Mon. Not. R. Astron. Soc. **000**, 1–?? (0000) Printed 1 February 2008 (MN LaTeX style file v1.4)

Constraints on the Merger Models of Elliptical Galaxies from their Globular Cluster Systems

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1 February 2008

ABSTRACT
The discovery of proto–globular cluster candidates in many current–day mergers allows us to better understand the possible effects of a merger event on the globular cluster system of a galaxy, and to foresee the properties of the end–product. By comparing these expectations to the properties of globular cluster systems of today's elliptical galaxies we can constrain merger models. The observational data indicate that *i*) every gaseous merger induces the formation of new star clusters, *ii*) the number of new clusters formed in such a merger increases with the gas content of the progenitor galaxies. Low–luminosity (about $M_V > -21$), disky ellipticals are generally thought to be the result of a gaseous merger. As such, new globular clusters are expected to form but have not been detected to date. We investigate various reasons for the non–detection of sub–populations in low–luminosity ellipticals, i.e. absence of an old population, absence of a new population, destruction of one of the populations, and finally, an age–metallicity conspiracy that allows old and new globular clusters to appear indistinguishable at the present epoch. All of these possibilities lead us to a similar conclusion, namely that low–luminosity ellipticals did not form recently ($z < 1$) in a gas–rich merger, and might not have formed in a major merger of stellar systems at all. High–luminosity ellipticals do reveal globular cluster sub–populations. However, it is difficult to account for the two populations in terms of mergers alone, and in particular, we can rule out scenarios in which the second sub–population is the product of a recent, gas–poor merger.

Key words: galaxies: interactions - galaxies: elliptical - globular clusters: general

1 INTRODUCTION

Globular clusters are thought to be good tracers of the past evolution of their parent galaxy. Recreating the history of a galaxy from the current properties of its globular cluster system is complex and challenging. However, if a specific event is expected in the history of a galaxy, such as a major merger, and this event is supposed to leave a clear signature in the globular cluster system (e.g. the formation of a new population of globular clusters), then studies of globular cluster systems can be used to confirm or rule out the occurrence of such events.

In this paper, we examine the constraints that can be set from the current observations of globular cluster systems on the merger model for elliptical galaxies. The main challenge is to understand the apparent presence of *only one* population of globular clusters in the luminosity and colour distributions of small ellipticals. Ashman & Zepf (1992) made a variety of predictions for the properties of globular cluster systems after a merger of two gas–rich galaxies. One of their main predictions is that mergers will leave a clear signature in the form of a *second* population of globular clusters, formed during the merger, which is added to the old populations of globular clusters brought in by the progenitors. A notable success of their model is the presence of young proto–globular cluster candidates in currently merging systems, confirming the basic idea that such events can modify the existing globular cluster systems. Furthermore some of their predictions seem to be verified for the globular cluster

systems of giant elliptical galaxies (Zepf & Ashman 1993): two or more globular cluster populations are detected in colour distributions, the red (presumably new) globular clusters are more concentrated toward the center of the galaxy as expected if these formed from the in–falling gas.

However, whether the globular cluster systems of all ellipticals verify these predictions remains an open question. The properties of globular clusters in small and large ellipticals seem to differ. Studies of systems in small ellipticals failed to detect more than one population of globular clusters (Kissler-Patig 1997a). Moreover, Forbes, Brodie & Grillmair (1997) have recently argued that the observational data on globular clusters in high–luminosity ellipticals (i.e. gE and cD galaxies) cannot be explained in detail by an Ashman & Zepf type merger, and could be explained in other formation scenarios.

We adopt a working definition of $-18 > M_V > -21$ for low–luminosity and $-21 > M_V > -23.5$ for high–luminosity ellipticals (for $H_0 = 75$ km s^{-1} Mpc^{-1}) throughout this paper. Further, we will refer to the *new* population of globular clusters as the population formed in the merger event, and to the *old* population of globular clusters as the "original" population, present before any merger event.

We examine the numerous observations of proto–globular clusters in merging galaxies to extract the signature that these events will leave on the globular cluster systems (Sect. 2). In particular, we examine if, and how many, globular clusters are expected to form in the different (gas–rich/gas–poor) mergers. In Section 3, we consider low–luminosity and high–luminosity galaxies in turn. We investigate the various alternatives that could explain the presence of only one population of globular clusters in low–luminosity ellipticals, despite the fact that they are generally thought to have formed several Gyr after a gaseous merger event and thus should show a second population of globular clusters. The most interesting alternative (Sect. 3.2) is the presence of two populations whose mean ages and metallicities conspire to let them appear the same in colour and magnitude distributions. The various alternatives allow us to put constraints on the occurrence of a merger event in the recent history of the parent galaxy. We then examine in Sect. 3.4 if similar arguments can also constrain the history of high–luminosity ellipticals, and in Sect. 3.5 if additional constraints can be obtained from the properties of ongoing mergers. We summarize our findings and conclusions in Sect. 4.

2 OUR PRESENT KNOWLEDGE

In the following section, we use the recent studies of globular clusters in mergers to derive two important facts: new globular clusters will form in a gas–rich merger event, and their number will roughly scale with the amount of gas involved. Further, we summarize briefly the current scenarios of early–type galaxy formation by mergers.

2.1 The formation of globular clusters in gaseous mergers

Proto–globular clusters have been observed in all recent merger systems studied to date: e.g. NGC 3597 (Lutz 1991, Holtzman et al. 1996), NGC 1275 (Holtzman et al. 1992), NGC 7252 (Whitmore et al. 1993, Schweizer & Seitzer 1993), NGC 4038/4039 (Whitmore & Schweizer 1995), NGC 5128 (Minniti et al. 1996), NGC 5018 (Hilker & Kissler-Patig 1997), NGC 3921 (Schweizer et al. 1996), NGC 3256 (Zepf et al. 1997), NGC 6052 (Holtzman et al. 1996), NGC 3610 (Whitmore et al. 1997).

Further, the number of newly formed globular clusters seems to vary with the type of the progenitor galaxies. During the collision of two gas–rich galaxies such as NGC 4038/4039 (two Sb/Sc spirals), a very large number of globular clusters have formed. Whitmore & Schweizer (1995) report 700 potential new globular clusters, while the spiral progenitors might have had a few hundred each, i.e. around 100% new globular clusters (by which we mean as many as old ones) might have formed. Further examples are NGC 7252 (the merger of two massive Sc galaxies, Fritze-v.Alvensleben & Gerhard 1994) and NGC 3610 (also a good candidate for a disk/disk merger, Schweizer & Seitzer 1992) formed 40% and 70% new globular clusters compared to the existing ones (Whitmore et al. 1997). A large number of new globular clusters is also seen in the case of NGC 3256 (Zepf et al. 1997), which is rich in molecular gas.

