of star clusters with $\mathrm{R_{eff}} \leq 10$ pc (**a**) and of star clusters with $\mathrm{R_{eff}} > 10$ pc (**b**) at the present time as derived from WS95's observations.

to be obtained from the same parent population is 20 % if all clusters are considered and 4 % for clusters brighter than the completeness limit $\mathrm{M_{V_0}} = -9.6$ mag.

The observed crowding of YSCs may raise the suspicion that some of the apparent large $\mathrm{R_{eff}}$ clusters are in fact blended pairs of small $\mathrm{R_{eff}}$ clusters. To test for a possible contamination of the large $\mathrm{R_{eff}}$ sample by unresolved pairs we extrapolate the LF of the small $\mathrm{R_{eff}}$ clusters to fainter magnitudes (to $\mathrm{M_{V_0}} = -7.6$ mag), randomly draw pairs from this extrapolated LF and compare the LF of pairs to the LF of the large $\mathrm{R_{eff}}$ clusters. The LF of pairs contains a significant number of clusters brighter than the brightest clusters in the large $\mathrm{R_{eff}}$ subsample and a larger number of bright clusters. A KS $-$ test shows that the probability for the pair LF to be drawn from the same parent population as the LF of the large $\mathrm{R_{eff}}$ sample is $\lesssim 10$ % at levels brighter than the completeness limit.

If instead of subdividing the Antennae's YSC sample at $\mathrm{R_{eff}} = 10$ pc we divide at $\mathrm{R_{eff}} = 5$ pc the statistics becomes very poor for the YSCs with $\mathrm{R_{eff}} \leq 5$ pc but no qualitative changes in the LFs are indicated.

We conclude from Fig. 2 that the LFs evolved to an age of 12 Gyr of YSCs with $\mathrm{R_{eff}} > 10$ pc and $\mathrm{R_{eff}} \leq 10$ pc are significantly different. The similarity of the small $\mathrm{R_{eff}}$ clusters' LF with GC systems' LFs does question the use of the LF as an argument against them being young GCs, as done by van den Bergh (1995) for the entire sample using solar metallicity models from Bruzual & Charlot (1993). Unresolved close pairs of YSCs do not significantly contribute to the large $\mathrm{R_{eff}}$ cluster sample.

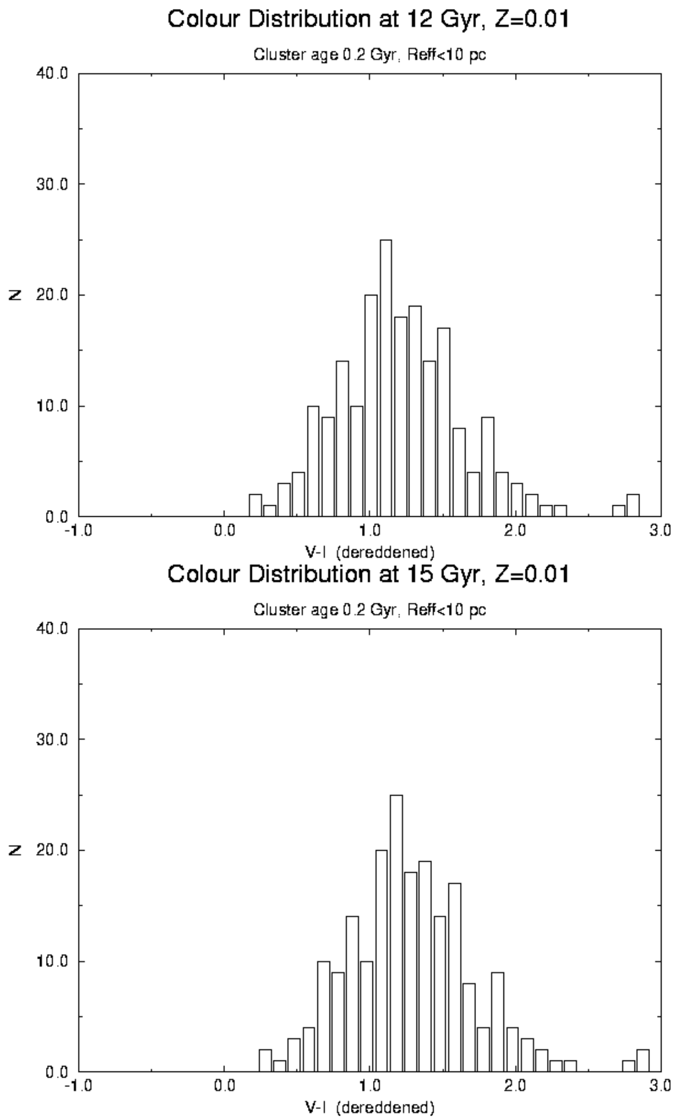

Fig. 4a and b. Dereddened $(\mathrm{V}-\mathrm{I})_0$ colour distribution of star clusters with $\mathrm{R_{eff}} \leq 10$ pc at a time of 12 Gyr (**a**) and at a time of 15 Gyr (**b**) as calculated from our models.

Fig. 3 presents the observed colour distribution (WS95) for YSCs with $\mathrm{R_{eff}} \leq 10$ pc (Fig. 3a) and for clusters with $\mathrm{R_{eff}} > 10$ pc (Fig. 3b). For the more extended clusters the colour distribution is broader than for the small $\mathrm{R_{eff}}$ subsample and slightly shifted to the blue. For clusters brighter than the completeness limit, a KS-test gives a 15 % probability for the two colour distributions to be drawn from the same parent population.

Fig. 4 shows the dereddened colour distribution of the small $\mathrm{R_{eff}}$ subsample after 12 (Fig. 4a) and 15 Gyr (Fig. 4b) of undisturbed evolution. With $\langle \mathrm{V}-\mathrm{I}\rangle_0 = 1.15$ and $\langle \mathrm{V}-\mathrm{I}\rangle_0 = 1.23$ at 12 Gyr and 15 Gyr, respectively, the mean colour of YSCs in the Antennae, when only passively aged for our assumed metallicity of Z$= 0.01$ and a common age of the YSCs of 0.2 Gyr, is very close to the mean $\langle \mathrm{V}-\mathrm{I}\rangle = 1.20$ of the Milky Way halo GC system.

We caution, however, that these colours distributions simply were obtained by shifting the observed colour distribution (Fig. 3a) by the amount of reddening given by our evolutionary models during aging of the YSCs. Age spread effects that change the LF will also affect the colour distribution as shown in the next section. We expect the red clusters to be older than average and therefore to redden less during further evolution, while blue clusters may tend to redden more. Thus, we expect age spread effects to reduce the width of the colour distribution over a Hubble time.

5. Age distribution of star clusters in the Antennae: young star clusters and old globular clusters

In an ongoing starburst as in the Antennae, the age spread among YSCs can be comparable to their ages, and age spread effects may be expected to significantly affect the time evolution of the LF (see also Meurer 1995).

We therefore, in a second step, derive individual ages for the YSCs from their individual $(\mathrm{V}-\mathrm{I})_0$, dereddened using a common internal dust correction $\Delta(\mathrm{V}-\mathrm{I}) = 0.3$ mag as given by WS95 for all clusters and assuming that all YSCs have the same metallicity Z$= \frac{1}{2}$ $\mathrm{Z}_\odot$.

