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The dichotomy of early-type galaxies from their globular cluster systems

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Abstract. Growing evidence for the existence of two classes of ellipticals calls for a comparison of the properties of their globular cluster systems. I compiled information on the properties of 53 globular cluster systems of faint and bright early-type galaxies, and investigated them in the light of the properties of the parent galaxies. The properties of globular cluster systems appear to separate into two classes rather than to follow continuous relations with their host galaxy properties.

The "faint" systems have a low specific frequency (less than about 5), less than roughly 1500 globular clusters, a relatively low metallicity ([Fe/H]< -1.2), and a steep density profile that follows the galaxy light. These systems appear essentially unperturbed, and are hosted by faint (about $M_V > -21.5$), disky early-type galaxies with unresolved cores.

On the other hand, "bright" globular cluster systems had a higher efficiency in producing globular clusters and have higher specific frequencies (higher than 5). They have larger number of globular clusters (more than 2000), have flat density profiles ($\alpha > -1.7$) and their color distributions are often broad, and show several peaks or gradients in many cases. Finally the mean metallicity is higher than in "faint" globular cluster systems. "Bright" globular cluster systems show all signs predicted for globular cluster systems that experienced a merger event, and are associated with bright (about $M_V < -21.5$) boxy ellipticals with resolved cores.

I conclude that every galaxy is likely to have formed globular clusters during the early proto-galactic collapse, but "bright" systems were enriched and disturbed during merger events. These two classes of globular cluster systems support the idea that major merger events could be a cause for the dichotomy of early-type galaxies.

Key words: globular clusters – galaxies: elliptical and lenticular – galaxies: star clusters

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1. Introduction

More and more facts support the idea of a dichotomy in early-type galaxies. Early work from Davies et al. (1983) already identified kinematically low luminosity ellipticals ($M_B \geq -20.8$) with the bulges of spiral galaxies. They distinguished between faint ellipticals that rotate rapidly and are approximately isotropic and bright ones that rotate slowly and are anisotropic. Similar distinction came from Nieto (1988) and Bender (1988), who divided ellipticals in disky and boxy objects (with possible sub-classes, Nieto & Bender 1989) from isophotal analyses, and suggested the division in two classes: disky ellipticals, galaxies having kept their original structure; and "merger products", galaxies showing signatures of merging of all kinds. This was supported by the fact that radio-loud galaxies and those surrounded by X-ray halos were found to be boxy or irregular, while disky galaxies are mostly radio-quiet and show no X-ray emission in excess of the discrete source contribution (Bender et al. 1989). Nieto et al. (1991) strengthen the similarity between disky ellipticals and S0 galaxies, having both more peaked, unresolved central profiles, while a fair proportion of boxy and irregular ellipticals have flat, well-resolved central profiles. This idea was confirmed by a series of papers on "Centers of Early-Type Galaxies with HST" in which early-type galaxies were found to be divided into two classes based on their surface-brightness profiles: those with cuspy cores and those whose steep power-law profiles continue unchanged into the resolution limit (Lauer et al. 1995, see also Jaffe et al. 1994 for a similar classification). This bi-modal distribution was found to correlate with luminosity (Kormendy et al. 1993, Gebhardt et al. 1996), defining a bright and faint class (the division occurring at about $M_V \simeq -21$), which were further identified with the boxy/non-rotating and disky/rotating classes (Faber et al. 1996).

Another approach to this problem is the investigation of the globular cluster systems of early-type galaxies. Since almost all early-type galaxies contain a system of old globular clusters (see reviews of Harris & Racine 1979, Harris 1991, Richtler 1995), and globular clusters are believed to have followed the galaxy formation and evolution, differences in formation and evolution of two classes of early-type galaxies might be visible in the properties of the globular cluster systems. Further predictions for the properties of globular cluster systems having experienced a merger were made by Ashman & Zepf 1992 to which the observations can be compared. Finally the properties of a sample of individual objects might more clearly show what causes the difference between the two families of early-type galaxies.

Globular cluster systems have been identified in more than 50 early-type galaxies (see list of Harris & Harris 1996), from which roughly half were investigated in more detail. The properties that can be derived are the number of globular clusters, which can be normalized to the luminosity of the galaxy (specific frequency S_N, see Sect. 3.1), morphological properties such as surface density profile and spatial distribution, and finally the color distribution of the globular clusters.

Various attempts have been made to find correlations between some of these properties and galaxy parameters. The most extensive study being the multivariate analysis of Santiago & Djorgovski (1993) who looked for relations between number globular clusters or specific frequency and galaxy parameters, and concluded that the mechanisms of formation of globular clusters must be closely tied to those operating during the formation and evolution of their host galaxies. Further studies will be discussed in detail below. However the correlations were looked at in sparse samples available at that time, mainly including bright ellipticals because of their large globular cluster systems and/or only linear or continuous relations were assumed.

In Sect. 2 I present the compilation of early-type galaxies with studied globular cluster systems. Sect. 3 shows the correlations between globular cluster system and galaxy parameters. In Sect. 4 I discuss the results and their implications.

2. The compilations of globular cluster systems

Over 50 early-type galaxies have their globular cluster systems investigated to date, unfortunately in a very heterogeneous way. Table 1 compiles the result for all systems of S0 and ellipticals presently known. The compilation is based on the Harris & Harris (1996) list, enriched with information from various sources, especially enclosing four fainter ($M_V \simeq -20.0$) ellipticals from the Fornax cluster (Kissler-Patig et al. 1996a), improving the statistics at the faint end. The reader is referred to Harris & Harris (1996) and Harris (1991) for references when not indicated differently in column 11 (see below). Differences might occur if articles were interpreted differently, but I stayed as close as possible to the original works.