An example of a merger between a gas–rich (Sc) and an S0/Sa galaxy is thought to be NGC 3921 (Schweizer et al. 1996). In this case the number of new globular clusters lies around 40% of the old globular cluster population. Going to even earlier types as for NGC 5128 or NGC 5018 (both of which may be the result of a disk system falling onto a gas–poor early–type galaxy), the number of new globular clusters is even smaller. In NGC 5128 the "intermediate" age globular clusters in the inner region represent about 20% of the old population (Minniti et al. 1996), however, since young clusters form preferentially in the center this might be an upper limit. In NGC 5018, Hilker & Kissler-Patig (1996) estimate that the new globular clusters represent at most 10% of the old population. NGC 1275 might be a peculiar case, but here also a disk system is falling onto a early–type galaxy, and while the estimated old population is of several thousands globular clusters (Nøgaard–Nielsen et al. 1994), the number of new clusters appears to be small (Holtzman et al. 1992).

In summary, the observations indicate that: *i)* in a dissipational merger (i.e. one involving gas) new globular clusters will always form. Thus galaxies that underwent a gaseous merger event at any epoch *must* have formed a population of globular clusters associated with that merger event. *ii)* The number of new globular clusters produced will be proportional to the available gas content. Although there will be other factors involved (e.g. gas density, collision velocity) we expect mergers that involve a large amount of gas to create a large number of new globular clusters. A general assumption is that the proto–globular clusters seen today will indeed evolve into globular cluster like objects after several Gyr (see Sect. 3.2 and 3.5 for a more detailed discussion of this point).

2.2 The formation of early–type galaxies in mergers

Faber et al. (1997, see also e.g. Bender 1997) have recently summarized the properties of hot galaxies within the framework of hierarchical clustering and merging. They concluded

that low–luminosity, disky ellipticals seem generally compatible with formation in dissipative, gas–rich mergers. Kauffmann (1996) further proposed a dependence on environment, in the sense that intermediate–luminosity galaxies in clusters are old, while those in the field were mostly formed by more recent mergers of spirals. Recently, De Jong & Davies (1997) found a correlation between the Hβ absorption index, indicative of age, and the isophotal shape of elliptical galaxies, in the sense that disky ellipticals are younger than boxy ones or had a small amount of recent star formation.

Boxy, high–luminosity ellipticals on the other hand are thought to have formed in gas–poor mergers. Their history can be divided in two parts: an early–phase of merging of the largely unknown progenitors, and a late phase of accretion involving small companions. Further, there is increasing evidence that these galaxies have formed the bulk of their stars at high redshifts, i.e. $z \sim 3$ (e.g. discussion in Renzini 1997).

Although there is not a well–defined separation between disky and boxy galaxies, the transition occurs around $M_V = -21$ (e.g. Bender et al. 1989).

3 ARE THE PROPERTIES OF GLOBULAR CLUSTER SYSTEMS COMPATIBLE WITH MERGER SCENARIOS?

Combining the results from the previous section, we expect small ellipticals, if they formed relatively recently in dissipational mergers, to have formed new globular clusters in addition to the old ones from the progenitors. We focus on these galaxies in Sect. 3.2 and discuss the different possibilities that would explain why only one population is seen today. We then examine what constraints this puts on the merger history. We will discuss the large ellipticals in Sect. 3.4. In particular, to see if such constraints are also valid in their case. We start by revisiting some arguments that have been put forward in favour or against mergers of spirals creating ellipticals, using the properties of the globular cluster systems.

3.1 Old problems revisited

The properties of globular cluster systems in early–type galaxies have been described in various reviews (e.g. Harris 1991, Richtler 1995, Ashman & Zepf 1997). Some of these properties have been used by van den Bergh (1990) to argue against mergers. In particular, ellipticals have more globular clusters per unit starlight (i.e. a higher specific frequency) than spirals. It is unclear whether this could be overcome by the creation of new globular clusters in the merger (e.g. Ashman & Zepf 1992) or not (e.g. Harris 1994, Forbes, Brodie & Grillmair 1997). This depends on the unknown ratio of globular clusters versus star formation efficiency in mergers. Several new compilations (Harris 1996, Kissler-Patig 1997a, Ashman & Zepf 1997) show that the specific frequency discrepancy between spirals and low–luminosity ellipticals is actually small, if existent at all, when the different mass–to–light ratios of spirals and ellipticals are taken into account (low–luminosity ellipticals have typically 200–500 globular clusters, similar to spirals of comparable mass). However, large differences remain when comparing spirals with high–luminosity ellipticals. So the problem of too many globular clusters present in bright ellipticals may still exist, but we stress that alternative explanations to the merger picture could overcome this problem (e.g. the summary in Forbes, Brodie & Grillmair 1997).

Another controversial point is the following. Recently it has become clear that several high–luminosity ellipticals have broad, multi–modal globular cluster colour distributions (e.g. Lee & Geisler 1993; Geisler, Lee & Kim 1996; Forbes, Brodie & Huchra 1997). This multi–modality indicates the presence of different globular cluster sub–populations, i.e. several epochs or mechanisms of formation. In the literature summary included in Kissler-Patig (1997a) and Forbes, Brodie & Grillmair (1997), only *high–luminosity* ($M_V < -21$) ellipticals revealed obvious bimodal globular cluster colour distributions (we will come back to this point in the next section). Moreover, typically the two peaks contain equal numbers of red and blue globular clusters within a factor two, which is contrary to the expectations from a gas–poor merger event. From observations of ongoing mergers (Sect. 2.1) we would expect the number of red clusters to be of the order of 10% or less, i.e. the ratio of red to blue clusters to be < 0.1, if the gas–poor merger was the only process responsible for the formation of the red globular clusters. Forbes, Brodie & Grillmair (1997) have concluded that the bimodality of the globular cluster colour distributions in the high–luminosity ellipticals is better explained by a multi–phase collapse than by a merger event. Recently, Kissler-Patig et al. (1998) obtained spectra for globular clusters in NGC 1399 (a galaxy with a multi–modal globular cluster distribution) and concluded from the absorption line indices, that all blue and most red clusters were old, but *a very small fraction* of extremely red clusters were much more metal rich and could be younger, i.e. they may have formed in a later merger. Cohen, Blakeslee & Rhyzov (1998) obtained spectra for globular clusters in M87 and came to the similar conclusion that most globular clusters around this galaxy are old. Therefore, care should be taken when reaching conclusions from multi–modal colour distributions. Their absence certainly hints at the absence of sub–populations (see below), but the presence of sub–populations does not automatically imply a recent (or even past) merger, nor does it exclude it (see Sect. 3.4).

