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The elliptical galaxy formerly known as the Local Group: merging the globular cluster systems

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Abstract. Prompted by a new catalogue of M31 globular clusters, we have collected together individual metallicity values for globular clusters in the Local Group. Although we briefly describe the globular cluster systems of the individual Local Group galaxies, the main thrust of our paper is to examine the collective properties. In this way we are simulating the dissipationless merger of the Local Group, into presumably an elliptical galaxy. Such a merger is dominated by the Milky Way and M31, which appear to be fairly typical examples of globular cluster systems of spiral galaxies.

The Local Group 'Elliptical' has about 700 $\pm$ 125 globular clusters, with a luminosity function resembling the 'universal' one. The metallicity distribution has peaks at [Fe/H] $\sim$–1.55 and –0.64 with a metal–poor to metal–rich ratio of 2.5:1. The specific frequency of the Local Group Elliptical is initially about 1 but rises to about 3, when the young stellar populations fade and the galaxy resembles an old elliptical. The metallicity distribution and stellar population corrected specific frequency are similar to that of some known early type galaxies. Based on our results, we briefly speculate on the origin of globular cluster systems in galaxies.

Key words: galaxies: formation – Galaxy: halo – galaxies: star clusters – cosmology: observations – cosmology: early Universe

1. Introduction

The Local Group (LG) of galaxies currently consists of two large spirals (the Milky Way and M31) and a host of smaller galaxies. Andromeda (M31) is approaching the Milky Way with a velocity of about 60 km s^{-1} and may ultimately collide and merge with our Galaxy (Dubinski et al. 1996). Such a collision of two near equal mass spiral galaxies is expected to form an elliptical galaxy (Toomre & Toomre 1972; Barnes & Hernquist 1992). Globular clusters (GCs) are relatively robust stellar systems and are expected to remain intact during such a merger. Direct evidence for this comes from the GCs associated with the Sgr dwarf galaxy which is currently being accreted (e.g. Ibata et al. 1995; Minniti et al. 1996). Furthermore *Hubble Space Telescope* studies of merging disk galaxies reveal evidence for the GC systems of the progenitor galaxies (e.g. Forbes & Hau 1999; Whitmore et al. 1999). Thus GCs should survive the merger of their parent galaxies, and will form a new GC system around the newly formed elliptical galaxy.

The globular clusters of the Local Group are the best studied and offer a unique opportunity to examine their collective properties (reviews of LG star clusters can be found in Brodie 1993 and Olszewski 1994). By examining them as a single GC system we are 'simulating' the dissipationless (i.e. we assume that gas processes are unimportant) merger of the two large spiral galaxies, their satellites and associated galaxies. The dissipationless build–up of ellipticals and their GC systems has been discussed recently by Cote et al. (2000). We note that the Milky Way and M31 are close in luminosity to L* galaxies, and so are highly relevant to a typical major merger in the local Universe. In reality, the merger of two spirals, like M31 and the Milky Way, will involve gas which may lead to the formation of new GCs (Ashman & Zepf 1992). Here we do not speculate about the number or properties of such new GCs but simply examine the limited case of all currently existing Local Group GCs contributing to the new GC system.

Thus our assumptions are: 1) that no GCs are destroyed in the merger (as stated above, this is a reasonable assumption); 2) that no GCs are created in the merger (in general, gaseous mergers will create new clusters but here we are limiting ourselves to the simplier case of no new GC formation); 3) the GCs without metallicity determinations have a similar distribution to those measured (in practice there will be a bias for missing GCs to be metal–rich as they are hidden by inner bulges); 4) the missing GCs have a similar luminosity distribution to the confirmed ones (our sample will be biased towards the more luminous ones).

In this paper, we collect together individual GC metallicities for all known GC systems in the LG. Such a compilation is dominated by the GC systems of the Milky Way and M31. We have used the June 1999 version of Harris (1996) for our Galaxy, and the recent catalogue of Barmby et al. (1999) for M31 but for the other 33 galaxies this required an extensive search of the literature. First we summarise the membership and properties

Send offprint requests to: D.A. Forbes of the Local Group in the next section. Sect. 3 briefly discusses the GCs in the individual LG galaxies.