The following properties were retained for the globular cluster systems: the total number of globular clusters around the galaxy (N_{gc}, column 7) as extrapolated by the authors, with preference for H_0 = 75 km$\cdot$ s$^{-1}\cdot$ Mpc^{-1} when values were given as a function of the distance; the specific frequency S_N (Number of globular clusters normalized on the galaxy luminosity, Harris & van den Bergh 1981) based on the number of globular clusters and the absolute luminosity given in the table (column 8); the slope of the density profile (α, column 9) as the exponent of a power-law fitted to the globular cluster density profile; and finally qualitative color informations (column 10), where "s" means single peaked color distribution, "b" means broad (or bi-modal) color distribution (e.g. Zepf & Ashman 1993, Kissler-Patig et al. 1996a for meaning and implications), and "g" means that a color gradient was detected in the globular cluster system. Results marked with a question mark (?) are quoted as uncertain by the authors. The slope of the density profile and color informations were not available for all galaxies.

For the galaxies, I list the name and type (column 1 and 2); the assumed distance modulus (column 3) where distances were computed with H_0 = 75 km$\cdot$ s$^{-1}\cdot$ Mpc^{-1} only when no other distance indicator was available; the absolute luminosity (column 4) derived with the distance stated in column 3; the $a4/a$ coefficient characterizing the isophotal shape (column 5) taken from Bender et al. (1989), Bender et al. (1996), and Goudfrooij et al. (1994), where $a4/a > 0$ indicates disky isophotes, and $a4/a < 0$ indicates boxy isophotes; and finally the logorithmic slope of the central luminosity density (γ, column 6) taken from Gebhardt et al. (1996).

The galaxies are listed in increasing order of absolute magnitude. The names of the galaxies are marked with a star (*) when less then 10% of the total number of globular clusters were observed, and thus the results for these galaxies are rather uncertain. The references in column 11 refer to: 1,2: reference to be found in the lists of Harris 1991 and Harris & Harris 1996 respectively, 3: Ajhar et al. 1994, 4: Forbes et al. 1996 5: Minniti et al. 1996a, 6: Kissler-Patig et al. 1996a, 7: Minniti et al. 1996b, 8: Madejski & Rabolli 1994, 9: Elson & Santiago 1996, 10: Whitmore et al. 1995, 11: Hilker & Kissler-Patig 1996, 12: Geisler et al. 1996, 13: Bridges et al. 1996, 14: Couture et al. 1991, 15: Dirsch 1996.

3. Globular cluster system vs. galaxy parameters

3.1. The specific frequency

The specific frequency $S_N = N \times 10^{(0.4\cdot(M_V+15))}$, where N is the total number of globular clusters, and M_V the absolute luminosity of the galaxy, was introduced by Harris & van den Bergh (1981). It was thereafter often used to look for correlations of globular cluster system properties with galaxy properties (e.g. the extensive analysis by Santiago & Djorgovski 1993), mainly being interpreted as a possible influence of the galaxy environment on the efficiency of forming globular cluster (e.g. Harris 1991, Kumai et al. 1993 for a quantitative relation). The outstanding (> 10) specific frequencies of some very luminous central ellipticals still wait for a definitive explanation, but were shown to be compatible with a scenario were these galaxies were formed through major merger events (e.g. Zepf & Ashman 1993).

We show the correlations of S_N versus the total luminosity of the galaxy M_V, and the $a4/a$ coefficient of the isophotal analysis of the galaxy in Fig. 1 (upper and lower panel respectively). Values from galaxies marked with a star in Table 1 (i.e. with less

Table 1. Properties of the globular cluster systems and their parent galaxies (see Sect. 2)

