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Letter to the Editor

The mass function of Young Star Clusters in the Antennae

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Abstract. The Antennae is a pair of late type spirals in the course of merging. The interaction triggered an ongoing strong burst of star formation that also produced a large number of Young Star Clusters (YSCs), many of which seem to be young Globular Clusters (GCs). The observed Luminosity Function of the YSC system is a power-law. We use evolutionary synthesis models for star clusters in comparison with HST WFPC observations of the YSC system in the Antennae to analyse the mass function of this $\sim 2 \times 10^8$ yr young star cluster system. Properly accounting for age spread effects by individually age-dating the YSCs we find that the intrinsic Mass Function (MF) is log-normal in shape and in intriguing agreement with the MF of old GC systems. We discuss this MF in the context of cluster formation and dynamical effects in the tidal field of the parent galaxy and speculate about its future evolution.

Key words: Galaxy: globular clusters: general – Galaxy: open clusters and associations: general – galaxies: interactions – galaxies: starburst – galaxies: star clusters

1. Introduction

The Antennae (NGC 4038/39 = Arp 244) is a pair of late type spirals in the course of merging. It is the youngest in Toomre's (1977) dynamical age sequence of 11 interacting and merging systems and comfortably nearby. This makes it a well-studied system all over the wavelength range from X-ray through radio wavelengths. The interaction has triggered a strong burst of star formation that has also produced a large number of ~ 700 bright star clusters as first observed with HST by Whitmore & Schweizer (1995) (hereafter WS95). Many of those bright clusters seem to be young Globular Clusters (GCs) due to their small effective radii and high luminosities. The Luminosity Function (LF) of this bright star cluster system looks like a power law $\Phi(\mathrm{L}) \sim \mathrm{L}^{-1.78\pm0.05}$ with no hint of a turnover at fainter magnitudes down to the completeness limit of $\mathrm{V} = 22.3$ mag which, at the distance of The Antennae (19.2 Mpc for $\mathrm{H}_0 = 75$), corresponds to $\mathrm{M_V} = -9.6$ mag (WS95). In Fritze – v. Alvensleben (1998) (hereafter Pap.I) I analysed WS95's HST data with evolutionary synthesis models for single burst single metallicity populations (SSPs) using stellar evolutionary tracks for various metallicities from the Geneva group and a Scalo IMF from 0.15 to 60 $\mathrm{M}_\odot$ (Fritze – v. Alvensleben & Burkert 1995, hereafter FB95). In analogy to the YSC system in NGC 7252 which, like the Antennae, is an Sc – Sc merger, we assume that the metallicity of the YSC population that forms out of the spirals' ISM is $\sim \frac{1}{2} \times \mathrm{Z}_\odot$ (Fritze – v. Alvensleben & Gerhard 1994). In Pap.I individual ages are determined from $(\mathrm{V}-\mathrm{I})$ colours for the 550 star clusters with I – band detections. The age distribution clearly reveals two populations of clusters, ~ 70 old GCs from the original spirals, and ~ 480 *Young* Star Clusters (YSCs) with ages in the range $(0-4) \times 10^8$ yr formed in the ongoing interaction-induced starburst. Only the secondary population of YSCs will be considered in the following. Meurer (1995) was the first to point out the possible importance of age spread effects on the future evolution of the LF of a YSC system. With individual YSC ages and the fading in various passbands as given by our SSP models we were able to calculate the future evolution over a Hubble time of the LF and of the colour distribution of the YSC system under the unrealistic assumption that all clusters will survive. At an age of ~ 12 Gyr, when age differences of the order of 10^8 yr do no longer play any role, the LF is shown to be undistinguishable from a typical GC LF (i.e. Gaussian with a turnover at $\mathrm{M_V} \sim -6.9$ mag – appropriate for the metallicity [Fe/H] ~ -0.3 (Ashman et al. 1995) – and $\sigma(\mathrm{M_V}) = 1.3$ mag). The colour distribution will by then also be compatible with the one observed on old GC systems. While accounting for stellar mass loss, this modelling, however, did not take into account dynamical effects like two-body relaxation, dynamical friction, or disk shocking that might act heavily on a YSC system over a Hubble time. Already for the Milky Way, where the potential is rather well known, it is difficult and not uncontroversial to model the dynamical processes on individual clusters (e.g. Chernoff & Weinberg 1990, Fukushige & Heggie 1995, Gnedin & Ostriker 1997, Vesperini 1997). This is, of course, even more difficult, if not impossible, in an ongoing merger like The Antennae. Before one can try and quantify the efficiency of various destruction mechanisms, the intrinsic MF underlying the presently observed LF has to be determined. Knowing individual cluster ages offers the possibility to use M/L values from evolutionary synthesis models to derive the Mass Function (MF) underlying the presently observed LF and this is what we attempt in this Letter. Since the age distribution of the YSCs is strongly peaked within $\leq 2 \times 10^8$ yr and the YSCs have a mean distance to the galaxy center of ~ 3.5 kpc, a YSC on average cannot have had more than 1 or 2 revolutions. We do not expect the MF therefore to already be significantly affected by cluster destruction processes. Rather we expect the presently derived MF to reflect the MF produced by the cluster formation process.

