Abstract. A brief overview of the properties of massive star clusters in early-type galaxies is given. All ellipticals (with only one known exception) host massive star clusters in the form of globular clusters, suggesting that their formation is very common. The number of clusters per unit galaxy mass appears very constant, pointing at similar formation processes on large scales. Furthermore, the luminosity/mass functions of the globular cluster systems appear to be very similar from galaxy to galaxy, pointing at similar formation processes on small scales.

Probably the most important recent discovery is the presence of cluster sub-populations in many (if not all) early-type galaxies. The latter seem to be closely linked to galaxy formation and evolution, and appear to support hierarchical clustering models, however with an early spheroid formation.

1. Introduction

This short contribution is aimed at giving an overview of the current state of the research on globular clusters systems in early-type galaxies. It is, obviously, not aimed at giving a review on the subject. Excellent reviews have recently been written by Ashman & Zepf (1998), and Harris (1999a,b). I will focus on aspects related to the formation of massive clusters rather than on what can be learned from similar studies about the formation and evolution of the host galaxies. In early-type galaxies showing no signs of a recent star formation event, massive star clusters are exclusively globular clusters.

After a brief historical introduction (Sect. 2), similarities of the globular cluster properties in all ellipticals are highlighted (Sect. 3). Section 4 addresses the important aspect of multiple globular cluster sub-populations in ellipticals, before a brief summary is presented in Sect. 5.

2. A brief history

Globular clusters in spirals (and in particular in our Milky Way) were studied for a century already. Shapley (1918) was the first to consider the system of globular clusters as an entity in our Milky Way. Hubble (1932) followed up with the globular cluster system of M31. But it lasted another 23 years before Baum (1955) suggested the presence of globular clusters in an elliptical (M 87), and
another 13 years before Racine (1968) studied the colors and luminosities of these clusters. The first thesis on extragalactic globular cluster systems was composed by Hanes (1977) and launched what is now a very active field of research. The 80’s saw a number of studies with the first generation of CCDs. A number of properties of globular cluster systems were identified and correlations with host-galaxy properties observed (see Harris 1991 for a review of the 80’s). The 90’s, with a new generation of wide field imagers and the WFPCs on board of HST, allowed a number of more detailed studies for \( \sim 100 \) galaxies. One of the most important discoveries of the last decade was the presence of several globular cluster sub-populations around many early-type galaxies (Zepf & Ashman 1993, Gebhardt & Kissler-Patig 1999), which will be commented in Sect. 4. Thus, globular clusters in spirals are known for a century already, but globular clusters in ellipticals have a much shorter history, which should be kept in mind when assessing the conclusions drawn from a limited number of studies.

3. General properties of globular cluster systems and what they tell us about the formation of massive clusters

3.1. Their presence around all galaxies

As emphasized already by Harris (1991), all early-type galaxies host globular clusters. Studies since then only confirmed this trend in the sense that no galaxy was observed not to host any globular clusters. The number of observed clusters in normal (non-dwarf) galaxies ranges from a few hundreds to a few thousands. The only exception to date is M 32, the low-luminosity \((M_V \sim -16.4)\), high surface-brightness companion of M 31, in which 15-20 globular clusters are expected, but none was detected. It remains unclear whether its population could have been efficiently removed during interactions with M 31, or destroyed by dynamical friction and tidal shocks from the dense nucleus of M 32 itself. M 32 remains a minor puzzle.

Nevertheless, the other \( \sim 100 \) cases demonstrate that the formation of massive star clusters during the formation and evolution of early-type galaxies is very common. The formation of star clusters as a common mode of star formation might not be surprising, but the abundant presence of globular clusters in all early-type galaxies is one of its best proofs.

3.2. Their number per unit luminosity

To compare the relative numbers of globular clusters in galaxies of different sizes, Harris & van den Bergh (1981) introduced the specific frequency: the number of globular clusters per unit \((M_V = 10^{15})\) of galaxy light. The specific frequency of early-type galaxies was found to be pretty constant except in central cD galaxies which appeared to exhibit a large overabundance of globular clusters. The latter galaxies, however, were shown not to be overabundant in globular clusters when the total mass (in particular the hot gas) surrounding them was properly taken into account (see McLaughlin 1999, and in these proceedings).

To better compare spirals and ellipticals, Zepf & Ashman (1993) introduce a quantity similar to the specific frequency, but normalized to mass (taking into account the different mass-to-light ratio as a function of galaxy type). Ellipti-
Massive clusters in ellipticals

3. Their luminosity/mass function

Another “universal” property of globular clusters is their luminosity or mass function that appears to have a characteristic scale (see also the contribution of Miller; Fritze-von Alvensleben; and McLaughlin in these proceedings).

The constancy of the turn-over magnitude of the globular cluster luminosity function was recognized early on and explored as a standard candle (cf. Hanes 1979). Various authors claimed that a dependence of galaxy type or environment could exist (e.g. Whitmore 1997 for a summary). It appears, however, very likely that the underlying mass distributions are very similar and that the slightly different turn-overs in the luminosity functions can be fully explained by the dependency of the luminosity from age and metallicity. Towards the center of galaxies (closer than \( \sim 5 \) kpc) dynamical effects will obviously also play a role.