NGC	Galaxy parameters T	$(m-M)_V$	M_V^T	$a4/a$ (x100)	γ	GCS parameters N_{gc}	S_N	α	Color	Refs
artif.	dE	0	-15.0			6 ± 0	6 ± 0	-2.2 ± 0.2		5
221	E2	24.54	-16.3			3 ± 0	0.8 ± 0	0		1
3115DW1	dE1,N	30.2	-17.7			59 ± 23	4.9 ± 1.9	-1.8 ± 0.4	s	2
3226	E2	31.0	-19.6			480 ± 170	7 ± 2.4	-2.5 ± 0.5		1
4278	E1	30.0	-19.8	-1		730 ± 85	8.7 ± 1.4	-1.85 ± 0.2	s?	1,4
1374	E1	31.0	-19.8	0		410 ± 82	4.9 ± 1.3	-1.8 ± 0.3	s	6
1379	E0	31.0	-19.9	0.2		314 ± 63	3.4 ± 0.9	-2.1 ± 0.6	s	6
1427	E3	31.0	-20.0	0.7		510 ± 87	5.1 ± 1.3	-2.0 ± 0.3	s	6
4340*	S0	31.0	-20.0			775 ± 310	8 ± 3.2			1
4564*	E6	31.0	-20.1	2.2	1.91 ± 0.03	1000 ± 300	10 ± 3			2
3377	E5	30.3	-20.1	1.2	1.95 ± 0.05	235 ± 50	2.1 ± 0.5	-1.9 ± 0.2		1
1387	S0	31.0	-20.2			389 ± 110	3.2 ± 1.1	-2.2 ± 0.3	s	6
5481	E3	32.7	-20.2			300 ± 70	2.5 ± 0.6	-1.7 ± 0.0	s?	8
3384	S0	30.3	-20.3	0	2.07 ± 0.04	140 ± 60	1.1 ± 0.5			1
1052	E4	31.3	-20.4	irr		430 ± 80	3 ± 0.4	-2.26 ± 0.27		1
3607	S0	30.7	-20.7	irr		800 ± 560	4.2 ± 3	-2.6 ± 0.5		1
1549	E0	30.7	-20.8	-0.4		165 ± 60	0.8 ± 0.3	-1.8 ± 0		1
5813	E1	31.7	-21.0	irr	0.64 ± 0.15	1800 ± 400	7.2 ± 1.9	-2.18 ± 0.33	s	2
3379	E1	30.3	-21.0	0.2	1.07 ± 0.06	290 ± 150	1.2 ± 0.7	-1.8 ± 0.2		1
4494	E0	30.8	-21.0	0.3		1400 ± 350	5.4 ± 1.3	-1.06 ± 0.38	b?	2,4
1404	E1	31.0	-21.0	0.5		880 ± 140	3.5 ± 0.8	-2 ± 0.1	s	2
1553	S0	30.5	-21.0			587 ± 130	2.3 ± 0.5	-2.3 ± 0		1
3115	S0	30.2	-21.1		1.87 ± 0.03	630 ± 150	2.3 ± 0.5	-1.84 ± 0.23		1
720	E5	31.4	-21.2	0.7	0.73 ± 0.32	660 ± 190	2.2 ± 0.9	-2.2 ± 0.1		2
4552*	E0	31.0	-21.2	-2	0.63 ± 0.14	2400 ± 0	8 ± 0		b?	2,3
4621*	E5	31.0	-21.2	1.5	2.03 ± 0.03	1900 ± 400	6.3 ± 1.2			1
4526*	S0	31.0	-21.4			2700 ± 400	7.7 ± 1.2			1
4697	E6	30.8	-21.6	1.4		1090 ± 420	2.5 ± 1.0	-1.9 ± 0.2		15
4881	E0	34.9	-21.6			390 ± 40	1 ± 0.1	0		2
4636	E0	31.2	-21.7	-0.2	1 ± 0.09	3600 ± 500	7.5 ± 2	-1 ± 0.1		2
4374*	E1	31.0	-21.7	-0.4		3040 ± 400	6.6 ± 0.9		s?	1,3
1399	E1/cD	31.0	-21.7	0.1	0.78 ± 0.14	5940 ± 570	12.4 ± 3	-1.6 ± 0.15	bg	2,6
5629	E/cD	34.0	-21.7			2000 ± 0	5 ± 0			2
4406*	E3	31.0	-21.8	-0.7		3350 ± 400	6.3 ± 0.8		s?	1,3
4365	E2	31.4	-21.8	-1.1	1.06 ± 0.09	2500 ± 200	5 ± 0.4	-1.15 ± 0.25	bg	2,3
524	S0	32.5	-21.9			3300 ± 1000	4.8 ± 1.1	-1.71 ± 0.12		1
5128	E0p	28.25	-22.0			1700 ± 400	2.6 ± 0.6	-1.5 ± 0.2	bg	1,7
5846	E0	32.3	-22.1	0.0		3120 ± 1850	4.5 ± 2.7			1
3923	E3	31.9	-22.1	-0.4		4300 ± 1000	6.4 ± 1.5		bg	2
4649*	E2	31.0	-22.2	-0.5	0.82 ± 0.16	5100 ± 160	6.9 ± 0.2		g	1,14
3311	E0/cD	33.4	-22.3			12400 ± 5000	15 ± 6	-1.3 ± 0.2	b	2
4486	E0	31.0	-22.4	0		13000 ± 500	13.9 ± 0.5	-1.61 ± 0.08	bg	2,9,10
5018	E4p	33.4	-22.6			1200 ± 500	1.1 ± 0.5	-1.3 ± 0.4	b	11
3557*	E3	33.0	-22.6	0.0		400 ± 300	0.4 ± 0.3			1
4472	E2	31.0	-22.6	-0.3	0.9 ± 0.19	6300 ± 1900	5.6 ± 1.7	-1.68 ± 0.13	bg	1,3,12
6166	E2/cD	35.45	-22.74			11000 ± 8000	9 ± 6	-0.95 ± 0.1	s?g?	2,13
7768	E2/cD	35.3	-22.9			4050 ± 2600	2.8 ± 1.8	-1.3 ± 0		2
4874	E0	34.9	-23.0		0.76 ± 0.17	22600 ± 2700	14.3 ± 1.7			2
4073	E1/cD	34.6	-23.1			8290 ± 460	4.8 ± 0.3	-0.95 ± 0.3		2
3842	E3	34.7	-23.1	-0.3		14000 ± 2500	7.7 ± 1.4	-1.2 ± 0		2
1275	Ep/cD	34.9	-23.3			7750 ± 2520	4.3 ± 1.4		b	2
UGC9958	E/cD	36.3	-23.4			27000 ± 13000	12 ± 5.6	-1.2 ± 0		2
UGC9799	E/cD	35.9	-23.4			48000 ± 16000	21 ± 7	-1.4 ± 0		2
4889	E4	34.9	-23.5	irr	0.33 ± 0.44	17300 ± 3000	6.9 ± 1.2			2