2. The Local Group of galaxies

Reviews of the LG membership have been given by van den Bergh (1994a), Grebel (1997), Mateo (1998) and Courteau & van den Bergh (1999). Here we use the membership list of Courteau & van den Bergh (1999).

Within the Local Group, galaxies can be divided into three main subgroups. The first consists of the Milky Way and its satellites. This includes the Large and Small Magellanic Clouds, Fornax, and Sagittarius as well as 9 other small dwarf galaxies. The second group consists of M31 and its satellites, the largest of which is M33, a spiral galaxy. The compact elliptical galaxy M32, the irregular galaxy IC 1613 and numerous dwarf galaxies including NGC 147, NGC 185 and NGC 205 are also in the M31 subgroup. Recently, two independent groups (Armandroff et al. 1998a,b and Karachentsev & Karachentseva 1999) have found three new dwarf satellites of M31 named And V, Pegasus II (And VI) and Cassiopeia (And VII) which are included in our LG list. The third group is known as the Local Group Cloud (LGC), which is a large cloud of mainly dwarf galaxies extending throughout the Local Group. All of the galaxies in the Courteau & van den Bergh (1999) list are included in a subgroup, with 2 galaxies having somewhat uncertain assignments (Mateo 1998).

Galaxies that have at some point been associated with the Local Group but are not on the Courteau & van den Bergh (1999) list have not been included here. Notable examples of these are the galaxies in the NGC 3109 (or Antlia-Sextans) subgroup (NGC 3109, Antlia, Sextans A and Sextans B in Mateo 1998). Of these galaxies NGC 3109 is the only one with evidence of a globular cluster system – Demers et al. (1985) found ten globular cluster candidates. NGC 55 is another example of a galaxy we have not included. This had been associated with the LGC subgroup (Mateo 1998) but seems more likely to actually belong in the Sculptor (South Polar) Group (Courteau & van den Bergh 1999). NGC 55 has an estimated total GC population of 25$\pm$15 (Liller & Alcaino 1983) but only 3 with any information (Da Costa & Graham 1982; Beasley & Sharples 1999). Other galaxies that have been removed by Courteau & van den Bergh (1999) include IC 5152 (which has 10 unconfirmed candidate GCs suggested in Zijlstra & Minniti 1999), GR 8 which has no known GCs, and various other dwarf galaxies with no known GCs.

Simulations (e.g. Valtonen & Wiren 1994) have suggested that the IC 342/Maffei Group of galaxies (which consists of IC 342, Maffei 1 and 2, Dwingloo 1 and 2, NGC 1569, NGC 1560, UGCA 105, UGCA 92, UGCA 86, Cassiopeia 1 and MB 1; see Krismer et al. 1995) might once have been part of the LG but was thrown out by interaction with M31. Courteau & van den Bergh (1999) do not include this group in the LG based on their criteria for membership and we follow this assignment. It appears that no study has been carried out of the GC systems of galaxies in this group, although several galaxies might be expected to have some based on their luminosity. We also mention the Sab spiral M81 (NGC3031) in passing. Although not in the LG, at $\sim$ 3 Mpc it is sufficiently close for a detailed spectroscopic study. A recent spectroscopic study using the Keck 10m telescope by Schroder et al. (2000) finds that the GCs have similar spectra and line indices to Milky Way halo GCs.

Our final list of LG galaxies is summarised in Table 1. We give galaxy names, Hubble type, subgroup, distance, absolute V band luminosity and number of GCs. Most properties come directly from Courteau & van den Bergh (1999), except the number of GCs which is the result of our investigation (see Sect. 3). The table is ordered by subgrouping within the Local Group.