Another interesting point is that globular cluster system properties seem to differ between low–luminosity ellipticals, and high–luminosity ellipticals, and that two classes may be preferred to a continuous relation (Kissler-Patig 1997a). It seems therefore misleading to discuss the properties of globular clusters in ellipticals without differentiating between low– and high–luminosity galaxies. In particular, the globular cluster systems in low–luminosity ellipticals do not obviously show the properties first predicted by Ashman & Zepf (1992) for systems resulting from a recent merger of two spirals. Since these two classes of ellipticals are thought to have different formation histories from various independent lines of evidence (see Sect. 2.2), it is worth examining them in turn.

3.2 Low–luminosity ellipticals

We focus on the low–luminosity ellipticals which, as mentioned above, are generally thought to be the result of a gaseous merger and so should have formed many new globular clusters. One also expects such ellipticals to show the old globular clusters associated with the progenitor galaxies. These two globular cluster populations (one new and one old) should show up in the globular cluster luminosity and colour distributions of the final system. Small ellipticals are therefore ideal candidates to search for the signature of a merger event in their globular cluster system.

Interestingly, the properties of the globular cluster systems in small ellipticals (see Kissler-Patig 1997a) do not clearly imply the presence of sub–populations. There is no known case with a clear bimodal colour distribution or a colour gradient in the globular cluster system of a low–luminosity elliptical. Further, the globular clusters are not more extended, but follow the stellar light distributions (in radial density, ellipticity, position angle), despite the prediction that after a merger, the old population should be more diffuse than the newly formed stars and globular clusters. From the properties of their globular cluster systems, low–luminosity ellipticals do not, a priori, require a recent merger event. The predictions of the simple Ashman & Zepf (1992) merger scenario (implying the formation of a new globular cluster population) have yet to be seen in the globular cluster systems of any low–luminosity ellipticals.

One disadvantage of studying low–luminosity ellipticals is that they tend to have fewer globular clusters in total, making any colour bimodality more difficult to observe. But, if hidden by small number statistics, we might expect the colour distributions to be on average as broad as those for large ellipticals. However, this does *not* appear to be the case (Kissler-Patig et al. 1997a) with small ellipticals having distributions that are 3 to 4 times narrower than the ones in large ellipticals.

In summary, gas–rich mergers would imply the formation of a large number of new globular clusters, in addition to the existing old globular clusters associated with the progenitor galaxies. One expects to see these two populations of globular clusters in low–luminosity ellipticals, and yet they are not seen. There are several possibilities to explain this apparent absence of sub–populations:

- only old globular clusters are present, as the new globular clusters were rapidly destroyed,
- or only new globular clusters are present because the progenitor galaxies had very few old globular clusters,
- or only new globular clusters are present because old globular clusters have been preferentially destroyed or removed from the galaxy,
- or only old globular clusters are present as very few were created in the merger,
- or new and old globular clusters are present but are essentially indistinguishable in magnitude and colour.

We discuss each point in turn.

- The rapid destruction of all newly formed globular clusters seems unlikely given the observations of similar masses for the new and old globular clusters (see Sect. 3.2.1). Elmegreen & Efremov (1997) summarized recent observations and argued that newly formed globular clusters in mergers resemble more closely open clusters in their formation process *but* are much more massive and more compact than the latter, and have an initial mass distribution similar to that of the old globular clusters, i.e. new and old clusters will be indistinguishable after several Gyr. Destruction processes would be expected to affect both populations. The new globular clusters are expected to be more spatially concentrated and therefore suffer preferentially from efficient destruction processes such as bulge shocking (Gnedin & Ostriker 1997). But such processes need of the order of a Hubble time to destroy a significant fraction of the globular clusters. Destruction processes would have had a longer time to act on the old globular clusters. Further, in the Elmegreen & Efremov picture destruction would be less efficient for the more compact young objects, eliminating if anything, more old globular clusters. Finally, the fact that new globular clusters survive at least a few Gyr is directly demonstrated by observations of "young" globular clusters in Gyr old mergers (e.g. NGC 3610, NGC 5018, NGC 5128, NGC 7252). It appears therefore unlikely that a large population of newly formed globular clusters would be rapidly and efficiently destroyed without the old population being much affected, unless the new clusters turned out to be very different from old globular clusters (see Sect. 3.5).

- Another possibility for the absence of sub–populations in low–luminosity ellipticals might be that today's population of globular clusters formed *entirely* in the merger event, i.e. little or no old globular clusters have been brought in by the progenitors. However, *all* current galaxies (late– or early–type) larger than $M_V \simeq -15$ are known to host a population of globular clusters. Even Sd galaxies, with presumably the lowest globular cluster to mass ratio (e.g. Harris 1991), would, when scaled up to masses able to produce a low–luminosity elliptical, bring a few hundred clusters with them, and produce at most around a thousand new ones, if NGC 4038/4039 (a late–type galaxy merger, see Sect. 2.1) is taken as reference. The progenitor galaxies must have been unevolved gas disks if they did not bring with them globular clusters into the final system. Further, since the globular clusters in low–luminosity ellipticals are thought to be old from their colours and magnitudes, any merger that formed them must have happened at an early epoch. Low–luminosity ellipticals would have formed before or only shortly after the main epoch of globular cluster and star formation, from mainly gaseous progenitors. The globular clusters seen today would be the "new" ones in the sense that they were formed in the merger, but they would be about 15 Gyr old.

- Another explanation for the presence of only new globular clusters could be the preferential destruction or removal of the old globular clusters. The preferential destruction of old globular clusters is unlikely (see the first point). However, a preferential removal of the old globular clusters, which are spatially more extended around the galaxy, is not excluded. Muzzio (1987) summarized the effects of stripping and harassment in clusters of galaxies on globular cluster systems. Although the exact effects depend on the characteristics of environment, galaxy, and globular cluster system, tidal stripping is not negligible and will affect primarily the outer globular clusters. This could explain the absence of a large blue population in some ellipticals, but this needs a more detailed analysis to estimate its importance. The

consequence would be similar to the previous point, i.e. we would see only the "new" globular clusters, but they formed long ago.

• The absence of new globular clusters may simply mean that they never formed or that they are very few in number. Either way, given the observational situation described in Sect. 2.1, this would rule out that low–luminosity elliptical formed by major gaseous merger events.

• Yet another option could be that new globular clusters are missed in these galaxies, because they neither differ in luminosity nor colour from the old globular clusters. This would have to be the result of a conspiracy between mass, age, and metallicity of the various sub–populations. In the following, we investigate in more detail the allowed range for these parameters, that will allow new globular clusters to appear similar in luminosity and colour to old, metal–poor globular clusters.

3.2.1 Hiding a second population: Constraints from the similar luminosity functions

We first examine the conditions necessary to obtain similar luminosity functions for the new and old globular clusters. We then derive the constraints on age and metallicity to reproduce the current observations.