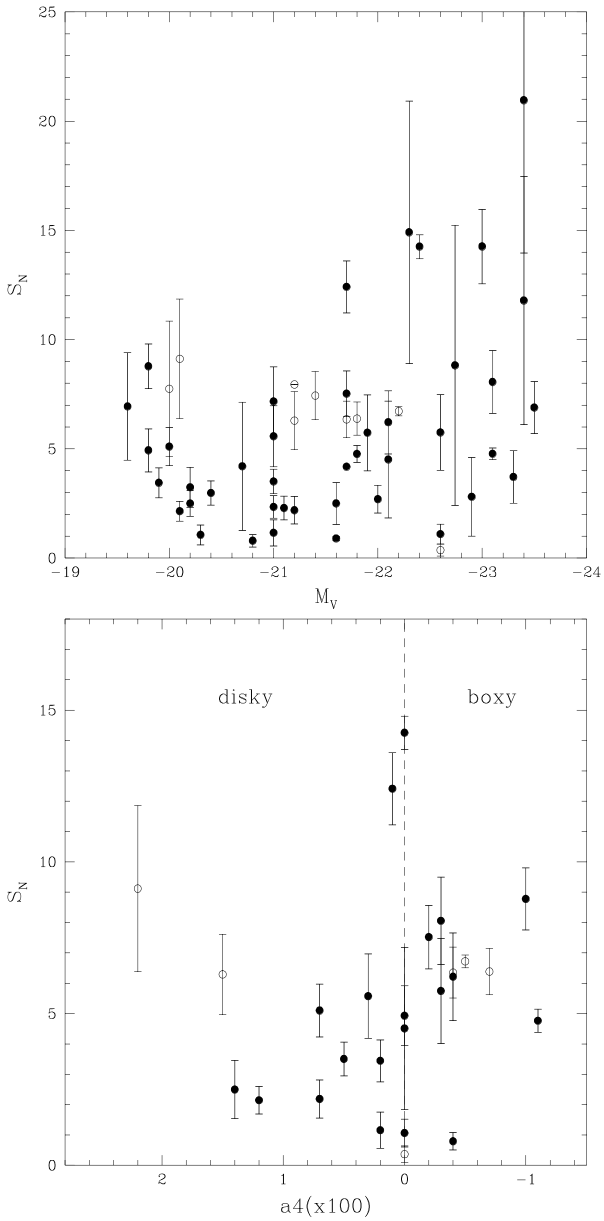

Fig. 1. Upper panel: The specific frequency S_N plotted versus the absolute luminosity of the parent galaxy M_V. Lower panel: S_N versus the $a4/a \cdot 100$ coefficient of the isophotal analysis of the galaxy ($a4/a > 0$ indicates disky isophotes, $a4/a < 0$ indicates boxy isophotes). Open circles mark the globular cluster systems for which less than 10% of the total number of globular clusters was observed.

then 10% of the total number of globular clusters observed) are plotted as open circles, the others as dots.

Fig. 1 upper panel, S_N vs M_V, does not show any clear correlation. However note that S_N spans a narrower range for faint galaxies; 17 out of 21 galaxies with $M_V > -21.6$ mag and well determined total numbers of globular clusters have S_N values of 5 and below with a mean of 4.0. For more luminous galaxies the mean specific frequency is much higher (at 7.5) and only 4 out of 21 galaxies with $M_V < -21.6$ have S_N values below 4. Further the dispersion in S_N is twice as large for bright galaxies than for faint ones.

We tested whether the specific frequency rather follows a continuous relation with luminosity than representing two classes of ellipticals with different globular cluster formation efficiencies. The division between the two classes of ellipticals galaxies occurs between $M_V = -21$ and -22 mag (see references in introduction). We arbitrarely divided our sample at $M_V \simeq -21.5$ (the result is not significantly influenced by small shifts of this limit) and tested the fit by a linear relation between S_N and M_V over the full luminosity range against a composite function with a constant $S_N = 4$ down to $M_V \simeq -21.5$ and a linear fit at higher luminosities. While a F-test slightly prefers the composite model, Kolmogorov-Smirnov (hereafter K-S) tests rather rejects (80% confidence) linear relations over the bright or full range. Only the faint end seems to be marginally well represented by a constant value.

The correlation with the $a4/a$ coefficient (Fig. 1 lower panel) is clearer: disky galaxies have small S_N values (around 5 and below), while boxy galaxies have high S_N values (at least 5 and up to 10). This partly reflects the fact that disky ellipticals are generally fainter than boxy ellipticals (Bender et al. 1989). Environmental effects should not significantly influence the result since an equal amount of disky and boxy galaxies here are galaxy cluster members. The peculiar S_N values of central giant ellipticals are apparent in our plot with NGC 1399 (central gE in Fornax, $S_N \simeq 12$) and M87 (gE in the center of Virgo, $S_N \simeq 14$) that clearly drop out of the sample. A K-S test rejects with 95% confidence the hypothesis that disky and boxy ellipticals have similar specific frequencies.

In summary: if the specific frequency is interpreted as an efficiency of producing globular clusters, bright, boxy ellipticals must have been more efficient in forming globular clusters than faint, disky ellipticals, or must have been enriched by some process, in addition to any possible environmental effect.

3.2. The number of globular clusters

The specific frequency relates the number of globular clusters to the absolute luminosity of the parent galaxy. One can check if the apparent relations of S_N with galaxy parameters still hold for absolute numbers of globular clusters. Zepf et al. (1993) recently discussed a possible increase of the number of globular cluster (N_{gc}) with increasing galaxy luminosity and agreed with Djorgovski & Santiago (1992) that N_{gc} increases with L to a power greater than one. Zepf et al. (1993) interprete the trend as the increase of importance of dissipationless merging with increasing luminosities in the frame of gE being products of mergers.

In Fig. 2 we show N_{gc}, the total number of globular clusters versus M_V and $a4/a$. One is tempted to fit a linear relation in Fig. 2 upper panel. The resulting fit returns a slope of -0.50 ± 0.05, which physically is the exponent of a power-law since two logarithmic values are plotted versus each other. Keeping in mind that the sample might divide around $M_V \simeq -21.5$ (see introduction and last section), one could fit linear relations to