3. Globular clusters of the Local Group

3.1. Luminosities

Of the 35 LG galaxies, 13 of them are known to host GCs, giving a total number of GCs in the LG to be $N_{GC} = 692 \pm 125$. Individual V band magnitudes are available for a large number of these Local Group GCs. We have collected V band apparent magnitudes, irrespective of photometric error, for as many GCs as possible. The total number with V magnitudes available is 656, with about 2/3 of these coming from the M31 catalogue of Barmby et al. (1999). We note that the Barmby et al. list includes a number of GC candidates in addition to the confirmed GCs.

For some GCs it is not obvious which galaxy they should be associated with. Although we try to assign the correct identity, it has little impact on our final conclusions as we combine all GCs. We also note that none of the GCs, except those of the Milky Way, have been corrected for extinction. In the case of the Milky Way the magnitudes can be reliably corrected using the reddening values quoted by Harris (1996; June 1999 version). All apparent magnitudes are converted into absolute magnitudes using the distances quoted in Table 1, or from Harris (1996) in the case of Milky Way GCs.

We have chosen to exclude young clusters, i.e. with ages $<$ 3 Gyr or $(B-V) < 0.6$, as they may not evolve into *bona fide* globular clusters. From the point of view of comparison with elliptical galaxies, it is reasonable to include only clusters older than $\sim$ 3 Gyr as elliptical galaxies younger than this will tend to have extensive fine structure, possibly tidal tails, and will probably not even be classified as an elliptical galaxy.

In Fig. 1 we show the combined V band luminosity for 656 Local Group GCs out of a total of 692 $\pm$ 125. The histogram is dominated by M31 GCs, which have not been extinction corrected, and therefore the peak of the distribution is somewhat fainter than for the Milky Way alone (e.g. Della Valle et al. 1998). Nevertheless the distribution resembles a Gaussian with a dispersion of $\sim$1 mag, and is similar to those seen in many elliptical galaxies (e.g. Whitmore 1997 for a review).

3.2. Metallicities

The main aim of this paper is to examine the overall metallicity distribution of LG globular clusters. Unfortunately there are

Table 1. Local Group Galaxy Properties. Subgrouping is given by MW = Milky Way, M31 = Andromeda, LGC = Local Group Cloud. Most quantities in this table are from Courteau & van den Bergh (1999). Distance is in kpc. See text for the number of globular clusters. A dash in the last column means that no reliable mention of globular clusters in this galaxy could be found in the literature.

Name	Alternative Name	Hubble Type	Subgroup	Dist.	M_V	N_{GC}
Milky Way		S(B)bc I-II	MW	10	–20.9	160±20
LMC		Irr III-IV	MW	50	–18.5	19±16
SMC	NGC 292	Irr IV/IV-V	MW	60	–17.1	8±7
Sagittarius		dSph(t)	MW	30	–13.8	4±1
Fornax		dSph	MW	140	–13.1	5±0
Leo I	Regulus	dSph	MW	250	–11.9	–
Leo A	DDO 69	dIrr V	MW	690	–11.5	–
Leo II	DDO 93	dSph	MW	210	–10.1	–
Sculptor		dSph	MW	90	–9.8	–
Phoenix		dIrr/dSph	MW/LGC	400	–9.8	–
Sextans		dSph	MW	90	–9.5	–
Carina		dSph	MW	100	–9.4	–
Ursa Minor	DDO 199	dSph	MW	60	–8.9	–
Draco	DDO 208	dSph	MW	80	–8.6	–
M31	NGC 224	Sb I-II	M31	760	–21.2	400±55
M33	NGC 598	Sc II-III	M31	790	–18.9	70±15
M32	NGC 221	E2	M31	760	–16.5	0
NGC 205	M110	Sph	M31	760	–16.4	11±6
IC 10	UGC 192	Irr IV	M31	660	–16.3	–
NGC 185	UGC 396	Sph	M31	660	–15.6	8±1
IC 1613	DDO 8	Irr V	M31/LGC	720	–15.3	0
NGC 147	DDO 3	Sph	M31	660	–15.1	4±1
And I		dSph	M31	810	–11.8	–
And II		dSph	M31	700	–11.8	–
Pegasus II	And VI	dSph	M31	830	–10.6	–
Pisces	LGS 3	dIrr/dSph	M31	810	–10.4	–
And III		dSph	M31	760	–10.2	–
And V		dSph	M31	810	–10.2	–
Cassiopeia	And VII	dSph	M31	690	–9.5	–
NGC 6822	DDO 209	Irr IV-V	LGC	500	–16.0	1±1
WLM	DDO 221	Irr IV-V	LGC	930	–14.4	1±1
Pegasus	DDO 216	Irr V	LGC	760	–12.3	–
Aquarius	DDO 210	Irr V	LGC	1020	–11.3	1±1
SagDIG	UKS1927-177	Irr V	LGC	1400	–10.7	–
Tucana		dSph	LGC	870	–9.6	–