Various arguments lead to believe that the characteristic mass in the mass distributions of globular clusters is not a product of dynamical evolution of the system (cf. the above mentioned contributions to these proceedings). One of the arguments is the presence of this same characteristic mass in galaxies with very different gravitational potential including dwarf galaxies, spirals, cuspy and core ellipticals of various masses. It rather seems that the characteristic scale is implemented right from the beginning, although it remains unclear whether this is linked to the exact formation process of massive clusters inside a given molecular cloud, or whether this is an implication of a characteristic scale already present in the mass distribution of the molecular clouds at the origin of the globular clusters. Both cases, however, support a “universal” and very homogeneous formation process of globular clusters in the universe, also on the small scales of molecular clouds.

4. The presence of multiple globular cluster sub-populations in early-type galaxies

4.1. Discovery and frequency of multiple globular cluster populations in early-type galaxies

One of the currently most interesting aspects of globular cluster systems of early-type galaxies is the presence of multiple sub-populations in many galaxies. In retrospective, this discovery could have been anticipated since the discovery of halo and bulge clusters in the Milky Way (e.g. Jablonka in the proceedings).
came, nevertheless, as a surprise when these sub-populations were first discovered in globular cluster color distributions by Zepf & Ashman (1993). The most recent studies suggest that \( \sim 50\% \) of all early-type galaxies host more than one globular cluster population (Gebhardt & Kissler-Patig 1999, see also Kundu 1999). This number is only a lower limit given the fact that the studies were conducted with \( V - I \) colors that are not very sensitive to metallicity. The absence of multi-modal distributions around more galaxies could therefore be due to the observational limits combined with the age-metallicity degeneracy present in optical colors, rather than to the physical absence of multiple sub-populations in these galaxies (see also Kissler-Patig, Forbes, Minniti 1998).

4.2. The properties of metal-rich and metal-poor populations

The reality of the distinction, first observed in colors only, was established in studies that derived very different spatial distributions for the metal-poor and metal-rich clusters around their host galaxies (to date, NGC 1380: Kissler-Patig et al. 1997; NGC 4472: Lee et al. 1998; NGC 3115: Kundu & Whitmore 1998).

Generally speaking, the metal-poor clusters have a more spherical (or less flattened) distribution and are somewhat more extended than the diffuse stellar light, while the metal-rich population closely follows the ellipticity and position angle of the observed (high surface-brightness) stellar light. Thus, the metal-poor population gets associated with the halo, while the red population appears associated with the spheroid/thick-disk component. Interestingly, both from spectroscopic studies, as well as from photometric studies, the metal-poor and metal-rich globular clusters appear coeval and old, with ages similar to the ones of the Milky Way globular clusters (see Kissler-Patig in these proceedings).

From dynamical studies, the metal-poor clusters in ellipticals seem to dominate the rotation or at least to be on tangentially biased orbits and have a high velocity dispersion, as opposed to the metal-rich clusters that exhibit little rotation, are apparently on more radial orbits and have a lower velocity dispersion (cf. Kissler-Patig & Gebhardt 1998; Sharples et al. 1998; Kissler-Patig et al. 1999).

Finally, the three studies in this respect (Kundu & Whitmore 1998; Puzia et al. 1999; Kundu et al. 1999) showed that the red globular clusters are systematically smaller than the blue ones, and this at all radii out to several kpc (tested up to \( \sim 20 \) kpc). Dynamical effects could play a role, given that the red clusters appear to be on more radially biased orbits, however the reason for this discrepancy is still unclear.

4.3. The origin of the sub-populations

Deriving the origin of these sub-populations from their properties is currently the subject of many papers. Originally, the presence of the two populations was predicted by Ashman & Zepf (1992) in the frame of elliptical formation through spiral–spiral mergers. Their first simple scenario turned out to have problems explaining all the properties of the blue and red sub-populations (e.g. Kissler-Patig et al. 1997; Forbes et al. 1997), and it became clear that several other scenarios can explain the presence of the two populations (see Kissler-Patig 1997; Kissler-Patig et al. 1998; Côté et al. 1998; Harris et al. 1998; Hilker et al. 1999; Harris et al. 1999). Which mode of globular cluster formation dominates the build-
ing up of most globular cluster systems around galaxies is the matter of current studies. The main questions being (i) whether or not the clusters associated with the bulge (and the bulges themselves) primarily formed in gas-rich mergers, as opposed to early-type collapses – falling back on the older debate on galaxy formation; (ii) whether or not the metal-poor clusters formed in association with their final host galaxies. The latter does not seem to be the case (see Burgarella et al. 2000, and in these proceedings), although it appears difficult to distinguish between a formation completely decoupled from the galaxy and a formation in individual fragments within the initial dark halo.

5. Summary

The common presence of globular clusters around early-type galaxies, as well as their universal properties suggest a very homogeneous formation of star clusters in the universe. The characteristic mass scale is either telling us about their formation process or implies a characteristic mass already present in the molecular clouds out of which these clusters form.