The mass spectra of molecular clouds, molecular cloud cores, open clusters, and the LF of giant HII regions (in non-interacting galaxies) all are power laws with exponents α in the range $\alpha \sim -1.5 \ldots -1.7$ (e.g. Solomon et al. 1987, Lada et al. 1991, Kennicutt 1989, see Harris & Pudritz 1994 and Elmegreen & Efremov 1997 for overviews) as is the mass spectrum of open clusters in the Milky Way and the LMC (e.g. van den Bergh & Lafontaine 1984, Elson & Fall 1985). Both the LF and the MF of old GC systems are Gaussians with typical parameters $\langle \mathrm{M_V} \rangle \sim -7.3$ mag, $\sigma \sim 1.3$ mag, and $\langle \mathrm{Log\ (M/M_\odot)} \rangle \sim 5.5$, $\sigma \sim 0.5$, respectively (e.g. Ashman et al. 1995).

The question immediately arises: Is the transition from a power law molecular cloud mass spectrum to a Gaussian old GC mass spectrum performed in the star/cluster formation process or by secular destruction effects within a GC system? Or, else, is already the mass spectrum of molecular clouds or molecular cloud cores different in strongly interacting and starbursting galaxies from what it is in normal spirals?

2. The mass function of the YSCs in the Antennae

On the basis of individual YSC ages we use our SSP models giving $\mathrm{M/L_\lambda}$ in the passbands $\lambda = \mathrm{UBVRIK}$ as a function of time to derive masses of individual clusters from their observed V – luminosities.

This is done for all the 393 YSCs with ages $\leq 4 \times 10^8$ yr and V – luminosities brighter than the completeness limit $\mathrm{M_V} = -9.6$ mag. It is stressed that our model $\mathrm{M/L}$ - values include the decrease in cluster mass due to stellar mass loss (cf. Pap.I), but not that due to the evaporation of stars from the cluster. The MF we recover in this way from the presently observed LF is presented in Fig. 1. A Gaussian with $\langle \mathrm{Log\ (M_{YSC}/M_\odot)} \rangle = 5.6$ and $\sigma = 0.46$, normalised to the number of YSCs in the histogram, is overplotted. The intrinsic MF we obtain for the YSCs brighter than the completeness limit in The Antennae clearly looks log-normal in shape with the maximum at a mean YSC mass of $\sim 4 \times 10^5\ \mathrm{M_\odot}$. Stellar mass loss within the clusters from the present mean age of $\sim 2 \times 10^8$ yr through an age of ~ 12 Gyr will lead to a decrease in mass of $\lesssim 15\%$ for a Scalo – IMF ($< 10\%$ for Salpeter).