In Fig. 5a, we present the age distribution of all star clusters in the Antennae. It shows two strictly distinct peaks, a very strong one at ages $(0-4)\cdot 10^8$ yr and a smaller one around 12 Gyr. Out of the 714 clusters of WS95, 164 do not allow for age determination because they lack I $-$ band observations. Of the remaining 550 clusters, 399 have ages $(0-4)\cdot 10^8$ yr, 32 are as old as 12 Gyr, provided they do not suffer from much larger than average extinction. 119 are interlopers with $4\cdot 10^8$ yr < age < 12 Gyr, most of them with ages below 1 Gyr. We estimate ages derived from $(\mathrm{V}-\mathrm{I})_0$ colours to be accurate within ± 60 % over the range from $\sim 10^7 \ldots 10^{10}$ yrs. $(\mathrm{U}-\mathrm{V})_0$ colours allow for slightly more precise (± 40 %) age dating at early stages.

If the 37 clusters with apparent ages $3\,\mathrm{Gyr} < \mathrm{age} < 12$ Gyr had a lower metallicity of $\mathrm{Z} = 1\cdot 10^{-3}$ or $\mathrm{Z} = 1\cdot 10^{-4}$, they might well have ages of 12 or 15 Gyr, respectively. On the other hand, if the 82 clusters with ages in the range $4\cdot 10^8$ to $< 3\cdot 10^9$ yr were in an environment with a higher than average dust reddening or if they had a metallicity $\mathrm{Z} > 0.01$, their ages could easily be reduced to $\lesssim 4\cdot 10^8$ yr. Thus, we believe that there is no convincing evidence for the existence of intermediate age clusters, rather we expect a non-homogeneous internal dust distribution and an intrinsic scatter in metallicity comparable to the one observed for every GC system to be responsible for the apparent interlopers. The 32 old clusters from the 12 Gyr peak in Fig. 5a and the 37 interlopers with ages ≥ 3 Gyr for which we argue that their ages may be underestimated must be part of the original GC population of the interacting spirals NGC 4038 and 4039. 53 of them are brighter than the completeness limit of $\mathrm{M_V} = -9.1$ mag. Comparing to the Milky Way and M31 GCLFs we find that 10/131 GCs (Milky Way) and 27/200 GCs (M31) are brighter than the completeness limit. By analogy one would expect NGC 4038 and NGC 4039, together, to have had of the order of $20-50$ GCs brighter than -9.1 mag.

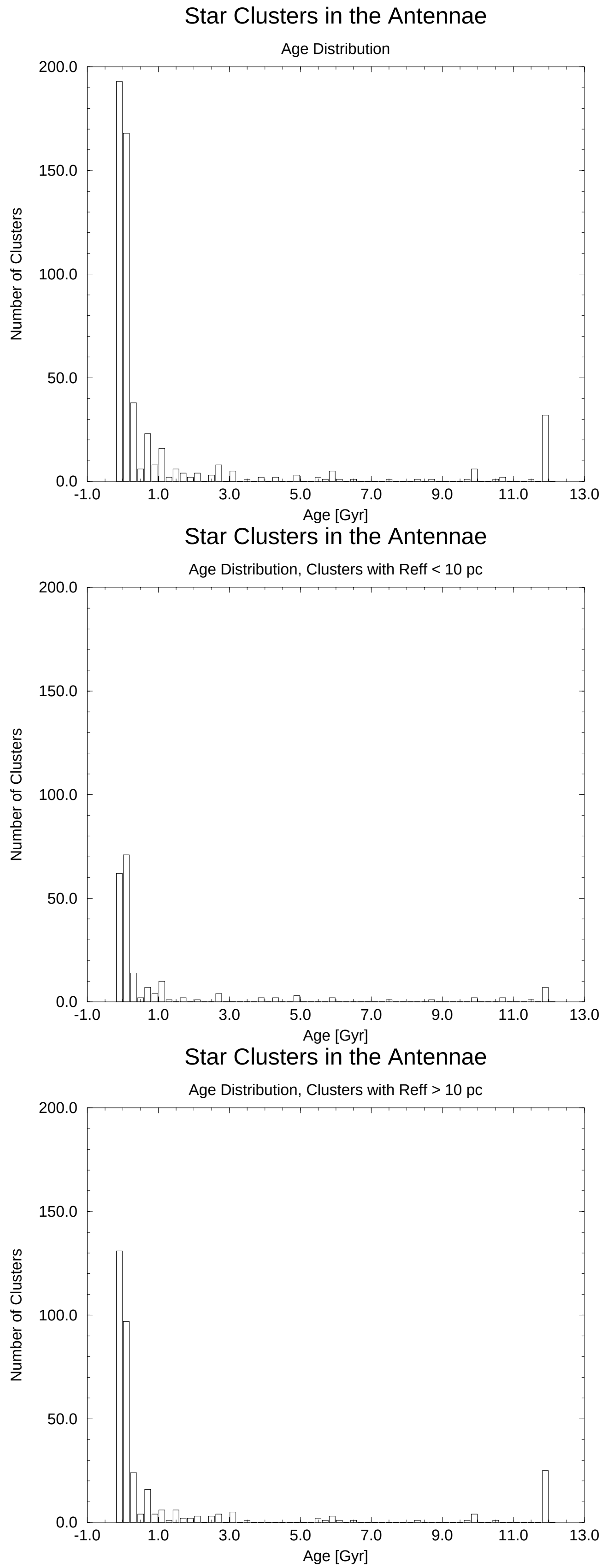

Fig. 5a–c. Age distribution of star clusters in the Antennae. **a** all clusters, **b** clusters with $R_{eff} \leq 10$ pc, **c** clusters with $R_{eff} > 10$ pc.

The number ratio of young to old clusters is ~ 12, while including the interlopers the number ratio of probably young to probably old clusters drops to ~ 7.

Some of the 69 objects we tentatively identify as old GCs from the Antennae system's progenitor spirals might in fact be extremely reddened YSCs. However, they have $(V-I)$ colours in the range $1.3-2.7$ mag and if they were YSCs with their red colours entirely due to larger than average internal extinction, their $V-$magnitudes should be affected by $A_V = 1.3-3.8$ mag which is much larger than the observed luminosity difference between the red and blue star cluster subsamples (cf. Sect. 7.1). Moreover, visual inspection of the projected distribution of what we chose to call old GCs shows that they are not as strongly clustered as are the blue YSCs, nor do they trace the internal tidal structure of NGC 4038/39 as do the blue clusters. While a few of the very red clusters lie close to very blue ones, their overall distribution looks much more spherically symmetric than that of the blue clusters.

WFPC2 imaging is expected to go $\gtrsim 2$ mag deeper for the Antennae (WS95) and thus should reach or come close to the turn-over of the LF of the original GCSs. This would then allow for a reasonable statistical analysis of the spatial distribution of the red clusters, for a reliable estimate of the progenitor spirals' total number of GCs, and for a detailed comparison of the old GCS and the YSC systems. Until then, we cannot exclude the possibility that a small fraction of the red clusters may be exceptionally reddened bright YSCs.

38 out of the 48 YSCs with $(U-V)$ colour available allow for age dating while 10 have $(U-V)$ bluer than ever reached by our $\frac{1}{2}\ Z_\odot$ model. Either their extremely blue $(U-V)$ is influenced by gaseous emission, or their metallicity is particularly low, or $-$ perhaps most plausibly $-$ they are affected by less than average reddening inside the Antennae. For the 38 YSCs with $(U-V)_0 \geq -1.15$, i.e. within the range of our $\frac{1}{2}\ Z_\odot$ model, ages derived from $(U-V)_0$ agree with those derived from $(V-I)_0$ to within $\leq 1 \cdot 10^7$ yr.