The luminosity function of old globular clusters in all well–studied systems are observed to be single peaked, with a "universal" absolute turn–over magnitude $M_V^{TO} \simeq -7.5$. This turn–over magnitude depends only weakly on galaxy luminosity and type (Harris 1996). The difference in the peak of the luminosity function between different globular cluster populations must be smaller than the detection limit, that we estimate to be ≤ 0.4 mag in the current data sets (e.g. Forbes et al. 1996, Kissler-Patig et al. 1997b, Forbes, Brodie & Huchra 1996). Can new and old globular clusters have similar luminosities? In general, the luminosities of globular clusters can vary *i)* with the mass of the objects if a constant mass–to–light ratio (M/L) is assumed, *ii)* with M/L if a constant globular cluster mass distribution is assumed or in other words with the stellar initial mass function (IMF) within the clusters, *iii)* with the cluster ages, and *iv)* with the cluster metallicities.

i) Similar mass distributions:

Will new and old globular clusters have comparable mass distributions to allow similar luminosity functions? Meurer (1995) first argued that newly formed globular clusters in NGC 4038/4039 have, at the observed bright end, a magnitude distribution that is compatible with that observed for old globular clusters in galaxies, i.e. the underlying globular cluster mass distributions must be similar. Schweizer et al. (1996) confirmed in NGC 3921 that the luminosity function of the young objects followed a power–law, but also pointed out that it does so down to lower masses than expected. They pointed out that this luminosity function will only evolve into what is currently seen for old globular clusters, if globular clusters are preferentially destroyed by processes acting more efficiently at the low–mass end. Recently, Elmegreen & Efremov (1997) argued that the star cluster formation mechanism was universal, and explicitly that old globular clusters and younger ones (formed in mergers) have identical initial mass distributions. As time evolves, destruction processes will make the luminosity function look like the one observed today in nearby galaxies. This was recently supported observationally by Harris, Harris & McLaughlin (1998) who found no significant difference in the luminosity functions of the two old populations in M87 and concluded that the destruction processes at the low–mass end do not affect the bright end and turn–over of the luminosity function. We will therefore assume that two populations will be indistinguishable by their mass distribution, down to and slightly beyond the turn–over of the luminosity function, after several Gyr.

ii) Similar mass–to–light ratios:

The mass–to–light ratio of a globular cluster changes with age but is predictable by population synthesis models (see below) if the IMF of the globular cluster is known. Are large variations of the IMF expected between the new and the old globular clusters? Dubath & Grillmair (1997) showed that globular clusters in the Milky Way, M31, Fornax, the Magellanic Clouds, and Cen A have extremely similar M/L_V ratios, after correcting for the different ages. The result of Dubath & Grillmair indicate that only small variations at the lower end of the IMF are expected and the mass function of the low–mass stars in clusters will be constant. We note that Brodie et al. (1998) recently found evidence from spectroscopy of a slightly flatter than Salpeter IMF for the newly formed star clusters in NGC 1275. However, the difference is mostly noticeable at the high–mass end and while these clusters are young. Once these clusters will have aged by a few Gyr, the different M/L between these clusters and the ones with a Salpeter IMF will be only marginal.

iii) and iv) An age–metallicity conspiracy

From the two points above, we conclude that no significant variations of the mass function of globular clusters and/or the mass–to–light ratio are expected between young and old globular clusters. This implies further that neither the mass distribution nor M/L can be significantly fine–tuned to compensate for any age or metallicity differences. To explain the similar luminosity functions of the new and old clusters, despite different mean ages and mean metallicities, *we must invoke a age–metallicity conspiracy.* Such a conspiracy might partly be expected since the luminosity of a globular cluster decreases with age and metallicity but new (young) globular clusters are expected to be more metal–rich than old ones, since they probably formed from more enriched material. We quantify this conspiracy in the next section together with the constraints set by the narrow colour distributions.

3.2.2 Hiding a second population: Constraints from the narrow colour distributions

If the mean age and metallicity of new and old globular clusters conspire, we can use the narrow colour distribution observed in low–luminosity ellipticals to give us another constraint. The colour of a globular cluster gets redder with increasing age and increasing metallicity. The narrow colour distributions observed in small ellipticals (e.g. Kissler-Patig et al. 1997a, Neilsen, Tsvetanov & Ford 1997), do not allow all age–metallicity combinations. If we assume that the four low–luminosity ellipticals in Fornax are representative, then the typical dispersion in a V–I colour distribution (after correcting for errors in the photometry) is about $\sigma < 0.1$ mag (Kissler-Patig et al. 1997a).

We have combined the constraints from luminosity and colour in Fig. 1. The mean V–I colour of a globular cluster population is plotted versus its metallicity as a function of age. We start with the observed single population, then add a second population and vary its mean age and metallicity until the two populations match both in colour and magnitude within the detection limits ($\Delta(V-I) = 0.1$ and $\Delta V = 0.4$). We will use the models of Worthey (1994) in the following, but obtained very similar results when using the models of Bruzual & Charlot (1993, 1997) and of Fritze–v.Alvensleben & Burkert (1995). The latter predict even tighter constraints than derived below.

We start in the upper left panel with the colour distribution typically observed in low–luminosity ellipticals, i.e. with a mean colour around V–I $\simeq$1.0 and a dispersion of about 0.1 mag. We have assumed the colour distribution of NGC 1427 to be representative (mean V–I $= 1.05 \pm 0.05$, see also Sect. 3.3). We associate this mean colour with the old population, and assume an age of 17 Gyr (the oldest available age in the Worthey models). The corresponding mean metallicity of $-1.5 <$[Fe/H]< -0.75 dex, is in good agreement with spectroscopic determinations (Kissler-Patig et al. 1998). The dotted lines show the colour range ($\pm$0.1 mag) within which a second population would be indistinguishable in colour from the old population. In the upper right panel, we now introduce three new populations. One has the same age as the old population (17 Gyr), the second is half as old (8 Gyr), the third has an age of 5 Gyr . Their mean colours vary along the solid lines as a function of metallicity (isochrones from Worthey 1994). The range of colours spanned by the initial old globular cluster population is now shown as a hatched horizontal band. All new populations match the old one in colour, if their mean metallicities are approximately [Fe/H]< -0.3, [Fe/H]< -0.1 and [Fe/H]< 0.0 dex for 17 Gyr, 8 Gyr and 5 Gyr respectively.