Thus, without any destruction or evaporation effects the mean mass of the secondary GC system in The Antennae at the age of a Hubble time would be $\sim 3.4 \times 10^5\ \mathrm{M_\odot}$. A cluster with this mean mass would have $\mathrm{M_V} = -6.9$ mag at an age of 12 Gyr according to our models. This is the position of the maximum of the Gaussian YSC LF we obtain at a hypothetic YSC age of 12 Gyr (cf. Fig. 6a in Pap.I). The agreement is no surprise since this is, in fact, the way how we obtained the parameters for the Gaussian in Fig. 1. We stress that these parameters are

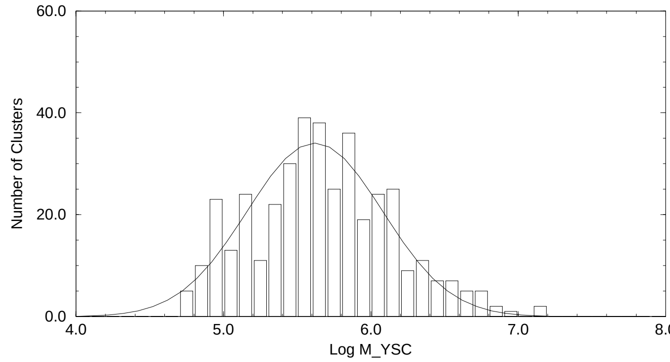

Fig. 1. Mass Distribution of the YSCs in The Antennae: 393 YSCs brighter than the completeness limit. A Gaussian with $\langle \mathrm{Log\ (M_{YSC}/M_\odot)} \rangle = 5.6$ and $\sigma = 0.46$ is overplotted, normalised to the number of YSCs in the histogram.

derived from the LF in Pap.I and are not the result of any fit to the cluster MF in Fig. 1.

Remarkably enough, the parameters of this Gaussian – which in Fig. 1 is seen to reasonably describe the MF of the secondary GC population – are quite similar to those given by Ashman et al. (1995) for the Milky Way and M31 GC systems. Using evolutionary synthesis results from Worthey (1994) for $\mathrm{M/L_V}$, Ashman et al. find $\langle \mathrm{Log\ (M/M_\odot)} \rangle = 5.47$ and $\sigma = 0.50$ for the Milky Way and $\langle \mathrm{Log\ (M/M_\odot)} \rangle = 5.53$ and $\sigma = 0.43$ for M31. The MF in Fig. 1 thus seems compatible with the bulk of the YSCs really being young GCs rather than open clusters or associations, as was already indicated by their small effective radii and high luminosities (WS95).

From the model side, uncertainties in the determination of YSC ages (and hence masses) on the basis of their $(\mathrm{V-I})$ colours are dominated by uncertainties in the YSC metallicities. Age uncertainties due to metallicity uncertainty ($\frac{1}{2} \times \mathrm{Z_\odot} \lesssim \mathrm{Z_{YSC}} \lesssim \mathrm{Z_\odot}$) are estimated to be of the order of $\pm 15\%$. The uncertainty in M/L at $\mathrm{Z} = \frac{1}{2} \times \mathrm{Z_\odot}$ due to the age uncertainty is $\sim 8\%$ and the uncertainty in M/L at all ages $\lesssim 4 \times 10^8$ yr due to the metallicity uncertainty is $\lesssim 5\%$. This leads to an overall uncertainty in the M/L of $\sim 10\%$.

Measurement uncertainties are $\sim \pm 0.2$ mag for the observed $(\mathrm{V-I})$ colours and $\lesssim 0.15$ mag for V magnitudes for YSCs brighter than the completeness limit. The uncertainties that the inhomogeneous reddening over the body of NGC 4038/39 brings along for the derived cluster ages and masses are difficult to quantify. Only a global average value is given for the internal reddening of the YSC population in NGC 4038/39 ($\mathrm{E_{V-I}} \sim 0.3$ mag (WS95)) and applied before our age-dating, but dust lanes and unrelaxed structures are seen all over NGC 4038/39. The very good agreement ($\leq 10^7$ yr) between ages determined from $(\mathrm{U-V})$ and $(\mathrm{V-I})$ colours, however, indicates that for the bright clusters seen on the short U exposure the reddening does *not* seem to significantly deviate from the average reddening we use.