Figs. 5b and 5c present the age distributions of compact and extended clusters, respectively. They are clearly different as confirmed by a KS-test. The probability that they are drawn from the same parent population is $4 \cdot 10^{-7}$. It is interesting to note that the number ratio of YSCs to old GCs is larger among the compact cluster subsample than among the extended clusters: $N_{YSC}/N_{GC} \sim 21$ for clusters with $R_{eff} \leq 10$ pc as compared to $N_{YSC}/N_{GC} \sim 10$ for clusters with $R_{eff} > 10$ pc. If we restrict the age analysis to clusters brighter than the completeness limit, we preferentially lose old GCs because they tend to be fainter than the bulk of the YSC population. This increases the ratio N_{YSC}/N_{GC} by about a factor of 2. Nevertheless, the number ratio of young to old clusters remains larger by almost a factor 2 among the small R_{eff} clusters than among the large R_{eff} clusters, contrary to what would be expected if the bulk of the YSCs formed in the merger were open clusters instead of proto-globulars. Restriction to clusters brighter than $M_{V_0} = -9.6$ mag drastically reduces the relative number of interlopers in the age distribution, supporting our argument in favour of 2 distinct episodes of cluster formation separated by a time span of more than 10 Gyr.

In summary, it turns out that the bright star cluster population detected with WFPC1 in the Antennae contains an important fraction of ~ 12 Gyr old objects (69 out of 550 clusters for which age dating is possible) most of which seem to be part of the bright end of the original spirals' GC population. The number ratio of YSCs to old GCs is larger by a factor ~ 2 among the small $\mathrm{R_{eff}}$ subsample than among the extended clusters.

6. Age spread effects on the LF

Meurer (1995) pointed out the possible importance of age spread effects on the future luminosity evolution of YSCs. Faint clusters, on average, will tend to be older than bright ones. As a consequence, they will fade less during further evolution, migrating from fainter to brighter bins in the LF. Clusters brighter than average, by analogy, tend to evolve to fainter bins of the LF.

So now, from the individual cluster ages derived in Sect. 5, we calculate the individual fading of each of the YSCs up to a common age of 12 Gyr.

In Fig. 6a, we present the LF of the YSC population evolved until an age of 12 Gyr, i.e. the aged LF of those 481 clusters with present ages < 3 Gyr, for which we argued in Sect. 5. that they most probably formed in the ongoing galaxy merger. To estimate the position of the competeness limit in this plot, we take a YSC at the observational competeness limit given by WS95 and evolve it from the mean YSC age to 12 Gyr. Thereby, it will fade to $\mathrm{M_{V_0}} = -5.7$ mag which we call the evolved completeness limit. The LF of the YSCs aged to 12 Gyr clearly shows a turnover ~ 1 mag brighter than the evolved completeness limit. Overplotting a Gaussian with $\mathrm{M_{V_0}} = -6.9$ mag and $\sigma(\mathrm{M_V}) = 1.3$ mag, normalised to the number of clusters in our histogram, we find that the agreement is not too bad. The turnover occurs at an $\mathrm{M_{V_0}}$ fainter by ~ 0.2 mag than for typical GCSs.

Ashman et al. 1995 show that the turn-over of the GCLF is metallicity dependent. Spiral galaxies typically have $\langle[\mathrm{Fe/H}]\rangle_{\mathrm{haloGCs}} = -1.35$ and a turnover $\mathrm{M_{V_0}} \sim -7.3$ mag, while a typical elliptical has a characteristic metallicity of its GCS higher by 0.5 dex and a turn-over fainter by ~ 0.15 mag, in agreement with FB95's models. We have argued that the metallicity of stars and clusters formed in the interaction-triggered starburst in the Antennae should be [Fe/H] ≥ -0.7 and, by analogy to NGC 7252, probably around [Fe/H] ~ -0.4. This means that if some of the bright blue knots are young GCs a bimodal metallicity distribution as e.g. observed in the suspected merger remnants NGC 4472 and NGC 5128 (Harris et al. 1992, Zepf & Ashman 1993, Ostrov et al. 1993) or in M87 (Elson & Santiago 1996) should be expected to persist over a Hubble time in the Antennae GC system. The original, low-metallicity GC population of the progenitor spirals then should show a LF peaking at $\mathrm{M_{V_0}} = -7.3$ while the higher metallicity secondary generation GCs will have a LF peaking at fainter magnitudes, e.g. for [Fe/H] $\gtrsim -0.4$ at $\mathrm{M_{V_0}} \gtrsim -7.0$ (cf. Fig. 2 of Ashman et al. 1995). Thus, the higher metallicity of a secondary GC population might explain the turn-over around $\mathrm{M_{V_0}} \sim -6.9$ mag that is indicated in Fig. 6a.

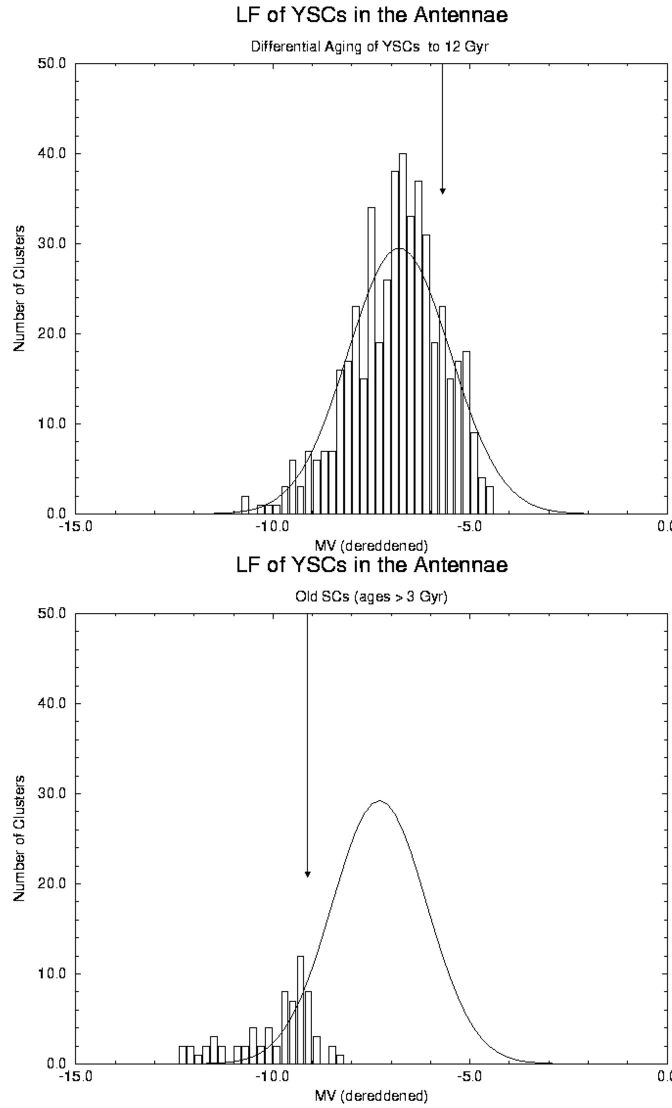

Fig. 6. a LF of YSCs in the Antennae as calculated from individual ages together with the resulting individual fading until 12 Gyr for every cluster. A Gaussian with $\langle\mathrm{M_{V_0}}\rangle = -6.9$ mag and $\sigma(\mathrm{M_{V_0}}) = 1.3$ mag is overplotted, normalised to the number of clusters in the histogram. **b** present dereddened LF of the old GC population from the progenitor spirals together with a Gaussian with $\langle\mathrm{M_{V_0}}\rangle = -7.3$ mag and $\sigma(\mathrm{M_{V_0}}) = 1.2$ mag (Ashman et al. 1995), normalised to the total number of GCs in the Milky Way and M31. Vertical arrows indicate the observational completeness limit.