However, as mentioned above, colour is not the only constraint and the mean magnitude of these two populations will change with age and metallicity. This is illustrated in the lower left panel. As the new 17 Gyr population gets more metal rich, the globular clusters become fainter. Once [Fe/H]> -0.25, their mean magnitude would differ by more then 0.4 mag in V from the faintest possible old population (17 Gyr, [Fe/H]$= -0.75$). Both populations could be disentangled in the globular cluster luminosity function. Similarly, the 8 Gyr population at metallicities of [Fe/H]< -0.5 becomes 0.4 mag brighter in V than the brightest possible old population (17 Gyr, [Fe/H]$= -1.5$). Such a population could then be identified in the globular cluster luminosity function. These metallicities ([Fe/H]> -0.25 for the new 17 Gyr population, [Fe/H]< -0.5 for the new 8 Gyr population) are therefore excluded if the new and old populations are to be indistinguishable in colour *and* luminosity. The 5 Gyr population shows an extreme case: it can match the colour of the old population for metallicities below solar, but would then always be much brighter than an old population. For this young age, no combination of age and metallicity allows the new globular clusters to be hidden both in colour and luminosity. The forbidden metallicity ranges due to the constraint from the luminosity function are marked as dashed lines.

Finally, we show in the lower right panel a larger range of ages and combine the colour and luminosity constraints to show the narrow range of age and metallicity combinations (shaded area) that any new population of globular clusters must occupy, in order to be indistinguishable in current observations from the old one. The mean age of the new globular cluster population must lie between 8 and 17 Gyr, and its mean metallicity between $-2.0 <$[Fe/H]< -0.4 dex. Furthermore, age and metallicity must tightly conspire (e.g. 8 Gyr old globular clusters would have to be have a mean metallicity of $-0.5 <$[Fe/H]< -0.1).

Note that we have assumed above an approximately equal number of young and old globular clusters. The parameter range would be relaxed if the ratio of new to old (or vis–versa) globular clusters is larger than 3:1, since it would be more difficult to disentangle the two populations in the colour or magnitude distributions. The Milky Way might be representative, with a halo and bulge/disk population in the ratio of 4:1 (Minniti 1995). These populations have roughly the same age, differ in mean metallicity by [Fe/H]$\simeq$ 1 dex but cannot be disentangled in a colour distribution (the dispersion in V–I lies around $\sigma = 0.08$ mag). However, if we do assume an unbalanced ratio of new to old globular clusters after a merger event, then, given the observational facts of Sect. 2.1, this would suggest that different progenitors than gas–rich galaxies were involved in the merger, e.g. at least one galaxy must be gas–poor to explain the low number of newly formed globular clusters.

3.2.3 Do low–luminosity ellipticals have two populations of globular clusters?

To summarize, the progenitor galaxies of a recent merger must have had a significant globular cluster system; further, observations suggest that a gas–rich merger will have induced the formation of a large number of new globular globular clusters. The fast and preferential destruction of one of these populations is very unlikely. Therefore, the fact that we do not detect a second population in low–luminosity ellipticals forces us to reject the assumption that these galaxies formed in a gas–rich merger, or as discussed above, to assume that mean age and metallicity of the new globular cluster population tightly conspire to make the new population appear similar to the old one both in the colour and magnitude distribution. However, in the latter case, the current photometric data imply mean ages for the new population less than half the age of the old population are excluded (i.e. cannot be compensated by any metallicity). This therefore rules out that low–luminosity ellipticals formed by a *recent* ($z < 1$) gas–rich merger.

3.3 Two examples: NGC 1380 and NGC 1427

In order to better illustrate the age–metallicity conspiracy, we briefly discuss two examples. The first is NGC 1380, a relatively luminous ($M_V \simeq -21.5$) early–type (S0) galaxy which has sub–populations of globular clusters and illustrates the accuracy with which age and metallicity can be disentangled from broad–band colours. The second is NGC 1427, a low–luminosity elliptical ($M_V \simeq -20.5$), in which no sub–populations could be detected, and which illustrates the current status of research on globular clusters in low–luminosity galaxies.