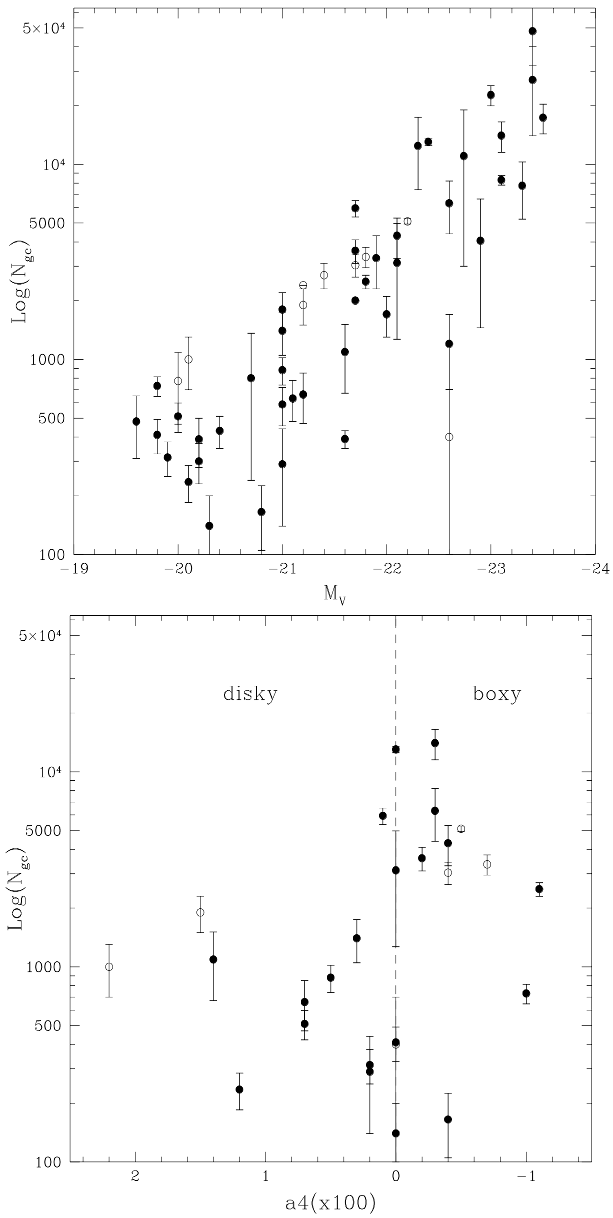

Fig. 2. Upper panel: Total number of globular clusters N_{gc} versus absolute magnitude of the galaxy. Lower panel: Total number of globular clusters N_{gc} versus the $a4/a$ coefficient from the isophotal analysis of the galaxy ($a4/a > 0$ indicates disky isophotes, $a4/a < 0$ indicates boxy isophotes). Open circles mark the globular cluster systems for which less than 10% of the total number of globular clusters was observed.

the two samples (fainter and brighter than $M_V \simeq -21.5$). The resulting slopes are flatter (-0.13 ± 0.06) for the faint galaxies and slightly steeper (-0.56 ± 0.05) for the bright galaxies. Here again a F-test slightly prefers (60% confidence) the composite model to a single law over all magnitudes. Further, a K-S test clearly favors the composite model as a representation of the data (68% confidence) to a continuous relation that is only a good representation with 49% confidence.

Interestingly the composite relation is then no longer continuous around $M_V = -21.5$ but the zeropoint jumps up by 500 ± 200 clusters between the two samples when going to brighter galaxies.

A non-continuous relation is also supported by the lower panel in Fig. 2 (N_{gc} versus $a4/a$) that, similar to Fig. 1 lower panel, clearly divides the systems: while all disky galaxies with well determined total numbers of globular clusters have less than 1500 clusters, all boxy galaxies but two have more than 2500 clusters.

In summary, faint, disky ellipticals host less globular clusters than bright, boxy ellipticals do, and two classes of ellipticals with a likely jump in their number of globular clusters between the two are preferred to a continuous relation with luminosity. Note however that Djorgovski & Santiago's (1992) and Zepf's et al. (1993) interpretation still holds for the bright ellipticals.

3.3. The slope of the surface density profile

The question rises whether the number of globular clusters (or the related S_N) is the only property by which globular cluster systems in bright, boxy and faint, disky early-type galaxies might divide. The slope of the globular cluster surface density profile α was suspected to be related to the galaxy luminosity by Harris (1986, 1993) who used sparser sample available to that time. His linear relation for globular cluster systems seemed to be displaced to lower central concentrations with respect to the galaxy light profiles. Harris proposed it to trace the formation of globular cluster systems in the still-extended proto-galaxies. Since then, however, especially faint galaxies were shown to have globular cluster systems with profiles (as well as ellipticities and position angles) compatible with the galaxy light (e.g. Kissler-Patig et al. 1996b and references therein).

The correlations of α with the galaxy properties (M_V and $a4/a$) are shown in Fig. 3. The slope of the surface density profile α turns out to be a strong discriminator between faint and bright, and disky and boxy ellipticals. Both upper and lower panel in Fig. 3 are roughly cut into four quadrants from which only two are populated: globular cluster systems with slope $\alpha < -1.8$ only appear in faint ($M_V > -21.5$) and disky ellipticals, while globular cluster systems in bright, boxy ellipticals have systematically flatter surface density profiles. K-S test rejects with more than 95% and 90% confidence respectively faint and bright, and disky and boxy ellipticals to have similar α values. Further an F-test prefers (70% confidence) two populations of ellipticals concentrated around mean α values of -2.0 ± 0.3 and -1.3 ± 0.3 rather than a linear relation with luminosity.

Faint, disky ellipticals seem to have globular cluster systems compatible with their light profiles, while bright, boxy ellipticals have more extended systems.

In Fig. 4 we plot a consequence of this relation: the total number of globular clusters N_{gc} versus the slope of the surface density profile α. The diagram shows that systems where the globular clusters have steep ($\alpha < -1.8$) density profiles and follow the galaxy light correspond to the systems with