WS95 present in their Fig. 9 the present-day LF of the entire YSC sample, which clearly looks exponential up to the completeness limit. In Sect. 4 we showed that without taking age spread effects into account aging simply shifts the LF to fainter magnitudes without changing its shape. Comparison with our LF in Fig. 6a clearly reveals the strong changes that the inclusion of the age spread among a YSC population induces on the shape of the LF during time evolution. In this respect we confirm and quantify Meurer's (1995) conjecture.

A release of our simplistic assumption of a homogeneous metallicity for all − older and younger − YSCs in the sense that the youngest of them should be expected to have a higher metallicity than those which formed at the very beginning of the starburst (cf. Fig. 12 in Fritze − v. Alvensleben & Gerhard 1994) would bring along further repartition effects because the fading gets stronger as the metallicity of a star cluster increases: e.g. between ages of 10^7 yr and 12 Gyr a YSC with $Z = 1 \cdot 10^{-3}$ would fade by 4.8 mag while with $Z = \frac{1}{2}\ Z_\odot$ it would fade by 5.4 mag and with $Z = 2 \cdot Z_\odot$ by as much as 5.6 mag (cf. Fig. 2 in FB95). The most metal-poor YSCs are expected to be the oldest, i.e. already somewhat fainter that at birth. They will fade less during subsequent evolution while the most metal rich ones should be the youngest, i.e. among the brightest, and they will fade more than average. In this way, a metallicity spread would cause the LF to become narrower over a Hubble time. Our LF calculated with a single homogeneous metallicity is already well fit by a Gaussian with $\sigma(M_V) = 1.3$ mag, the typical value for all known GCSs, so a strong metallicity spread among the YSCs in the Antennae might lead to a very narrow final LF. Our metallicity prediction, however, needs verification by individual spectroscopy of some YSCs, which, at the same time, will give an impression of the possible importance of a scatter in metallicity or abundance ratios.

The global detection limit given by WS95 is very conservative in the sense that it is valid for the central, most crowded regions with the brightest background. We verified this on LFs of YSCs from several rings centered on the nucleus of NGC 4038. Thus, we do not expect missing clusters to significantly affect the shape of the LF.

We caution that dynamical effects are still not included in our modelling. If they should be expected to further reshape the LF over a Hubble time − beyond the photometric evolution discussed here − will be investigated in Sect. 8.

It came as a surprise to us that the evolved LF of **all** the bright YSCs so closely resembles a typical GCLF. We started our analysis with the aim of finding out some selection criterion for a subsample of objects, as e.g. with small R_{eff} or high luminosity, that may evolve into an old GC population while we expected an unknown but − in view of the relatively young age of the burst − possibly important fraction of open clusters and associations to be present, too. Our results seem to indicate that either the bulk of the YSCs recently formed in NGC 4038/39 are indeed young GCs or else that from the range and distribution of integrated luminosities there are no strong intrinsic differences between young open and globular clusters **and** that dynamical destruction does not significantly reshape the LF down to ~ 1 mag below the turnover. In this respect, it will be very interesting to extend the present analysis of the LF to fainter magnitudes using WFPC2 data.

In Fig. 6b, we present the present-day, i.e. the observed and dereddened LF of the star cluster subsample with ages ≥ 3 Gyr for which, in Sect. 5, we argued that they might belong to the progenitor spirals' original GC population. It comprises 69 clusters, 55 of them brighter than the completeness limit of the observations corresponding to $M_{V_0} = -9.1$ mag. We compare this bright end of the old star cluster LF to a Gaussian with $M_{V_0} = -7.3$ mag and $\sigma = 1.2$ mag (Ashman et al. 1995), normalised to the total number of GCs in both the Milky Way and M31. While a different shape of their LF is, of course, not ruled out, the reasonable agreement at the high luminosity tail lends support to our conjecture that these red old clusters may belong to the original GC population. If the interacting galaxies NGC 4038 and 4039 together really had a number of GCs comparable to that of the Milky Way and M31, then the number of bright YSCs formed in the merger is of the same order as the number of GCs of the two spirals. This is the number ratio that is required if an elliptical galaxy with a typical GC frequency were to be formed from a merger of two spirals (Zepf & Ashman 1993). Major uncertainties, however, come from the fact that the starburst and cluster formation may go on in the Antennae as well as from the unknown fraction of open clusters/associations among the YSC population.

As seen in Fig. 2 of FB95, fading is strongest during the first Gyr ($\Delta M_V \sim 1$ mag from $2 \cdot 10^8$ to $1 \cdot 10^9$ yr), weaker during intermediate stages ($\Delta M_V \sim 0.42 \frac{\rm mag}{\rm Gyr}$ for ages $1 - 6$ Gyr), and very weak at old ages ($\Delta M_V \sim 0.075 \frac{\rm mag}{\rm Gyr}$ for $8 -$ 16 Gyr). Thus, if we evolve the LF until 16 Gyr instead of 12 as in Fig. 6a., its shape does not change any more, it will only be shifted by $\Delta M_V \sim 0.3$ to slightly fainter magnitudes.

Age spread effects will, of course, reshape not only the LF, but also the colour distribution of a YSC system. Over a Hubble time, the internal dust extinction in the Antennae may also be expected to change a lot, as the starburst consumes and/or blows out the gas and dust now observed. The bimodal metallicity distribution we predict for the Antennae GC system will result in a bimodal colour distribution similar to the one found by Whitmore et al. (1995) and Elson & Santiago (1996) for the M87 GC system.

7. Discussion

7.1. Comparison of young and old star cluster properties

Here we compare average properties of the red ($(V-I)_0 \geq 0.95$) and blue ($(V-I)_0 < 0.95$) star cluster subsamples. We argued that the red subsample may mainly consist of the brightest GCs from the original spirals while we expect the blue subsample to contain some mixture of young open clusters, associations and globular clusters.

Table 2 summarises average quantities of the two subsamples with $(V-I)_0 < 0.95$ and $(V-I)_0 \geq 0.95$. For 164 clusters, no $(V-I)$ observations are available. It is seen that the 69 red clusters populate an area within NGC 4038/39 somewhat more extended than the 481 blue ones. If dust were somehow concentrated to the center, the redder subsample should be less affected by dust than the bluer one, thus increasing the colour difference.

Plotted separately as projected on the sky, the blue YSCs and the red GCs show very different spatial distributions. While the

Table 2. Comparison of old and young star cluster subsamples.

	$(V-I)_0 \geq 0.95$	$(V-I)_0 < 0.95$
N_{obj}	69	481
$\langle R_{gc} \rangle$	$3.92 \pm .24$ kpc	$3.42 \pm .07$ kpc
$\langle V \rangle$	$22.05 \pm .12$ mag	$21.36 \pm .05$ mag
$\langle V-I \rangle$	$1.61 \pm .04$	$0.61 \pm .02$
$\langle U-V \rangle$	–	$-0.70 \pm .04$
$\langle R_{eff} \rangle$	$12.04 \pm .95$ pc	$12.41 \pm .30$ pc

blue clusters tightly trace the tidal structure as seen on WS95's HST image of the Antennae, the red clusters show a more spherically symmetric distribution as expected for the original GC population.

The redder clusters are fainter by ~ 0.7 mag with a scatter slightly smaller that the blue ones. If the difference in $\langle V-I \rangle$ of 1 mag were due to stronger than average internal dust reddening the red clusters should be fainter than the blue ones by as much as 1.7 mag, on average.