fewer individual GC metallicities available in the literature than magnitudes. We have found a total of 388, which represents over half of the suspected total number of 692 ± 125 GCs. The bulk of these metallicity determinations come from spectroscopy or colour–magnitude diagrams. However for a number of GCs we only have colour information available; typically $(B - V)$. In these cases we have used the Galactic [Fe/H]–colour relation as derived by Barmby et al. (1999). They used only GCs with low extinction, i.e. $E_{B-V} < 0.5$, from the latest Harris (1996) compilation. Colours are de-reddened using the Harris values for E_{B-V} and the extinction curve of Cardelli et al. (1989). For colours we have assigned a characteristic error in [Fe/H] of 0.5 dex. In the half dozen cases where the colours suggest (an implausible) [Fe/H] > 1 we have set the metallicity to [Fe/H] = 1.0.

The Barmby et al. Galactic relation assumes a linear relation, although there is some question whether this is valid at the high metallicities (see Barmby et al. 1999 for discussion). We also note that Kissler-Patig et al. (1998) have derived a new [Fe/H] vs $(V - I)$ relationship based on spectroscopic metallicities for GCs in the giant elliptical NGC 1399. This has the advantage of extending the metallicity range to GCs more metal-rich than typically found in the Milky Way. They find that the (linear) slope of the relation (3.27 ± 0.32) is almost twice as flat as conventional (Galactic) fits. Barmby et al. derive a $(V - I)_o$ slope of 4.22 ± 0.39. So for red GCs, metallicities derived from relations based on Galactic fits tend to be overestimated. Although this is a serious effect for the GC systems of elliptical galaxies (which tend to have fairly red median colours), it is much less important for late type galaxies, as found in the Local Group. Thus here we use the Galactic linear fits, which should be reasonable for our purposes.

Our compilation is dominated by the Milky Way and M31. For these we use the lists of Harris (1996; June 1999 version) and

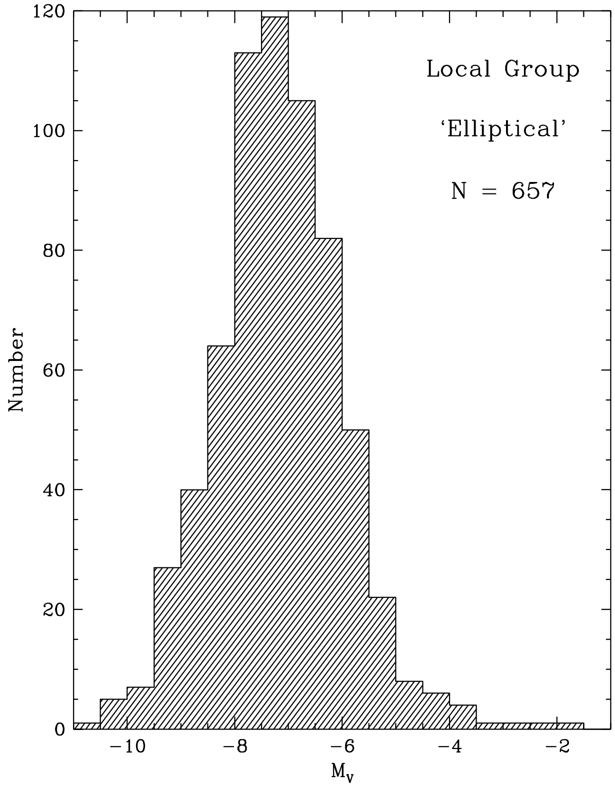

Fig. 1. Absolute magnitude distribution for the Local Group 'Elliptical'. The distribution resembles the 'universal' globular cluster luminosity function.