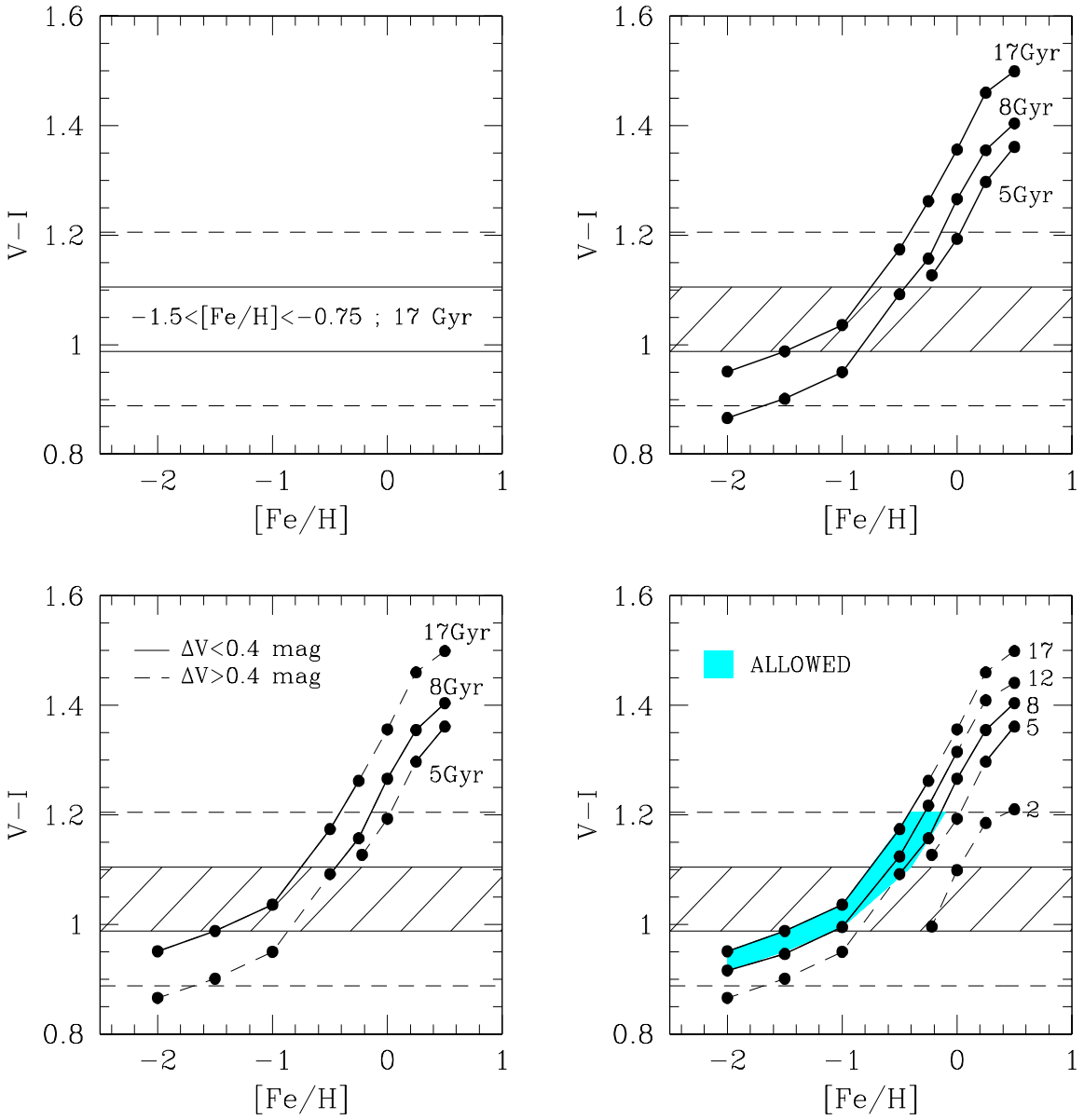

Figure 1. Hiding new globular clusters both in colour and luminosity. The upper left panel shows the colour distribution of an old globular cluster population, the dashed lines mark the range within which a new population would be indistinguishable from the old one in colour. The upper right panel shows how colour varies with metallicity for 3 different new populations (17, 8 and 5 Gyr). For some given age and metallicity combinations, a new population could match the old one in colour. The lower left panel shows the additional constraint in order to also match the luminosity function of the new and old globular clusters. The dashed part of the isochrones represent age and metallicity combinations for which the new population would differ by more than 0.4 mag from the old one and therefore be distinguishable in the luminosity function. Finally, the lower right panel combines all constraints and shows as a shaded area the range of allowed age and metallicity combinations for new globular clusters in order to look similar both in colour and magnitude to an old one. See text for further details.

NGC 1380 is the second brightest early–type galaxy in the Fornax cluster, and its globular cluster system was studied with deep photometry in three broad–band filters (Kissler-Patig et al. 1997b). Although the system is not very rich ($\sim$ 550 globular clusters), it showed a bimodal colour distribution. The globular cluster luminosity functions of the two sub–populations were indistinguishable. This could correspond in Fig. 1 to a second population of 12 Gyr with solar metallicity: indistinguishable in magnitude (solid line), but different enough in colour to be detected. The conclusion of that study was that the age difference between the two sub–populations must be $\simeq$ 4 Gyr or less, and the colour difference is mainly due to a metallicity difference (estimated to be around 1 dex). This example illustrates perhaps the highest accuracy with which age and metallicity differences can be determined. The high sensitivity to sub–populations was mainly due to deep photometry (complete down to B = 25.8), the associated small photometric errors, and the sensitivity to metallicity of the three combined colours (B, V, and R). We expect, with data of similar quality, to be

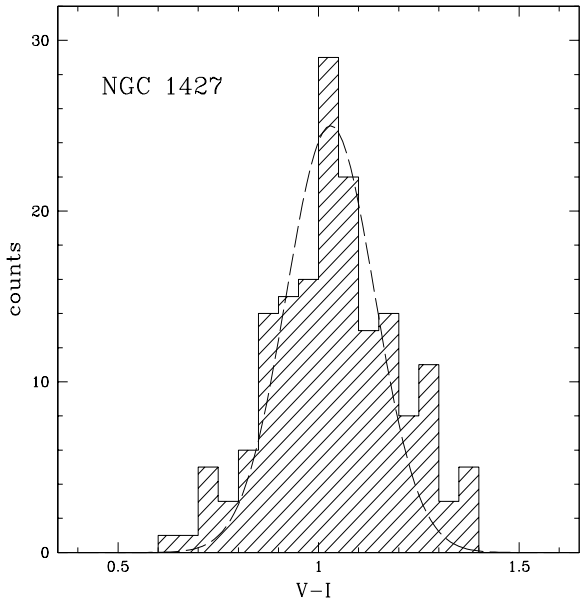

Figure 2. Globular cluster colour distribution in NGC 1427 ($M_V = -20.5$). The Gaussian represents the broadening from the photometry errors alone. There is no evidence for multi–modality.

able to detect similar sub–populations in low–luminosity ellipticals.

Probably the best photometrically studied *low–luminosity* elliptical is NGC 1427, an E3 galaxy in Fornax, a little more than a magnitude fainter than NGC 1380. It was studied by Forbes et al. (1996) with HST, and Kissler-Patig et al. (1997a) from the ground. We combined the ground–based data down to $V < 23.0$, with the HST data for $V > 23.0$. The sample now includes 176 globular clusters with good V and I photometry (mean error in V–I = 0.1 mag). The sample represents over 50% of the total existing 320 ± 60 globular clusters within 3 $r_{\rm eff}$ of the galaxy. No systematic differences were found between the photometry of the two data sets, thus no correction was necessary before combining the samples. The globular cluster colour distribution is shown in Fig. 2. No multiple populations are seen by eye, nor detected by a KMM (Ashman, Bird & Zepf 1994) statistical test. We over–plot a Gaussian with a width corresponding to our median error in V–I, $\sigma_{\rm ERR} = 0.11$ mag, to illustrate the broadening expected from the errors in the photometry alone. A free Gaussian fit to the histogram gives a width of $\sigma_{\rm TOTAL} = 0.15$ mag, thus the intrinsic width of the distribution must be less than σ(V–I)= 0.10 mag. According to the new V–I versus metallicity relation from spectroscopy of NGC 1399 globular clusters (Kissler-Patig et al. 1998), the mean colour reflects a metallicity of [Fe/H]$= -1.1 \pm 0.3$ dex, assuming an old mean age (i.e. similar to the age of the Milky Way globular clusters).

The luminosity function does not show any peculiarity either. It peaks in V and I at the same value, within the error, as do the globular cluster luminosity functions of other early–type galaxies in Fornax (Kohle et al. 1996). Using an independent distance modulus of 31.4 (from Cepheids, Madore et al. 1997), the globular cluster luminosity function of NGC 1427 peaks at $M_V^{TO} = -7.6 \pm 0.3$ mag, as does the one for the Milky Way globular clusters, supporting similar old ages as in the Milky Way. We conclude that NGC 1427 hosts a population of intermediate metallicity, old globular clusters, and that no other population is visible. Although V–I is not as sensitive as B–V and B–R (as was available for NGC 1380) to metallicity, we can further conclude that no sub–population of less than half the age of the old one is present (see Sect. 3.2). Therefore NGC 1427 cannot have been formed by a recent ($z < 1$) dissipational merger.

3.4 High–luminosity ellipticals

The above sections makes it clear that constraints can be put on the merger history of low–luminosity ellipticals from their globular cluster systems. Can similar constraints be applied to high–luminosity galaxies? The answer seems to be no, because large ellipticals often show bimodal globular cluster colour distributions (e.g. compilation by Forbes, Brodie & Grillmair 1997), whereas the constraints derived above mainly come from the detection of only one population. Moreover, the arguments used for low–luminosity ellipticals turns up some contradictions when applied to high–luminosity ellipticals.