Their $\langle V-I \rangle_0 = 1.31 \pm .04$ corresponds to a mean age of 13 ± 3 Gyr (7 ± 3 Gyr) with the full age dispersion ranging from $4-15$ Gyr ($1-10$ Gyr) for Z=0.01 (and for Z=0.04). Clusters with $Z < 0.01$ in our models do not reach colours as red as $(V-I)_0 = 1.3$ until 15 Gyr, values $(V-I)_0 > 1.6$ are not even reached by our model clusters with $Z = 0.04$. So we suspect, that these very red clusters are affected by stronger than average dust reddening. The average $\langle V-I \rangle_0$ of the bluer clusters is bluer by 1 mag than that of the redder ones and indicates a mean age of $(1 \pm .2) \cdot 10^8$ yr with a dispersion ranging from $5 \cdot 10^6$ to $5 \cdot 10^8$ yr for Z = 0.01. The mean dereddened luminosity of the red subsample is $\langle M_{V_0} \rangle = -9.87 \pm .12$, so it is only the brightest of the really old GCs from the parent galaxies of the merging system, which are seen in the red subsample.

From our models, the age difference between the subsamples corresponds to a fading by ~ 4.2 mag if they have the same metallicity and of 4.6 mag if the redder ones have $Z = 1 \cdot 10^{-3}$. If the redder ones are older and fainter, however, only the very brightest of them can be observed, so that their mean brightness is overestimated. On the other hand, this difference may also result if chances to survive a Hubble time were larger for brighter and more massive clusters (cf. Sect. 8).

7.2. Effective radii of GCs and YSCs

The mean effective radius of the red subsample is slightly smaller than that of the bluer clusters. If they are really old this can be understood in terms of a preferential destruction of large R_{eff} clusters strong enough to overcome the increase in R_{eff} caused by internal stellar mass loss ($\sim 20\%$ in R_{eff}) and mass loss through tidal stripping (cf. Sect. 8). The difference in R_{eff} is surprisingly small, however, in view of our expectation that the old star cluster population should consist of GCs while the blue and young star population might comprise open clusters and OB associations, as well. The distribution of effective radii of the YSC subsample has a clear maximum around 8 pc with a tail extending to ~ 32 pc, that of the old GC sample is somewhat flatter but otherwise very similar.

The breakdown of the age distribution into clusters with small and large R_{eff} in Figs 5b and 5c shows that while 11% of the 201 clusters with $R_{eff} \leq 10$ pc belong to the old and 89% to the young population, the respective fractions are 13% and 87% for the 349 clusters with $R_{eff} > 10$ pc. It is clear that the old objects must almost all be globulars, even those with $R_{eff} > 10$ pc, except for a small number of very old open clusters as reported for the Milky Way by Friel (1995). Galactic GCs typically have R_{eff} in the range $2-5$ pc, but a few (of the brightest) also reach $20-25$ pc (cf. Djorgovski & Meylan 1994). Among the old GC population the number ratio of objects with $R_{eff} \leq 10$ pc to those with $R_{eff} > 10$ pc is 23/46 while among the YSC population it is 178/303. This corresponds to a fraction of objects with $R_{eff} \leq 10$ pc of 33% among the old GC population, while this fraction amounts to 37% in the YSC population.

To summarize, the red old GC population is slightly more extended than the population of young blue star clusters forming in the merger-induced starburst in the Antennae. While the blue YSCs trace the tidal structure, the red clusters rather show a spherically symmetric distribution. Interestingly, the mean as well as the distribution of **effective radii are not significantly different for the bright end of the old GC population and for the less than 1 Gyr old young star cluster population** which might be expected to also comprise an unknown fraction of open clusters and OB associations together with young GCs.

7.3. Luminosity evolution of compact and extended YSCs

In Figs. 7a and b, we present the LFs of the YSCs (age < 3 Gyr) with $R_{eff} \leq 10$ pc and $R_{eff} > 10$ pc, respectively, both differentially aged to 12 Gyr. No significant difference comparable to the one discussed in Sect. 4 is visible any more. Strikingly and at variance with our simplified analysis in Sect. 4., **both the differentially aged LFs of subsamples with $R_{eff} \leq 10$ pc and $R_{eff} > 10$ pc now do show a turnover at $M_{V_0} \sim -6.9$ mag**, as seen in Figs. 7a, b.

So, while no doubt some open clusters may be among the YSC population, preferentially within the large R_{eff} subsample, **it might well be that the bulk of the YSC population are young GCs**.

7.4. Subdivision with respect to luminosity

Luminosity is another plausible criterion to subdivide the YSC sample of WS95 into GC and open cluster/association subclasses. One might conjecture that the most luminous objects might be young globulars while the fainter ones could also be open clusters/associations. To explore this hypothesis we subdivide the YSC sample of WS95 into subsamples of bright and faint clusters with a limiting $M_V = -9.5$ mag, corresponding to

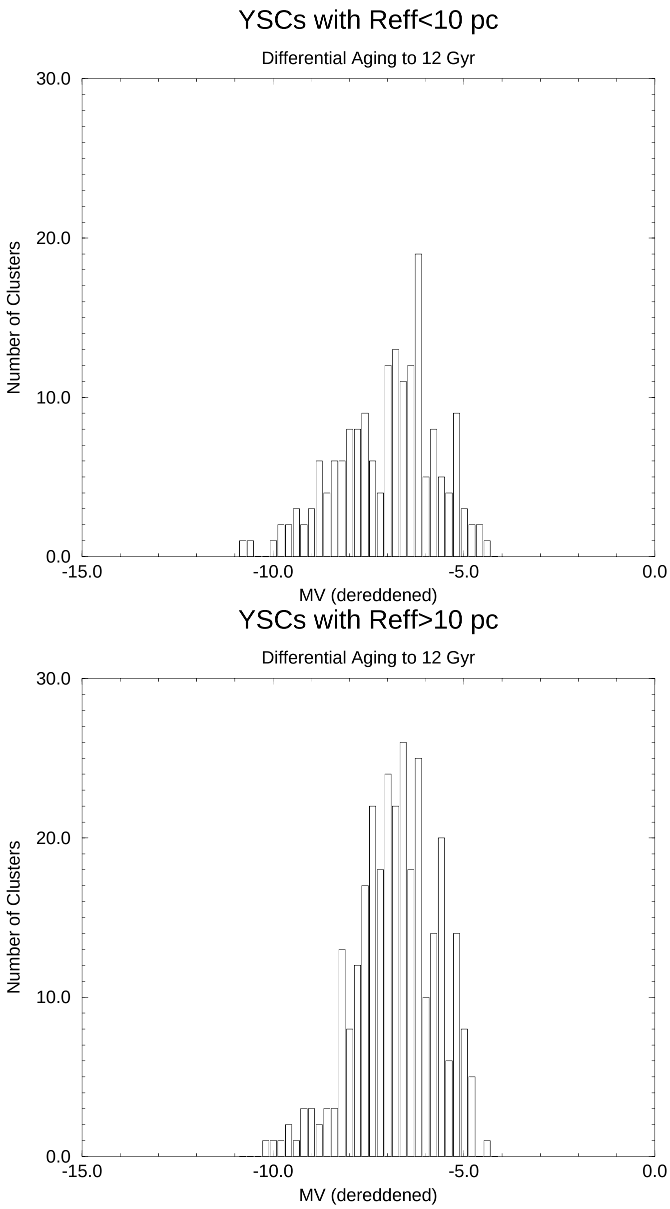

Fig. 7a and b. Differentially aged LFs of YSCs in the Antennae at 12 Gyr. **a** clusters with $R_{eff} \leq 10$ pc and **b** clusters with $R_{eff} > 10$ pc.

a dereddened $M_{V_0} = -10.0$ mag. Table 3 presents the average properties of the faint and bright subsamples. Our choice of the limiting magnitude makes both subsamples contain comparable numbers of objects.