It should be noted in this context that inclusion of YSCs fainter than the completeness limit – which tend to have significantly larger observational uncertainties – does *not* affect the agreement with the Gaussian in Fig. 1 or its parameters (beyond the normalisation to the number of clusters in the histogram).

We conclude that the secondary GC population in The Antennae is formed with a log-normal mass distribution very similar to the one in the Milky Way or M31. It is not necessarily the secular evolution but rather the cluster formation process that produces the Gaussian mass spectrum observed on old GC systems.

Since uncertainties in the MF from observational errors cannot be calculated in any straightforward way in the analysis presented here, we are currently trying an independent approach. We draw YSCs at random from different intrinsic MFs (Gaussians, power-laws), randomly assign ages to them from different age distributions (clusters formed uniformly over the burst duration or at an increasing or decreasing rate), and calculate their present luminosities and colours to which, then, observational errors can be added, again at random from the observed luminosity-dependent error distribution. Comparison of the resulting model LFs and colour distributions with the observed ones should then allow to constrain the intrinsic MF (Kurth et al. , *in prep.*). A somewhat similar procedure is used for YSCs in NGC 7252 and NGC 3921 by Miller & Fall (1997), who find that power-laws are preferred over Gaussians for the MFs of these YSC systems.

3. Comparison with YSCs in NGC 7252 and NGC 3921

NGC 7252 and NGC 3921 are the two oldest merger remnants from Toomre's (1977) list. Large enough YSC systems have been detected in both of them to define the bright end of their LFs (Whitmore et al. 1993, Miller et al. 1997, Schweizer et al. 1996). Distances, however, are larger than to NGC 4038/39 by factors 3 and 4 for NGC 7252 and NGC 3921, respectively, pushing the completeness limit to significantly higher luminosities. The higher mean ages of the YSCs in these cases ($650 - 750$ Myr for NGC 7252 and $250 - 750$ Myr for NGC 3921, depending on metallicity) add another argument in favour of them being young GCs, since they have survived $\gg 10 \times \mathrm{t_{cross}}$ (cf. Schweizer et al. 1996).

The LF we *calculate* for the YSCs in The Antennae at an age of ~ 1 Gyr does show a marginal turnover at the expected $\langle \mathrm{M_V} \rangle \sim -9.9$ mag for YSCs brighter than the completeness limit, indicating that by this age the distortion of the LF with respect to the MF due to age spread effects from the finite YSC formation timespan (of the order $200 - 400$ Myr) is already less important.

In order to estimate if a turn-over in their YSC LFs could be expected in NGC 7252 and NGC 3921, we assume that their YSC systems have the same MF as the YSC system in The Antennae. Then, we can calculate the mean absolute magnitude $\langle \mathrm{M_V} \rangle$ from $\langle \mathrm{M_{YSC}} \rangle$ at the above-quoted mean ages. We obtain $\langle \mathrm{M_V} \rangle = -10 \ \ldots \ -9.5$ mag and $\langle \mathrm{M_V} \rangle = -9.5 \ \ldots \ -9$ mag for YSCs in NGC 7252 and in NGC 3921, respectively. These luminosities are close to the 90% completeness limiting magnitudes of -9.5 (PC) and -8.5 (WF) for NGC 7252 (Miller et al. 1997) and of -9.0 for NGC 3921 (Schweizer et al. 1996). Together with the difficulty of disentangling the old GC population from the YSCs at these advanced ages the fact that no turnover is detected in the LFs for NGC 7252 and NGC 3921 does not seem to rule out a Gaussian MF similar to the one we obtain in The Antennae.