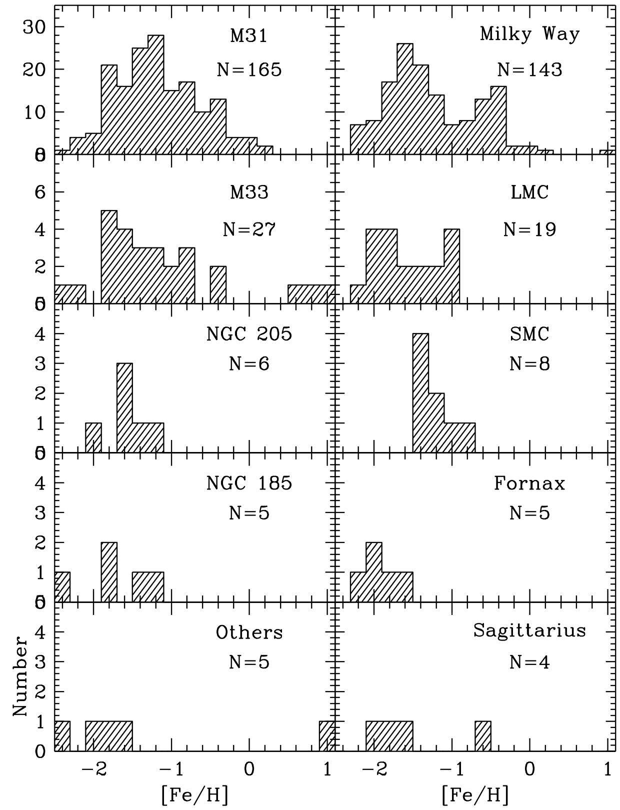

Fig. 2. Metallicities of Local Group globular clusters. The number of available globular clusters with individual measurements is indicated in each panel.

Barmby et al. (1999) respectively. For M33 we list individual GC metallicities in Table 2 and in Table 3 we list GC metallicities for the remaining LG galaxies.

Fig. 2 shows the metallicity distributions for all Local Group GC systems, with the number of individual [Fe/H] determinations available noted in each panel. It suggests multiple peaks in the distribution of several galaxies, with only the three LG spirals having a substantial population of relatively metal–rich GCs. In Table 4 we summarise the LG galaxies with GCs, giving their mean metallicity and the total specific frequency.

3.3. The Milky Way

The Milky Way galaxy has 147 globular clusters listed in the compilation of Harris (1996). However the discovery of the dSph galaxy Sagittarius (Ibata et al. 1995) has raised questions as to whether 4 of these clusters (NGC 6715/M54, Terzan 7, Arp 2 and Terzan 8) should actually be associated with Sagittarius. There has been some discussion in the literature about the inclusion of Terzan 7 in this list (e.g. Minniti et al. 1996), but van den Bergh (1998) argues that it probably should be associated with the Sgr dwarf so we will remove it and the other three from the Milky Way GC system.

The presence of younger, counter–rotating halo GCs (Zinn 1993; Majewski 1994) indicates that the Milky Way has accreted other small galaxies and their GC systems in the past. In particular, Unavane et al. (1996) have suggested that ≤ 6 Sgr or Fornax like dwarfs have been accreted over the last 10 Gyrs. This implies that less than 30 GCs are 'foreign' to the Milky Way system, and that past accretions of GCs are fairly rare.

Individual GC metallicities come from the latest (i.e. June 1999) electronic version of Harris (1996) which uses CMD diagrams and spectroscopy (see Harris 1996 for details). All but two GCs (BH 176 and Djorg 1) have listed metallicities. For these GCs we have estimates of the metallicities from Ortolani et al. (1995a) for BH 176 and Ortolani et al. (1995b) for Djorg 1. Both have [Fe/H] $\sim$ –0.4. This gives a total of 143 MW GCs with metallicities. Some metal–rich GCs are no doubt hidden from the Sun's position (Minniti 1995), and we adopt a total system population of 160$\pm$20 globular clusters from van den Bergh (1999).