The fainter clusters, on average, seem to have larger galactocentric distances. It is not clear, however, if this is a real effect or due to the fact that low luminosity clusters are harder to detect near the center. The mean V − magnitude of the faint subsample is ~ 1.7 mag fainter than that of the brighter one, the rms scatter is less than half that of the brighter one. Faint clusters are redder by 0.3 mag in $(V-I)$. Unfortunately, no $(U-V)$ colours are available for the faint subpopulation. It should be noted that the differences in V and $(V-I)$ cannot be explained by reddening differences but may be understood in terms of age

Table 3. Comparison of young star cluster subsamples.

	$M_V > -9.5$ mag	$M_V \leq -9.5$ mag
N_{obj}	358	356
$\langle R_{gc} \rangle$	$3.79 \pm .09$ kpc	$3.29 \pm .08$ kpc
$\langle V \rangle$	$22.50 \pm .02$ mag	$20.85 \pm .05$ mag
$\langle V-I \rangle$	$0.93 \pm .03$	$0.61 \pm .02$
$\langle U-V \rangle$	–	$-0.70 \pm .04$
$\langle R_{eff} \rangle$	$7.88 \pm .24$ pc	$8.94 \pm .26$ pc

differences (see below). Finally, the mean effective radius of the fainter subpopulation is smaller by ~ 1 pc and the rms scatter is smaller, too, than the respective values of the bright subsample. All differences between the bright and faint subsamples increase if we chose a brighter limiting magnitude for our subdivision.

The bright clusters have a mean age of their young population of $1.5 \cdot 10^8$ yr, younger by almost a factor of 2 than that of $2.7 \cdot 10^8$ yr for the fainter ones. In the age distribution of the bright subsample the vast majority of clusters is young, only 24/331 ($=7$ %) are $3-12$ Gyr old. The age distribution of the faint clusters shows 45/219 ($=20$ %) clusters to be old ($3-12$ Gyr) and 174/219 ($=79$ %) to be young ($0-3$ Gyr). In Sect. 5, we argued that because of inhomogeneous metal and dust distributions probably most clusters with ages < 3 Gyr are as young as $\lesssim 4 \cdot 10^8$ yr and most clusters with ages > 3 Gyr are as old as 12 Gyr. After differentially aging all clusters from their present individual ages to an assumed final age of 12 Gyr, however, the brighter subsample will keep a final luminosity $\langle M_{V_0} \rangle = -7.4$ mag, brighter than the fainter subsample which will end up with $\langle M_{V_0} \rangle = -6.7$ mag. As shown in Fig. 8, after 12 Gyr, the LF for the bright subsample clearly shows a turn-over definitely brighter than the completeness limit. It closely resembles the Gaussian LF of GCs with typical parameters $\langle M_{V_0} \rangle = -7.1$ mag, $\sigma = 1.3$ mag rather than the exponentially increasing LF of open clusters. The fact that the turn-over is slightly brighter than the one we expect on the basis of our metal prediction − if it is true − might indicate that a limiting magnitude $M_{V_0} = -10$ is still so bright as to exclude part of the young GC population. The LF of the faint clusters contains an important fraction of ~ 12 Gyr old clusters. If these are left aside when the LF is evolved over a Hubble time, we again observe a turn-over, however only slightly before the completeness limit is reached, i.e. at $\langle M_{V_0} \rangle = -6.2$ mag.

To summarise: the faint cluster subsample contains a $\sim$ 20% proportion of ~ 12 Gyr old GCs, it is a little less concentrated to the center on average than the bright subsample. It seems to have marginally smaller $\langle R_{eff} \rangle$ than the bright one, allthough we caution that large R_{eff} clusters are harder to detect among the faint subsample. The LF of the subsample of clusters brighter than $M_{V_0} = -10.0$ mag evolved over 12 Gyr closely agrees with a typical GC system's LF ($\langle M_{V_0} \rangle = -7.1$

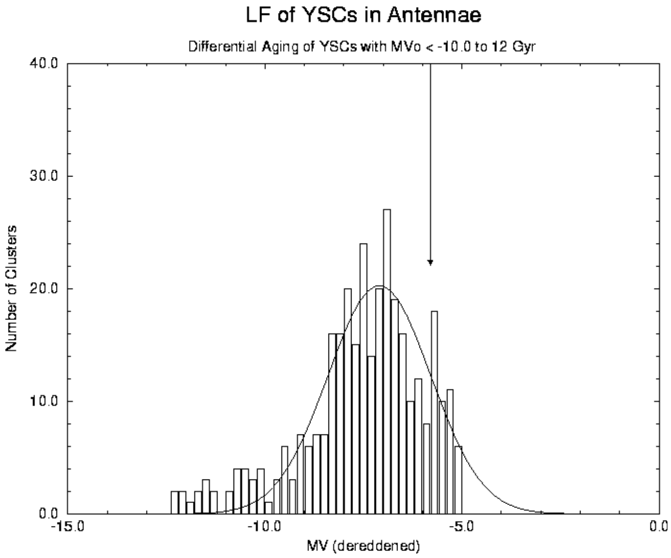

Fig. 8. LF of bright YSCs with $M_{V_0} \leq -10.0$ mag differentially aged to 12 Gyr. Overplotted is a Gaussian with $\langle M_{V_0} \rangle = -7.1$ mag, $\sigma = 1.3$ mag, normalised to the number of YSCs in the histogram.

mag, $\sigma = 1.3$ mag), provided age spread effects are properly accounted for.

7.5. Need for future observations

All the data discussed here were taken by WS95 with HST WFPC1, i.e. before the refurbishment mission. The Antennae are close enough to even identify the brightest members of the original GC population on these aberrated images. WS95 expect reobservations with WFPC2 to go deeper by 2−3 mag. If so, we might be able to observe beyond the turn-over of the original GC population. Then both the old GC population and the YSC population can directly be compared. It would be very interesting to have spectroscopy for some of the clusters to settle their metallicity range and to allow for better age-dating. At the same time, YSC spectra will provide information about the local dust distribution and, if spectral resolution allows, also about the kinematics of the YSC system.

The very youngest star clusters will give us the chance to directly study the upper IMF.

8. Dynamical effects on the GCLF

It is generally accepted that an old GCS, as e.g. observed in the Milky Way, only encompasses "the hardiest survivors of a larger original population" (Harris 1991).

Fall & Rees (1977) were the first to discuss the erosive effect on a GCS through its environment. Ostriker (1988) lists a number of − partly interrelated − processes, that modify star cluster properties and decimate the original cluster population. Dynamical effects are conveniently distinguished into internal dynamical effects due to stellar mass loss and external dynamical effects from the parent galaxy potential.

8.1. External dynamical effects

The most important external dynamical effect for clusters in the Antennae is probably tidal shocking of clusters near the center and of clusters on highly eccentric orbits that pass close to the high density central parts of the merging system, in particular, if the Antennae is to evolve into a high central density elliptical or S0 - like merger remnant. Tidal shocking leads to evaporation and is strongest for low concentration clusters, which, in turn, tend to be those with lower luminosity (Djorgovski 1991). Dynamical friction, as well, may destroy clusters near the center, and this process preferentially acts on the massive ones.

For GC populations in non-interacting galaxies, these effects were studied by Chernoff & Weinberg (1990), their results are largely confirmed by the independent and more realistic approach of Fukushige & Heggie (1995).

Unfortunately, it is the concentration parameter

$c := \mathrm{Log}\ R_T/R_C$ (= $\mathrm{Log}\ R_T/R_{eff}$ before core collapse)

that − besides the orbital parameters − plays the key role for the question of survival or destruction of a star cluster. Due to the fact that tidal radii are not accessible observationally the concentration parameters of YSCs as well as those of the old GCs in merger remnants like the Antennae remain unknown. An estimate of c from correlations to other quantities (eg. luminosity) as observed in **old** GCSs does not seem reasonable since it is not clear to what extent these correlations reflect intrinsic trends already present when these GCSs were young or else are, themselves, the result of dynamical evolution.