The presence of halo and bulge clusters appears to be common. The origin of these sub-population is still unclear. However, there is strong evidence that the metal-poor clusters formed in fragments independently of their final host galaxies, supporting hierarchical clustering models. The formation of the metal-rich clusters appears to be associated with the formation of the spheroid (eventually thick disk), but must have happened at early epochs given the old measured ages of the metal-rich clusters.

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Discussion

Daniella Calzetti: You mentioned that the observed properties of globular cluster populations do not support merging scenarios as only process for galaxy formation. Can you clarify which are the problems with the merging scenarios?

Markus Kissler-Patig: This was partly a statement to act against the “fashionable”, but in my opinion wrong, idea that the metal-rich populations are the sole product of spiral–spiral mergers. I would like to remind people that alternative scenarios exist which are perfectly compatible with the data (mainly because no exact/unique predictions exist for any scenario to date). Forbes et al. (1997), for example, list a number of problems disqualifying the very simple scenario as originally proposed by Ashman & Zepf (1992), mainly based on the ratios of blue to red objects. Furthermore, the old ages of the metal-rich clusters in the studied system (in galaxy clusters only, so far) rule out mergers since $z = 1$, which caused trouble to hierarchical merging scenarios when these still predicted the majority of star-formation to happen between $z = 0.5$ and $1.0$. Similar arguments can be made for other galaxies in which no sub-populations were detected yet with the current observations (see Kissler-Patig, Forbes, & Minniti 1998). Finally, it remains to be shown that large red populations with the observed properties (out to several tens of kpc) can be build up in spiral–spiral mergers. In other words, whether the new clusters observed in interacting systems have indeed globular properties (individually and as a system).
Hans Zinnecker: On the two populations of globular clusters (metal-poor and metal-rich): could they have their origin in two different types of galaxies merging, namely metal-poor Magellanic type dwarf galaxies coming together early on (halo clusters) and somewhat later a major collision of two more metal-rich spirals (bulge clusters)? Have people working on hierarchical galaxy formation considered this?

Markus Kissler-Patig: This is close to the most believed scenarios to date, although the first merging you mentioned is often referred to as accretion, and the accreted dwarf galaxies do not need to be of Magellanic type (the whole is then not too far from an Searle & Zinn picture, except with bigger fragments and outside a well defined initial halo). For the formation of the bulges, indeed a spiral–spiral merger could be the case, but if I understand you right, the spirals would not have bulges themselves, and remember that given the ages of the bulge clusters this must have happened a very high redshift: we fall back onto a formation of the bulge by one or more gas-rich entities. Concerning hierarchical galaxy formation models: they handle mostly dark halos, and the baryonic parts of these are usually viewed as disks of various sizes. It is non-trivial to link these simulations with such exact terms as Magellanic type dwarfs or spirals of a given type.

Pavel Kroupa: Will a large number of mergers of gas-rich galaxies not produce a Gaussian distribution of globular cluster properties, assuming globular clusters form during mergers.

Markus Kissler-Patig: Indeed a large number of globular clusters formed in mergers will “smear out” the color distribution but only for the red (metal-rich) objects. The metal-poor clusters are not though to have formed in gas rich mergers, and Côté et al. (1998) showed in simulations that for a steep galaxy luminosity function, a seed galaxy would accrete a large number of low-luminosity dwarfs, building up a distinct population of blue clusters, before a larger merger event (from the high-luminosity end of the galaxy luminosity function) would add a distinct metal-rich population that could later be smeared out by further mergers. So one should keep in mind that the metal-rich population is likely to be a composite of several episodes.

Georges Meylan: Photometric observations are an essential first step towards the study of globular cluster systems. But large pollution is present: checks by radial velocities, in NGC 1399 and NGC 1316, show that ~50% of the globular cluster candidates are actually foreground stars and background galaxies. Consequently, spectroscopic check is an essential second step.

Markus Kissler-Patig: The studies you refer too were conducted with the NTT, and prepared with ground-based, optical photometry. These samples are partly artificially contaminated because the masked were “filled” with bright objects when no good globular cluster candidate was present. More recent studies, prepared with combinations of optical and near-infrared photometry, as well as HST imaging, have typical contaminations of less than 10%–20% (also because 10m-class telescopes allow the spectroscopy of fainter objects and do not limit the choice of targets). But I agree that the next large step forward in the field will be spectroscopy for a very large number of globular clusters with instruments such as VIMOS (VLT) or DEIMOS (Keck). Also you are right that older
ground-based photometric studies dealing with a limited number of globular clusters can be severally affected by background contamination.

**Torsten Böker:** Why is the bimodal distribution attributed to metallicity effects alone, rather than e.g. age or extinction?

**Markus Kissler-Patig:** In the particular case of early-type galaxies, internal extinction is not a major concern given the lack of a significant amount of dust in these galaxies, at least at the large radii at which the clusters are observed. Further, the colors of old globular clusters are completely dominated by metallicity rather than by age. This was confirmed by all spectroscopic surveys conducted to date. For example, a metallicity difference of 1 dex in [Fe/H] would have the same effect on $V - I$ as an age difference of roughly 10 Gyr.