A KMM analysis of the metallicity distribution shown in Fig. 2 indicates a bimodal metallicity distribution with peaks at [Fe/H] = –1.59 and –0.55, which is consistent with the findings of Ashman & Bird (1993) who found [Fe/H] $\sim$ –1.6 and –0.6. We find that the ratio of metal–poor to metal–rich GCs is 2:1.

3.4. M31

Andromeda is the largest galaxy in the Local Group and has 14$\pm$1 companions (Courteau & van den Bergh 1999). Recently a new catalogue of the globular cluster system in M31 has been

Table 2. M33 Globular Cluster Metallicities. S = spectroscopy, CMD = colour-magnitude diagram, C = colour. 1 = Christian & Schommer (1988), 2 = Brodie & Huchra (1991), 3 = Sarajedini et al. (1998), a = assumed metallicity.

Name	[Fe/H]	σ([Fe/H])	Source	Ref.
U49	-1.43	0.30	S/CMD	1,2,3
R13	-0.75	0.5	C	1
R12	-1.19	0.27	S/CMD	1,3
R15	-1.79	0.5	C	1
R14	-1.37	0.41	S/CMD	1,3
M9	-1.67	0.29	S/CMD	1,3
U77	-1.59	0.58	S/CMD	2,3
H38	-1.14	0.22	S/CMD	1,3
H21	-0.40	0.40	S	1
C20	-1.57	0.50	S/CMD	1,2,3
C36	-1.00	0.30	S	1
C38	-0.77	0.24	S/CMD	1,3
C18	-0.46	0.56	S/CMD	1,2
H10	-1.40	0.66	S/CMD	2,3
C3	-2.38	0.56	S	2
C32	-1.77	1.12	S	2
U137	-0.85	0.29	S/CMD	2,3
C21	-1.85	0.5	C	1
U23	-0.91	0.5	C	1
C9	-2.12	0.51	S	2
S24	+0.52	0.5	C	1
S72	-1.30	0.5	C	1
S247	+1.0^a	0.5	C	1
U67	-1.74	0.5	C	1
S161	-1.90	0.5	C	1
S160	+0.85	0.5	C	1
U7	-1.52	0.5	C	1

compiled (Barmby et al. 1999). It includes 437 clusters and cluster candidates, of which 162 have metallicities from spectroscopy and 90 more have metallicities calculated from their colours. Twelve of the clusters are flagged as possibly being members of NGC 205, six of which have metallicites given. These 12 will be taken to be associated with NGC 205 as described below. We have removed the 59 clusters with $(B-V)$ $<$ 0.55, as these may not be *bona fide* GCs. As done in Barmby et al., we only use those GCs with metallicity errors $<$ 0.5 dex to give a total of 165, 121 of which have metallicities from spectroscopy. In this case, the colours of the M31 GCs were converted into [Fe/H] estimates using the transformation derived by Barmby et al. (1999) based on an extinction model and direct measurements of the M31 system. The total number of GCs in the M31 GC system is taken to be 400 $\pm$ 55 from van den Bergh (1999).

A KMM analysis of the metallicity distribution shown in Fig. 2 indicates a bimodal metallicity distribution with peaks at [Fe/H] = –1.40 and –0.58. This is similar to Ashman & Bird (1993) who found [Fe/H] $\sim$ –1.50 and –0.6, based on the earlier data of Huchra et al. (1991) (which forms a part of the Barmby et al. 1999 data set). The ratio of metal–poor to metal–rich GCs is 3:1.