Recent semianalytic modelling of the Galactic GCS by Vesperini (1997) yields the interesting result that − provided "the mass function is initially taken to be a log-normal distribution similar to the one currently observed in our Galaxy, its shape is not significantly altered during the entire evolution even though a significant number of clusters are disrupted before one Hubble time". If the same were true in the case of the merging pair of the Antennae galaxies, it would mean that the LF should not change its shape − beyond what we found from the proper consideration of age spread effects − during 12 Gyr of dynamical evolution allthough a significant number of clusters may be destroyed.

The process of referring the LF to a uniform age of the YSC system, as we have done in Fig. 6a, properly accounting for age differences in the presently observed YSC population mimics a transition from a LF to a cluster mass function since at fixed age models indicate a fixed M/L for all YSCs. Fig. 6a thus shows that the mass function of the YSC system currently forming in NGC 4038/39 is similar to a Gaussian, which, according to Vesperini's results seems to represent a sort of quasi-equilibrium distribution capable of surviving a Hubble time with its shape and parameters preserved.

All these external dynamical effects are already difficult to model in a galaxy for which the potential is comparatively easy to describe and not variable in time. In an ongoing merger like the Antennae, dynamical effects on star clusters with a variety of initial concentrations and orbits could only be modelled together with a detailed simulation of the interaction. Kinematic

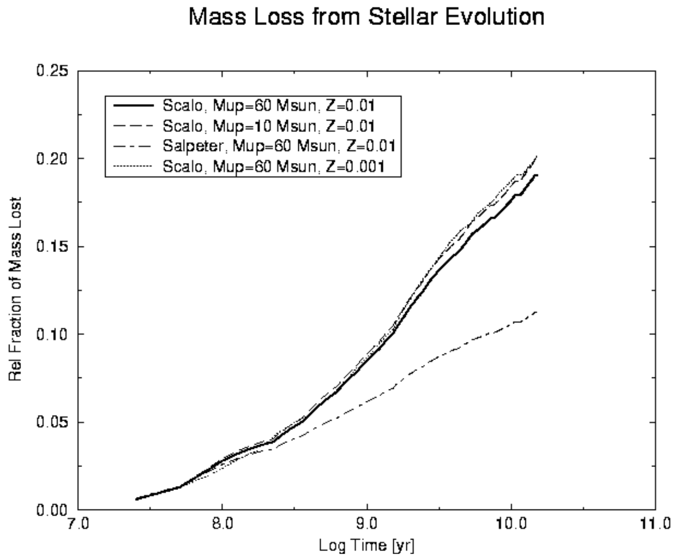

Fig. 9. Time evolution of the relative fraction of mass lost from a star cluster as calculated from our models for various IMFs, upper mass limits, and metallicities.

information from YSC spectroscopy with 10 m class telescopes together with a detailed dynamical modelling of the interaction process including gas dynamics and a SF criterion may bring further insight.

8.2. Internal dynamical effects

Internal dynamical effects are easier to estimate since they only weakly depend on the external tidal field and they are important since the dynamical evolution of young GCs is dominated by adiabatic mass loss due to stellar evolution (Chernoff & Weinberg 1990).

In addition to the photometric evolution, our models also give the mass ejection rates from stars as a function of time including stellar winds, SNe, and PNe. Thus, they allow direct following of the time evolution of the total stellar mass of a star cluster. In Fig. 9, we present the time evolution of the relative fraction of stellar mass lost from a star cluster with a Scalo (1986) or Salpeter (1955) IMF, a lower mass limit of 0.1 $M_\odot$ and various upper mass limits and initial metallicities.

For the case of a Scalo IMF, the time evolution of the mass loss rate can be well approximated by two linear regimes: a relative mass loss of about 2% per 10^8 yr during the first $3 \cdot 10^8$ yr, and of 1% of the total mass per Gyr over the rest of the Hubble time. Within the first $3 \cdot 10^8$ yr, $\sim 28\%$ of the total mass loss occurs; during the first Gyr, $\sim 50\%$ of the final mass loss is accomplished. These results confirm the idea that most of the young GCs that are going to be destroyed over a Hubble time will not even survive their first Gyr (Freeman 1995, priv. comm.).

For comparison, we have also calculated models with upper mass limits of 10 and 60 $M_\odot$ and we do not find any significant differences in the mass loss rates. Also, differences for clusters of various initial metallicities are small (cf. Fig. 9).

As compared to a Scalo IMF, a Salpeter IMF with the same normalisation to total mass contains more stars above 6.5 $M_\odot$ and below 0.5 $M_\odot$. The latter, however, do not contribute to mass loss as their lifetimes are longer than a Hubble time. At the same time, a Salpeter IMF contains less stars in the range $0.5 - 6.5\ M_\odot$. For both types of IMF the total mass loss over a Hubble time is dominated by stars $< 6.5 M_\odot$, more massive stars only account for ~ 1.5 % of the total mass loss. This explains why for a Salpeter IMF with same lower and upper mass limits, the total mass loss is less than for a Scalo IMF. By the end of the first Gyr, a cluster with Scalo IMF has lost ~ 8 % of its mass, with Salpeter IMF only ~ 6 %. After 3 Gyr, a Scalo cluster has lost ~ 13 % and a Salpeter cluster $\lesssim 9$ % of its mass through internal stellar evolutionary processes.

To maintain virial equilibrium, a star cluster's effective radius increases by the same percentage by which its mass decreases. The core collapse and subsequent reexpansion processes (cf. eg. Bettwieser & Fritze 1984) do not significantly affect the effective radius of a star cluster, they merely decouple the core radius from the effective radius.

8.3. Observational prospects

If, as suggested by the similarity of GCSs in galaxies of very different Hubble types, luminosities and metallicities, the formation process of GCs does not strongly depend on details of environmental conditions, comparison of YSC systems in starbursts of different ages may offer the possibility to follow the time evolution of YSC properties and to study from an observational point of view the influence of dynamical effects on a YSC population which otherwise are difficult to model in the case of ongoing or recent galaxy mergers.

9. Conclusions

Using our method of evolutionary synthesis for various metallicities we present a first analysis of WS95's WFPC1 data on bright star clusters in the ongoing merger-induced starburst in NGC 4038/39. Assuming a metallicity Z ~ 0.01 on the basis of the progenitor spirals' ISM properties and applying a uniform reddening as given by WS95 we age-date the bright cluster population from their (V−I) colors and, as far as available, also from their (U−V). It turns out that in addition to a large population of young clusters with a mean age of $2 \cdot 10^8$ yr (consistent with the dynamical time since pericenter) part of the original spirals' old GC population is also observed. A key question with far-reaching consequences as to the origin of elliptical galaxies is whether there are a significant fraction of young GCs among the YSC population. Two basic properties discriminate open clusters/OB associations from GCs in our Galaxy and others: the concentration parameter c = log (R_T/R_{eff}) and the LF which, in contrast to that for an open cluster system, is Gaussian for **old** GCSs. Tidal radii and, consequently, concentration parameters not being accessible to observations in distant galaxies we examine the LFs of cluster subsamples with large and small effective radii.

In a first step, we use a common mean age for all young clusters and a corresponding uniform fading until an age of $\sim$ 12 Gyr. We find that while the LF for extended clusters at 12 Gyr is definitely not Gaussian, that for the low R_{eff} clusters may well contain a Gaussian (= GC) subcomponent together with a strong overpopulation of the faint bins. Those faint bins, however, might be expected to be severely depopulated over a Hubble time by dynamical effects not included in our models.