4. Dynamical evolution of the YSC system

Quantitatively, nothing is known about the external dynamical effects on GC systems in interacting and merging galaxies. For the Milky Way, where dynamical modelling on the basis of the Galactic potential is possible and has been done by many groups (e.g. Chernoff & Weinberg 1990, Gnedin & Ostriker 1997, Fukushige & Heggie 1995, Vesperini & Heggie 1997, Vesperini 1997, 1998) it is clear that the GC system observed today is only "the hardiest survivors of a larger original population" (Harris 1991). Vesperini & Heggie (1997) present N-body simulations including effects of stellar evolution, two-body relaxation, disk shocking, and the tidal field of the Milky Way. Studying the secular evolution of a number of GC systems with different initial MFs, Vesperini (1998) shows that *if the initial MF is log-normal then this log-normal shape and its parameters are conserved over a Hubble time* despite the destruction of a large part ($\sim 50\%$) of the original GC population. While evaporation and dynamical friction preferentially destroy low and high mass clusters, respectively, both processes balance each other in the case of a log-normal ($=$ equilibrium) initial GC MF, so that no net selective destruction of specific GC masses results. If the GC destruction processes were similar in the Antennae and in the Milky Way, and if, as indicated in Fig. 1, the initial GC MF really were close to Vesperini's equilibrium MF, then the Gaussian MF could survive a Hubble time with its parameters $\langle \mathrm{Log}\ (\mathrm{M}/\mathrm{M}_\odot) \rangle$ and σ essentially unchanged despite the likely destruction of a large fraction of the YSC system seen today.

It will be interesting to analyse more YSC systems in the way we did in order to see if and in how far the YSC MF is universal or depends on parameters of the progenitor galaxies or the interaction event. Moreover, studying secondary GC systems on an age sequence of interacting, merging and merger remnant galaxies should allow to directly "observe" both the time evolution of the LF and of the MF and thus offer a unique possibility to study the effects of dynamical processes *in situ*. The turnover of an old GC population at $\mathrm{M_V} \sim -7.2$ mag occurs around $\mathrm{V} \sim 24.5$ at Virgo cluster distances and is well within the reach of 10m telescopes. HST imaging allows to identify clusters in regions not too crowded for ground-based MOS.

5. Discussion and open questions

The uncertainties in the metallicities and – more important – in the individual reddening of YSCs in The Antennae can be substantially reduced with spectroscopic observations of YSC selected from the HST images. With MOS facilities on 10m class telescopes this should be possible in the nearest future.

One question that poses itself immediately in the context of the cluster formation mechanism is whether the molecular cloud mass spectrum in a strongly interacting and starbursting galaxy like The Antennae does really have the same power-law form as that in an undisturbed spiral forming stars at a level orders of magnitude lower? Elmegreen & Efremov (1997) pointed out that the high pressure of the ambient ISM produced in a strong interaction might favor the production of more massive clouds. Information about the molecular cloud mass spectrum in merger-induced strong starbursting systems seems a prerequisite for the study of the star and cluster formation processes.

First spectroscopic observations of a handful of YSCs in NGC 7252 (Schweizer & Seitzer 1993, 1998) confirms the metallicity of $(\frac{1}{2} - 1) \times \mathrm{Z}_{\odot}$ (cf. FB95) we predicted on the basis of the progenitor galaxies' ISM abundances. This enhanced metallicity (with respect to the primary GC population) raises the question in how far the secondary GC formation process is comparable to the primary one in the early Universe?

6. Preliminary conclusions

1. The MF of the YSCs in The Antennae seems to be log-normal with parameters $\langle \mathrm{Log}\ (\mathrm{M}/\mathrm{M}_{\odot}) \rangle$ and σ very similar to those of the Milky Way GC system.

2. This suggests that the cluster formation process and not the dynamical evolution produce the Gaussian MF.

3. The close agreement of the YSC MF we obtain with Vesperini's equilibrium initial GC MF seems to indicate that the shape and parameters of this MF may survive a Hubble time despite destruction of a large fraction of today's YSCs.

4. In the older merger remnants NGC 7252 and NGC 3921 the completeness limit is close to the turn-over luminosity expected in case their MFs were similar to the one in The Antennae.

As long as the impact of observational colour and luminosity uncertainties on the MF we derive cannot be quantified rigorously, our conclusions have to remain preliminary.

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