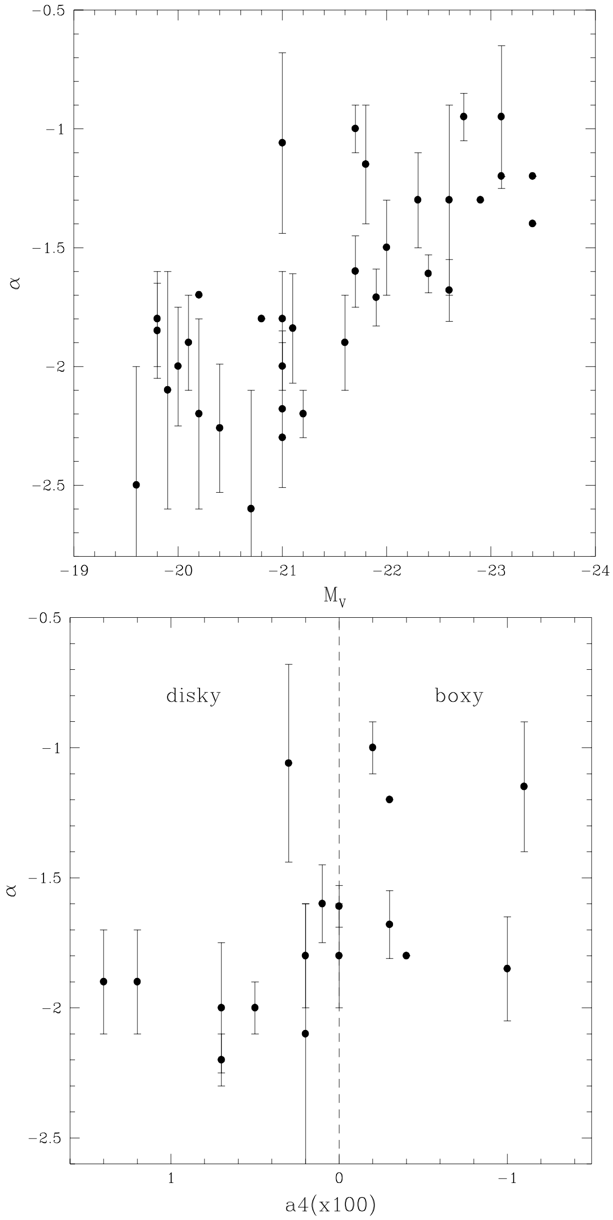

Fig. 3. Upper panel: The slope of the surface density profile of the globular cluster system (α) plotted against the absolute luminosity of the parent galaxy (M_V). Lower panel: The slope of the surface density profile of the globular cluster system (α) plotted against the $a4/a$ value of the parent galaxy ($a4/a > 0$ indicates disky isophotes, $a4/a < 0$ indicates boxy isophotes).

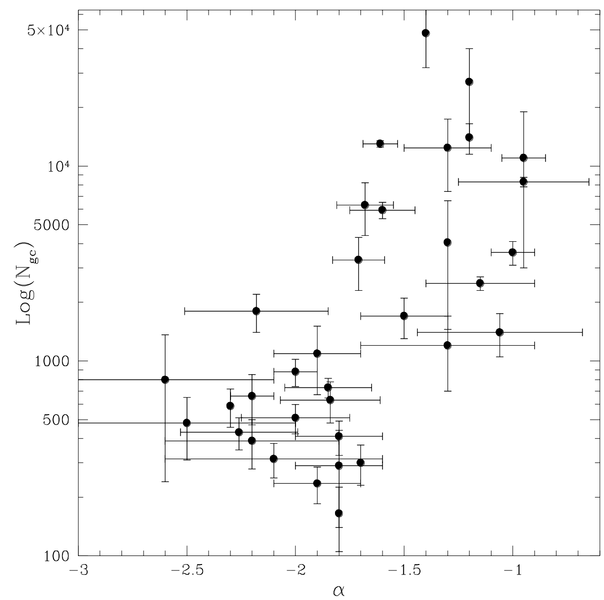

Fig. 4. The total number of globular clusters N_{gc} plotted against the slope of the density profile α of the globular cluster systems.

few ($N_{gc} < 1500$) globular clusters, while systems with flat ($\alpha > -1.8$) density profiles correspond to richer systems.

3.4. More globular cluster parameters

3.4.1. The mean metallicity

Perelmuter (1995), Forbes et al. (1996), and Bridges et al. (1996) recently recompiled metallicities of globular cluster systems and plotted them against the mass or absolute luminosity of the parent galaxy (their Figs. 2, 14, and 7 respectively). Perelmuter (1995) sees a discrepancy between spirals and ellipticals in the [Fe/H]-mass relation, but used only bright ellipticals in our sense for his relation. Forbes et al. (1996) see a correlation over 10 orders of magnitudes and take it as a strong argument for the formation of globular clusters during an early collapse. The plot of Bridges et al. (1996), showing more data towards bright ellipticals, rather implies a smooth rise of the metallicity from [Fe/H]$\simeq -2$ to -1.2 for galaxies from $M_V \simeq -14$ to $M_V \simeq -21$ mag, followed by a steep up-turn and larger dispersion over the brightest magnitudes with metallicity values up to near solar metallicities.

Thus metallicity also seems to be a parameter compatible with the division of the globular cluster systems in the sense that systems in faint galaxies have low ([Fe/H]< -1.2) mean metallicities correlated with the galaxy luminosity, while systems in bright ellipticals have higher mean metallicities and a larger dispersion.

3.4.2. The core radius of the globular cluster system

Forbes et al. (1996) determined the core radius of the globular cluster system (introduced by Lauer & Kormendy 1986) for their 14 ellipticals. They plotted them in their Fig. 10 versus the absolute magnitude of the galaxy. The authors claim only a weak correlation with luminosity and propose that most luminous ($M_V < -21$) galaxies have large core radii while the core radius of systems in small, rotating ellipticals is weakly, if at all, dependent on galaxy luminosity. This relation might be expected after Sect. 3.3, since core radius and surface density profile slope both describe the radial concentration of the globular clusters in the galaxy, and are therefore correlated. From a practical point of view, determining core radii involves observations towards the center and therefore requires very good seeing or HST observations, while surface density profiles can be estimated from normal ground-based observations.

4. The dichotomy of globular cluster systems

4.1. Two classes of globular cluster systems

Two points were shown in Sect. 3. First, two classes of globular cluster systems are preferred to continuous relations when their properties are investigated versus the absolute luminosity of the parent early-type galaxies. The "cut" systematically appears at about $M_V \simeq -21.5$ mag. In bright ellipticals the specific frequencies and mean metallicity of globular clusters show large dispersions up to extremely high values. Further, the number of globular clusters seem to slightly "jump up" between faint and bright galaxies, and while in faint galaxies the globular cluster systems have surface density profiles compatible with the galaxy light, they appear flatter in bright galaxies.

Second, the globular cluster systems systematically split into two groups when their properties are investigated in disky and boxy ellipticals. In disky galaxies globular cluster systems have lower specific frequencies, less globular clusters, and steeper density profiles than in boxy ellipticals.

We can further consider the information on the color distribution of the globular system (column 10 in Table 1) which shows that broad distributions and color gradients appear almost exclusively in bright ellipticals.

The above points suggest that globular cluster systems should rather be divided into two classes than assumed to form one group with properties scaling with the properties of their host galaxies.

The properties of the "faint" systems are: a small number of globular clusters (less than 1500), the related small specific frequency (less than 5, mean of our sample 2 to 3), a low mean metallicity of the globular clusters ([Fe/H]< -1.2), and a steep surface density profile of the globular clusters that follows the surface intensity profile of the host galaxy.