High–luminosity galaxies are generally thought to be the result of a merger involving little gas (see Sect. 2.2) and are, therefore, expected to have formed only a few new globular clusters in interactions (see Sect. 2.1). But the observed colour distributions are often bimodal with an equal number of blue and red globular clusters within a factor two. We are apparently facing two contradictions. The first being the fact that if the ages and metallicities of globular clusters in small ellipticals conspire to give a unimodal distribution, it is not the case in large ellipticals. The second is that the number of red (assumed young) globular clusters in large ellipticals is roughly the same as the number of the blue (old) globular clusters, in contradiction with the small amount of gas expected in the merger that formed the high–luminosity ellipticals. Is there an explanation other than relaxing one of our conclusions of Sect. 2, or the assumption that the red globular clusters in high–luminosity ellipticals formed in merger events?

3.4.1 No conspiracy in high–luminosity ellipticals?

The first apparent contradiction can be explained. We do not necessarily expect a conspiracy between the age and metallicity of the new globular clusters in high–luminosity ellipticals if present in low–luminosity galaxies. Forbes, Brodie & Grillmair (1997) showed that the metallicity of the red globular clusters correlates with the luminosity of the parent galaxy. A similar behaviour is known for the stellar component of galaxies (the Mg–σ relation, e.g. Burstein et al. 1988), and a similar relation for globular clusters would not be unexpected if the red globular cluster population is associated with the stellar light (e.g. Kissler-Patig et al. 1997b, Lee, Kim & Geisler 1998). According to this relation, red globular clusters in a low–luminosity galaxy (e.g. $M_V = -20.0$) would have a metallicity lower by about [Fe/H]= 0.5 dex than red globular clusters in a high–luminosity galaxy (e.g. $M_V = -22.5$). Assuming that the metallicity of the blue populations in these galaxies are independent of M_V (no correlation with M_V was found by

Forbes, Brodie & Grillmair 1997), a red population in a high–luminosity galaxy would differ from the blue one while this might not be the case in a low–luminosity galaxy. As an example, we assume an old population similar to the one in Fig. 1. In a low–luminosity galaxy ($M_V = -20.0$, similar to NGC 1427) a new population of 8 Gyr with a mean metallicity of [Fe/H]$= -0.5$ dex would be hidden in both the colour and magnitude distribution of the globular cluster system. The same new population would have a mean metallicity of [Fe/H]$= 0.0$ dex (solar) in a high–luminosity galaxy ($M_V = -22.5$, similar to M87) and would show up in the colour distribution as a second peak, offset by 0.2 mag in V–I from the old one. Note that this new population would still be hidden in the globular cluster luminosity function. This scenario is actually very close to the current observations, e.g. in M87, Whitmore et al. (1995) and Elson & Santiago (1996) see two peaks in the colour distribution separated by V–I$\simeq$ 0.2 mag and no significant ($\Delta V < 0.4$ mag) effect in the globular cluster luminosity function.

3.4.2 Did the red globular clusters form in a merger event?

The second contradiction is more serious. Given the observations presented in Sect. 2.1, the large number of red globular clusters in high–luminosity ellipticals is not compatible with a formation via gas–poor mergers. Either high–luminosity ellipticals formed by gas–rich mergers (but see Sect. 2.2), or the large number of red globular clusters is not associated with merger events. We investigate the latter possibility.

Recent spectroscopy of blue and red globular clusters in NGC 1399 and M87 (Kissler-Patig et al. 1998, Cohen, Blakeslee & Rhyzov 1998) has shown, that none of the major sub–populations has formed in a *recent* ($z < 1$) merger. Only a small fraction of very red objects in NGC 1399 seem compatible with a more recent formation, e.g. in a merger event involving a moderate amount of gas. This picture is supported to some extend by the photometry of globular clusters in NGC 1380 (Kissler-Patig et al. 1997b). The origin of blue and red clusters in this galaxy is unclear, both populations are old and could as well be associated with the bulge/disk and halo formation, as with a merger origin. Clearly the picture of blue globular clusters in a bimodal distribution being old and the red ones being young and formed in a merger is too simple and misleading.

We note that this prohibits a straightforward comparison of the properties of sub–populations with the expectations from the merger scenario of Ashman & Zepf (1992), as long as it remains unclear what fraction of the red globular clusters formed in a merger event. If other processes can form red globular clusters, the number of red versus blue clusters does not support nor rule out any merger model.

Alternatives for forming the large number of globular clusters around high–luminosity ellipticals and explaining the presence of sub–populations were discussed by various authors. Formation of the red clusters in dissipational mergers *at a very early time* in the history of the galaxy is not, a priori, excluded (although see arguments by Forbes, Brodie & Grillmair 1997). Blakeslee (1996) and Blakeslee et al. (1997) associate over–abundant globular cluster systems with the preferential position of the galaxy in a clusters, and with an early–formation of a number of globular clusters proportional to the available mass. However they do not comment on the origin of the different globular cluster sub–populations. Forbes, Brodie & Grillmair (1997) argued that the two–populations in large ellipticals are the product of a two–phase collapse. Kissler-Patig (1997b) suggested a global pre–galactic formation in fragments and a formation in the collapse of the disk/bulge forming the galaxies. The last two scenarios differ in the sense that the former assumes rather monolithic collapses with the metal–rich globular clusters in ellipticals being analogous to the metal–poor ones in spirals, invoking a third phase in late–type galaxies. The Kissler-Patig scenario would associate metal–poor globular clusters in ellipticals with metal–poor globular clusters in spirals and the intra–cluster medium. The metal–rich globular clusters in ellipticals would be analogous to the disk/bulge populations in spirals. The common point, independent of the exact formation mechanism, is that the sub–populations differ slightly in age and could differ considerably in metallicity (depending on the details of the enrichment process), since the second generation will form from more enriched gas. But in both scenarios the sub–populations are intrinsic to the galaxy and not mainly the product of a late merger.

These scenarios have gained some support recently. Harris et al. (1997) ruled out large age differences between halo globular clusters in the Milky Way. They interpreted their results in a picture where halo globular clusters formed in fragments that started star formation within the same Gyr and later merged to build the Galaxy. Further, Elson (1997) has detected a blue and a red stellar population in the early–type galaxy NGC 3115, with typical halo and bulge metallicities, hinting at the fact that all galaxies could have stellar halos but ellipticals are "bulge" dominated. The recent findings in the early–type galaxies NGC 1380, NGC 1399 and NGC 4472 that associate blue and red globular clusters with halo and bulge/disk stellar populations support this picture. As pointed out by Harris (1998) the early star formation in fragments will presumably cause its own demise, and lead to a "dormant" phase as suggested by Forbes, Brodie & Grillmair (1997). Star and globular cluster formation would then restart during the collapse of the fragments to a bulge/disk. We would then expect the presence of old, blue and red, globular clusters in all galaxies, independently of their types. Note that such a scenario would not rule out a contribution through mergers to the red globular cluster population (e.g. the very red globular clusters in NGC 1399, Kissler-Patig et al. 1998).