Since for an ongoing starburst the age spread among YSCs may be of the same order as their ages, age spread effects are expected to reshape the LF. Clusters from the bright end tend to be younger on average and fade more than clusters from the faint end. We therefore, in a second step, model the individual fading consistent with individual ages of the YSCs as derived from their $(V-I)$ and $(U-V)$ colours, and we follow the LF changing its shape over a Hubble time.

Surprisingly, accounting for these age spread effects, we find the final LFs of large **and** small R_{eff} cluster subsamples not to be significantly different any more. Instead, the LF of **all** YSCs evolved to a common age of 12 Gyr is well compatible with a “normal” GCLF. Its turn-over occurs at $\langle M_{V_0} \rangle \sim -6.9$ mag, i.e. slightly fainter than the average value $\langle M_{V_0} \rangle \sim -7.1$ mag for 16 galaxies. This difference is readily explained in terms of a higher metallicity of the secondary cluster population.

The number of old GCs from the Antennae progenitors is consistent with the number of bright GCs expected if the progenitors had GCSs similar to the ones of the Milky Way and M31.

Strikingly, neither the mean nor the distribution of effective radii is significantly different for the old GC sample and for the YSC sample. On the basis of these WFPC1 data we tentatively conclude that the bulk of the YSC population detected in the Antennae might well be young GCs and that the open clusters/associations probably also present among the YSCs do not seem to systematically differ from young GCs in terms of R_{eff}. We are looking foreward to repeat this kind of analysis on WFPC2 data which may reach close to the old GCS’s turn-over, reveal a number of fainter young objects, and will allow for more precise and definite conclusions.

Dynamical effects that eventually might further reshape the LF over a Hubble time are discussed. Referring the YSC luminosities to a uniform age allows the recovery of the intrinsic mass function of the YSC system. This mass function seems to be log-normal which, according to Vesperini (1997), represents a quasi-equilibrium distribution that is going to be preserved in shape though not in number of clusters over a Hubble time of dynamical evolution.

Dynamical effects, however, are extremely difficult to model in detail in an ongoing merger. Comparison of YSC populations in mergers/starbursts of various ages seems a promising tool in an attempt to understand these effects from an observational side.

Acknowledgements. I am deeply indebted to B. Whitmore & F. Schweizer for valuable discussions, encouragement and for sending us their star cluster data in machine readable form. I am grateful to Ken Freeman, Tom Richtler, and Andreas Burkert for interesting discussions on dynamical aspects. I wish to thank Prof. Appenzeller and all the collegues from the Landessternwarte Heidelberg for their warm hospitality during a 3 months stay, when this project was begun. My deep thanks go to the referee, Gerhardt Meurer, for his very detailed and constructive suggestions that greatly improved the paper. W. E. Harris’ GC catalogue was very helpful in the comparison with old GC systems. I gratefully acknowledge financial support from the SFB Galaxienentwicklung in Heidelberg and through a Habilitationsstipendium from the Deutsche Forschungsgemeinschaft under grant Fr 916/2-1 in Göttingen.

References

Ashman, K. M., Conti, A., Zepf, S. E., 1995, AJ 110, 1164
Barnes, J. E., 1988, ApJ 331, 699
Bernlöhr, K., 1990, in Paired and Interacting Galaxies, eds. F. W. Sulentic, W. C. Keel, C. M. Telesco, IAU Coll. 124, p. 731
Bettwieser, E., Fritze, U., 1984, PASJ 36, 403
Bruzual, G. A., Charlot, S., 1993, ApJ 405, 538
Carico, D. P., Graham, J. R., Matthews, K., Wilson, T. D., Soifer, B. T., Neugebauer, G., Sanders, D. B., 1990, ApJ 349, L39
Conti, P. S., Vacca, W. D., 1994, ApJ 423, L97
Chernoff, D. F., Weinberg, M. D., 1990, ApJ 351, 121
Djorgovski, S., 1991, in Formation and Evolution of Star Clusters, ed. K. Janes, ASP Conf. Ser. 13, 112
Djorgovski, S., Meylan, G., 1994, AJ 108, 1292
Elson,R. A. W., Santiago, B. X., 1996, MN 278, 617
Fall, S.M., Rees, M.J., 1977, MN 181, 37P
Freeman, K., 1995, priv.comm.
Friel, E. D., 1995, ARAA 33, 381
Fritze − v. Alvensleben, U., Burkert, A., 1995, A&A 300, 58, (FB95)
Fritze − v. Alvensleben, U., Gerhard, O.E., 1994, A&A 285, 751
Fukushige, T., Heggie, D. C., 1995, MN 276, 206
Harris, G. L. H., Geisler, D., Harris, H. C., Hesser, J. E., 1992, AJ 104, 613
Harris, W. E., 1991, ARAA 29, 543
Harris, W. E., Racine, R., 1979, ARAA 17, 241
Holtzman, J. A., Faber, S. M., Shaya, E. J., Lauer, T. R., Groth, E. J., Hunter, D. A., Baum, W. A., Ewald, S. P., Hester, J. J., Light, R. M., Lynds, C. R., O’Neil, E. J., Westphal, J. A., 1992, AJ 103, 691
Holtzman, J. A., Watson, A. M., Mould, J. R., Galagher, J. S., Ballester, G. E., Burrows, C. J., Clarke, J. T., Crisp, D., Evans, R. W., Griffith, R. E., Hester, J. J., Hoessel, J. G., Scowen, P. A., Stapelfeldt, K. R., Trauger, J. T., Westphal, J. A., 1996, AJ 112, 416
Hunter, D. A., O’Connell, R. W., Gallagher, J. S., 1994, AJ 108, 84
Keel, W. C., Kennicutt, R. C., Hummel, J. E., van der Hulst, J. M., 1985, AJ 90, 708
Lutz, D., 1991, A&A 245, 31
Meurer, G. R., 1995, Nat 375, 742
Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., Garnett, D. R., 1995, AJ 110, 2665
O’Connell, R. W., Gallagher, J. S., Hunter, D. A., 1994, ApJ 433, 65
O’Connell, R. W., Gallagher, J. S., Hunter, D. A., Colley, W. N., 1995, ApJ 446, L1
Östlin, G., Bergvall, N., Rönnback, J., 1998, astro-ph/9804072
Ostriker, J. P., 1988, in Globular Cluster Systems in Galaxies, eds. J. Grindley, A. G. D. Philip, IAU Symp. 126, p. 271
Ostrov, P., Geisler, D., Forte, J. C., 1993, AJ 105, 1762
Rubin, V. C., Ford, W. K., D’Odorico, S., 1970, ApJ 160, 801
Salpeter, E. E., 1955, ApJ 121, 161

Scalo, J. M., 1986, Fundam. Cosm Phys. 11, 1
Schweizer, F., Seitzer, P., 1993, ApJ 417, L29
Schweizer, F., Miller, B., Whitmore, B., Fall, M., 1996, AJ 112, 1839
Secker, J., Geisler, D., McLaughlin, D. E., Harris, W. E., 1995, AJ 109, 1019
Stanford, S. A., Sargent, A. I., Sanders, D. B., Scoville, N. Z., 1990, ApJ 349, 492
van den Bergh, S., 1995, Nat 374, 215
van der Hulst, J. M., 1979, A&A 71, 131
Vesperini, E., 1997, MN 287, 915
Whitmore, B. C., Schweizer, F., 1995, AJ 109, 960, (WS95)
Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., Robert, C., 1993, AJ 106, 1354
Whitmore, B. C., Sparks, W. B., Lucas, R. A., Macchetto, F. D., Biretta, J. A., 1995, ApJ 454, L73
Worthey, G., 1994, ApJS 95, 107
Zepf, S. E., Ashman, K. M., 1993, MN 264, 611