The properties of "bright" globular cluster systems are: a high number of globular clusters (more than 2500), the unproportionaly high specific frequency (from 5 to 15), a higher mean metallicity than would imply the relation up to $M_V \simeq -21$, a flat surface density profile ($\alpha > -1.7$) only compatible with the galaxy light when the galaxy has a cD envelope, and in most cases broad color distributions or color gradients.

These two different types of systems can be associated with the two classes of ellipticals that also emerged from recent studies of large sample of elliptical galaxies.

The "faint" globular cluster systems are hosted by faint (about $M_V > -21.5$ mag), disky galaxies with unresolved cores.

The "bright" globular cluster systems are hosted by bright (about $M_V < -21.5$ mag), boxy galaxies with resolved cores.

4.2. The interpretation

Various alternatives for the formation of globular clusters and their over-abundance in some galaxies were proposed. Some seem already rejected in the case of whole globular cluster systems, as the pre-galactic formation (Peebles & Dicke 1968) since no correlation with the later galaxies is then expected but seen. Some are believed to have played only a minor role, such as globular cluster stripping (Muzzio et al. 1984, Muzzio 1986), and the formation of globular clusters in cooling flows (e.g. discussion in Bridges et al. 1996), that appear to be able to contribute only few globular clusters.

The most popular remaining scenarios are the formation of globular clusters during the collapse of the proto-galaxy (e.g. Searle & Zinn 1978, Harris & Pudritz 1994), and the formation during mergers (Burstein 1987, Schweizer 1987, Ashman & Zepf 1992). Two classes of ellipticals do not argue for nor against one of these scenarios, it allows them to co-exist, since most properties that support the one or other formation mechanism dominates in one group.

4.2.1. "Faint" systems

Forbes et al. (1996) argue that the correlation of the mean metallicity of the globular clusters with the luminosity of the parent galaxy is a strong argument for the formation during the early collapse of the galaxy and the coalescent phase at high redshift. This relation however seems weakened towards brighter galaxies.

Further the recent investigation globular clusters of faint ($-19 < M_V < -21$ mag) early-type galaxies allowed a better statistic of "normal" properties of globular cluster systems. "Faint" systems were shown to spatially follow the galaxy light rather than being more extended (see Sect. 3.3) and suppressed the apparent discrepancy between globular cluster and star formation epoch in these systems. The properties of "faint" systems do no call for any formation mechanism beside the formation in the early collapse of the galaxy (Searle & Zinn 1978). Faint galaxies appear unperturbed from the properties of their globular cluster systems, as well as from dynamical point of view (see references in Sect. 1).

4.2.2. "Bright" systems

The predictions of Ashman & Zepf (1992) for globular clusters systems that formed in mergers are the following: New globular clusters should form; the newly formed clusters should be more metal-rich, since formed from processed material; the system should show a color gradient due to the new (metal-richer) globular clusters concentrating to the center; the color distribution should become multi-modal for the same reasons; and finally the surface density profile should be flatter due to the fact that star formation occurs in the center concentrating the light distribution, leaving the old globular clusters (if dominant) appear flatter than the light profile.

The formation of globular clusters during mergers is uncontested since several galaxies were found to form globular clusters in a merger event (NGC 3597: Lutz 1991; NGC 1275: Holtzman et al. 1992; NGC 7252: Whitmore et al. 1993, Schweizer & Seitzer 1993; He2-10: Conti & Vacca 1994; NGC 4038/4039: Whitmore & Schweizer 1995; NGC 5018: Hilker & Kissler-Patig 1996), the results for NGC 1275 and NGC 5018 are included in Sects. 2 and 3, the other galaxies do not have their whole globular cluster system investigated yet.

And indeed, the "bright" globular cluster systems show all the signs expected after a merger event. The specific frequency (or efficiency in producing globular clusters) is higher, calling for an extra process of globular cluster formation that could have been the merger event. In absolute numbers, bright galaxies host more globular clusters as shown by the likely break in the relation in Sect. 3.2. The bright systems have also a flatter density profile than the light of their host galaxies. Note however that it is not the galaxy light that steepens, but the globular cluster systems that are rather absolutely flatter, which could mean dynamically hotter after a merger event (see evidences in NGC 1399, Grillmair et al. 1994). Further the color information listed in column 10 of Table 1 show that multi-modal color distributions and color gradients in globular cluster systems are almost exclusively seen in bright galaxies, while faint galaxies show globular cluster systems with narrower, single peaked color distributions. Finally the brighter galaxies have globular cluster systems with higher mean metallicities that might be explained by contributions from newly formed, metal-richer globular clusters (e.g. Zepf et al. 1993). Thus Ashman & Zepf's (1992) predictions seem fulfilled for the "bright" systems.

5. Conclusions

"Faint" globular cluster systems do not show signs of perturbations. They globular clusters spatially follow the galaxy light, their efficiency in producing globular clusters (S_N values) show little scatter, and their mean metallicity scales with the galaxy luminosity. This facts are compatible with a formation of the globular clusters during the early collapse of the galaxy (Searle & Zinn 1978, Harris & Pudritz 1994).

On the other hand "bright" globular cluster systems seem to verify all the signs expected after the formation in merger events as predicted by Ashman & Zepf (1992). The specific frequency scatters up to very high values, the mean metallicities show a larger scatter with eventual multi-modal distributions, the spatial distribution of the globular clusters is more extended.

This would support a combination of two formation scenarios for globular clusters: every galaxy built up a system during the proto-galactic collapse, however systems in bright galaxies were then enriched during a merger event and still carry its signature.

Translated onto the host galaxies: "faint" systems appear in faint, disky early-type galaxies, while "bright" systems are hosted by bright, boxy ellipticals. This would support similar early suggestion of Bender (1988) and Nieto (1988) that early-type galaxies can be divided into those which formed by a major merger event (involving at least two galaxies), and those which remained largely unperturbed.