Clearly, a definitive understanding of globular cluster systems requires accurate age, metallicity and kinematic determinations of the different sub–populations from an observational point of view, and better predictions of the relative importance of the different globular cluster formation mechanisms from a theoretical point of view. We conclude that the large number of red globular clusters in high–luminosity galaxies imply that most did not form in a meger, unless these galaxies did experience a number of dissipational merger events in their past.

3.5 The smoking guns

The properties of globular clusters in low–luminosity galaxies have left us with two alternatives: these galaxies did not form in a gas–rich merger event, or the age and metallicity

of the new globular clusters conspire to look similar in their colour and magnitude distribution to the old ones. Can we discriminate between these two possibilities by investigating current day gas–rich mergers? In particular, what will these mergers and their globular cluster systems look like after several Gyr? Will they resemble low–luminosity galaxies such as NGC 1427?

The ongoing mergers listed in Sect. 2.1 typically involve gaseous sub–L^* galaxies and therefore would be expected to form intermediate–luminosity ellipticals. For example, Whitmore et al. (1997) estimate the final (after several Gyr) magnitude of NGC 1700 and NGC 3610 to be M_V = –21.26 and –20.45 respectively. If it could be shown that the age and metallicity of globular clusters will conspire in merger remnants to make them look unimodal in colour, and also if they match the other characteristics of globular cluster systems in early–type galaxies (see Sect. 3.2), then these systems might indeed be the progenitors of small, disky ellipticals. Whitmore et al. (1997) simulated the evolution of the newly formed globular clusters with population synthesis models. However, they did not allow for the metallicity of the new globular clusters to vary (fixing it at a solar metallicity) which excludes any age–metallicity conspiracy. They concluded that in this case, the newly formed globular clusters will look redder than the globular clusters of the progenitors after several Gyr, in agreement with our result in Sect. 3.2. Indeed, for a large metallicity difference, age will not be able to "compensate" the metallicity effect on colour. The assumed metallicity for the new globular clusters is critical for the colour distribution of the end–product, and before we can claim a contradiction between ongoing mergers and low–luminosity galaxies, we would need spectroscopic metallicity determinations of the new globular clusters.

A second aspect by which low–luminosity ellipticals and merger remnants could differ, are the spatial distributions of their globular cluster systems. The newly formed stars and clusters in NGC 4038/4039 and NGC 1275 are preferentially located in the center, and it remains unclear if the new systems will show the spatial properties of today's low–luminosity globular cluster systems, namely a surface density profile following that of the stellar light. This will depend on the amount and distribution of the newly formed stars.

In summary, it is unclear whether or not the ongoing mergers seen today and their globular cluster systems will evolve into low–luminosity galaxies as we see them, given the few observational constraints and in particular the lack of information about the nature of the new clusters.

4 CONCLUDING REMARKS

4.1 Summary and present conclusions

Recent observations of merging galaxies indicate that globular clusters form in all gaseous merger events, and the more gas is involved, the more new globular clusters form. The observational data suggests that ∼10% to ∼100% new globular clusters are created compared to old ones when going from early–type/early–type, to early–type/late–type, to late–type/late–type galaxy collisions. These observations naturally imply that low–luminosity ellipticals, thought to have formed in gaseous mergers, should have two distinct populations of globular clusters – old globular clusters from the progenitor galaxies and new ones created from the gas of the merger. Observations of globular cluster systems in low–luminosity ellipticals to date do *not* show evidence for two globular cluster populations. We have examined several solutions to this problem (Sect. 3.2).

- The absence of sub–populations due to the absence of an old blue population implies the early formation by merging essentially gaseous progenitors that did not have time to build up an old globular cluster system. Alternatively old globular clusters could have been preferentially removed or destroyed. In both cases today's globular clusters would be the "new" ones, but are observed to be as old as the Milky Way ones.
- The preferential destruction of the newly formed globular clusters is not ruled out, but we still see young clusters in mergers that are several Gyr old. The absence of young clusters in low–luminosity ellipticals would then set a lower age limit for the merger event.
- If age and metallicity of young and old globular clusters tightly conspire to make them appear as one population, then constraints from the colour and magnitude distributions of globular clusters allow us to constrain the maximum age and metallicity differences between the two sub–populations to be about a factor of two in age, and 1 dex in [Fe/H].
- If a large young population is absent because it simply did not form, then the current observational evidence would rule out the formation of low–luminosity ellipticals by gaseous mergers.

All solutions to this problem, regardless of their likelihood, imply that *low–luminosity ellipticals, if they formed by dissipational mergers, formed at early times with a rough lower limit of* $z > 1$.

While the absence of sub–populations in low–luminosity ellipticals can put constraints on merger histories, the presence of sub–populations in high–luminosity ellipticals is more complicated to interpret. In particular, the multiple sub–populations are not likely to be the product of the last dissipationless merger event, and many plausible alternatives to mergers exist to explain the formation of the globular cluster systems in these galaxies.

4.2 Sharpening the constraints

We have presented constraints on merger models from the properties of their globular cluster systems in nearby ellipticals. Clearly, the study of globular clusters can constrain these models, but evidently our knowledge is still very incomplete. In the following we list briefly list the points that would help to sharpen these constraints, and that were the limiting factors in our analysis.

- The nature of the young star clusters in ongoing mergers needs to be better understood. Will these objects really evolve into objects similar to old globular clusters seen today and what is their metallicity?
- The globular cluster systems of low–luminosity ellipticals need to be better studied with deep, accurate three–colour photometry, or, even better, with multi–object spec-

troscopy to detect or finally rule out the presence of sub–populations of globular clusters.

• The origin of sub–populations needs to be better understood. Mergers are one, *but not the only*, alternative for building up a second population of globular clusters. Accurate, *unique*, predictions for the different scenarios (mergers, in situ formation, stripping, accretion of dwarf galaxies, etc...) need to be explored via modeling, before the properties of globular cluster systems can be fully interpreted.

Acknowledgments
We thank Jean Brodie for useful comments on the manuscript, as well as the referee for a careful reading and helpful comments that substanstially improved the manuscript. MKP was partly supported by the DFG through the Graduiertenkolleg 'The Magellanic System and other dwarf galaxies'. Part of this research was funded by the HST grant GO.05990.01-94A. DM is supported by Lawrence Livermore National Laboratory, under DOE contract W-7405-Eng-48.

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