Of course this picture needs a more detailed investigation. A major merger event might not be the only cause for a dichotomy in early-type galaxies and many different kind of mergers between very different galaxies can occur. Globular cluster systems after merger events might show a large diversity: more or less new globular clusters might have formed (e.g. Hilker & Kissler-Patig 1996), one old system can still largely dominate, galaxies in the center of cluster still exhibit extremely high S_N values that could have a additional cause, etc... Furthermore, "faint" globular cluster systems look very similar to the system of the Milky-Way (e.g. Kissler-Patig et al. 1996a), that might not have been "unperturbed" but accreted some smaller companion galaxies that could have built up part of the halo (e.g. Minniti et al. 1996a and references therein). This immediately calls for transition cases between mergers and accretion of big companions: is the cut between the two classes really sharp?

Further investigations especially of the often neglected "faint" globular cluster systems is needed to give further support to the dichotomy in globular cluster systems. Making a reliable model for the formation of the associated galaxies will probably have to wait for detailed spectroscopic data of whole globular cluster systems. But approaching the problem of formation of early-type galaxies from the globular cluster point of view seems promising.

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References

Ajhar E.A., Blakeslee J.P., Tonry J.L., 1994, AJ 108, 2087
Ashman K., Zepf S.E., 1992, ApJ 384, 50
Bender R., 1988, ApJ 193, 7
Bender R., Surma P., Dörbeiner S., Möllenhoff C., Madejsky R., 1989, A&A 217, 35
Bender R., et al., 1996 in preparation
Burstein D., 1987, in Nearly Normal Galaxies, ed. S.Faber (New York Springer), 47
Bridges T.J., Carter D., Harris W.E., Pudritz C.J., 1996, MNRAS in press
Conti P.S., Vacca W.D., 1994 ApJ 423, L97
Couture J., Harris W.E., Allwright J.W.B., 1991, ApJ 372, 97
Dirsch B., 1996, Master Thesis, University of Bonn
Davies R.L., Efstathiou G., Fall S.M., Illingworth G., Schechter P. 1983, ApJ 266, 41
Djorgovski S., Santiago B.X., 1992, ApJ 391, L85
Elson R.A.W., Santiago B.X., 1996, MNRAS 278, 617
Faber et al. 1996, AJ in preparation
Forbes D.A., Franx M., Illingworth G.D., Carollo C.M., 1996, AJ 467, 126

Gebhardt K., Richstone D., Ajhar E.A., et al., 1996, AJ 112, 105
Geisler D., Lee M.G., Kim E., 1996, AJ 111, 1529
Goudfrooij P., Hansen, L., Jorgensen H.E., et al., 1994, A&AS 104, 179
Grillmair C.J., Freeman K.C., Bicknell G.V., et al., 1994, ApJ 422, L9
Harris W.E., 1986, AJ 91, 822
Harris W.E., 1991, ARA&A 29, 543
Harris W.E., 1993, in *The Globular Cluster-Galaxy Connection*, ASP Conf. Series Vol.48, eds G.H.Smith and J.P.Brodie, p.472
Harris H.C., Harris W.E., 1996, Astrophysical Quantities 4th ed., in press
Harris W.E., Pudritz, R.E., 1994, ApJ 429, 177
Harris W.E., Racine R., 1979, ARA&A 17, 241
Harris W.E., Van den Bergh S., 1981, AJ 86, 1627
Hilker M., Kissler-Patig M., 1996 A&A 314, 357
Holtzman J.A., et al., 1992, AJ 103, 691
Jaffe W., Ford H.C., O'Connell R.W., van den Bosch F.C., Ferrarese L., 1994, AJ 108, 1567
Kissler-Patig M., Richtler T., Hilker M., 1996b, A&A 308, 704
Kissler-Patig M., Kohle S., Richtler T., et al., 1996a, A&A in press
Kormendy J., Dressler A., Byun Y.-I., et al., 1993, in *Dwarf Galaxies*, ESO/OHP workshop proceedings, eds. G.Meylan and P.Prugniel
Kumai Y., Hashi Y., Fujimoto M., 1993, ApJ 416, 576
Lauer T.R., Ajhar E.A., Byun Y.-I., et al., AJ 110, 2622
Lutz D., 1991, A&A 245, 31
Madejski R., Rabolli M., 1994, A&A 297, 660
Minniti D., Meylan G., Kissler-Patig M., 1996a, A&A 312, 49
Minniti D., Alonso M.V., Goudfrooij G., Jablonka P., Meylan G., 1996b, ApJ 467, 221
Muzzio J.C., 1986, ApJ 301, 23
Muzzio J.C., Martinez R.E., Rabolli M., 1984, ApJ 285, 7
Nieto J.-L., 1988, in *Early-Type Galaxies* invited lectures at the 2nd Regional Extragalactic Astronomy Meeting, Academia Nacional de Ciencas de Cordoba, Argentina
Nieto J.-L., Bender R., 1989 A&A 215, 266
Nieto J.-L., Bender R., Surma P., 1991 A&A 244, L37
Peebles P.J.E., Dicke R.H., 1968, ApJ 154, 891
Perelmuter J.-M., 1995, ApJ 454, 762
Richtler T., 1995, in "Reviews of Modern Astronomy", Vol.8, eds. G. Klare, Springer, p.163
Santiago B.X., Djorgovski S., 1993, MNRAS 261, 753
Schweizer F., 1987, in Nearly Normal Galaxies, ed. S.Faber (New York Springer), 19 Schweizer F., Seitzer P., 1993, ApJ 417, L29
Searle L., Zinn R., 1978, ApJ 225, 357
Whitmore B.C., Schweizer F., Leitherer C., Borne K., Robert C., 1993, AJ 106, 1354
Whitmore B.C., Schweizer F., 1995, AJ 109, 960
Whitmore B.C., Sparks, W.B., Lucas R.A., Macchetto F.D., Biretta J.A., 1995 ApJ 454, L73
Zepf S.E., Geisler D., Ashman K.M., 1994, ApJL 434, L117
Zepf S.E., Ashman K.M., 1993, MNRAS 264, 611

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