Table 3. Globular Cluster Metallicities. S = spectroscopy, CMD = colour-magnitude diagram, C = colour. 1 = Suntzeff et al. (1992), 2 = Olsen et al. (1998), 3 = Dutra et al. (1999), 4 = Sarajedini (1998), 5 = Olszewski et al. (1991), 6 = Da Costa & Hatzidimitriou (1998), 7 = Mighell et al. (1998), 8 = Harris (1996), 9 = Buonanno et al. (1998), 10 = Dubath et al. (1992), 11 = Barmby et al. (1999), 12 = Da Costa & Mould (1988), 13 = Cohen & Blakeslee (1998), 14 = Hodge et al. (1999), 15 = Greggio et al. (1993), a = assumed error, b = assumed metallicity.

Name	[Fe/H]	σ([Fe/H])	Source	Ref.
		LMC		
Hodge II	-2.06	0.20	S	1
NGC 1466	-1.85	0.20	S	1
NGC 1754	-1.46	0.18	S/CMD	1,2
NGC 1786	-1.87	0.20	S	1
NGC 1835	-1.68	0.18	S/CMD	1,2
NGC 1898	-1.25	0.18	S/CMD	1,2
NGC 1916	-2.08	0.20	S	1
NGC 2005	-1.57	0.18	S/CMD	1,2
NGC 2019	-1.44	0.18	S/CMD	1,2
NGC 2210	-1.97	0.20	S	1
NGC 2257	-1.80	0.10	CMD	1
NGC 1841	-2.11	0.10	S	1
Reticulum	-1.71	0.10	S	1
NGC 1928	-1.2	0.3^a	S	3
NGC 1939	-2.0	0.3^a	S	3
ESO 121-SC03	-0.96	0.13	S/CMD	4,5
NGC 2121	-1.04	0.13	CMD	4
SL 663	-1.05	0.16	CMD	4
NGC 2155	-1.08	0.12	CMD	4
		SMC		
NGC 221	-1.48	0.11	CMD/S	6,7
Lindsay1	-1.21	0.10	CMD/S	6,7
Kron3	-1.10	0.11	CMD/S	6,7
Lindsay113	-1.26	0.13	CMD/S	6,7
NGC 339	-1.38	0.12	CMD/S	6,7
NGC 416	-1.44	0.12	CMD	7
NGC 361	-1.45	0.11	CMD	7
Lindsay11	-0.81	0.14	CMD/S	6,7
		Sagittarius		
NGC 6715/M54	-1.59	0.11	S	8
Ter7	-0.58	0.09	S	8
Arp2	-1.76	0.10	S	8
Ter8	-2.00	0.12	S	8

3.5. NGC 205

There has been much debate in the literature about exactly how many GCs are associated with NGC 205 and which belong with M31. NGC 205 is close in position to M31 and has a radial velocity within the range given for the internal dispersion of the M31 GC system (Reed et al. 1992). This makes it difficult to determine which galaxy the GCs should be associated with, and is further complicated by the fact that NGC 205 appears to be interacting with M31 (Zwicky 1959). Barmby et al. (1999) flag

Table 3. (continued)

		Fornax		
Fornax-1	-2.20	0.20	CMD	9
Fornax-2	-1.78	0.20	CMD	9
Fornax-3	-1.94	0.18	CMD/S	9,10
Fornax-4	-1.55	0.18	CMD/S	9,10
Fornax-5	-2.00	0.18	CMD/S	9,10
		NGC 205		
Hubble I/009-061	-1.52	0.21	C/S	11,12
Hubble II/011-063	-1.51	0.26	C/S	11,12
Hubble IV/328-054	-1.58	0.22	C/S	11,12
Hubble VI/331-057	-1.30	0.49	C/S	11,12
Hubble VII/330-056	-1.40	0.10	S	12
Hubble VIII/317-041	-1.93	0.28	C/S	11,12
		NGC 147		
NGC 147-1	-1.90	0.15	S	12
NGC 147-3	-2.50	0.25	S	12
		NGC 185		
NGC 185-1	-1.40	0.10	S	12
NGC 185-2	-1.20	0.25	S	12
NGC 185-3	-1.70	0.15	S	12
NGC 185-4	-2.50	0.25	S	12
NGC 185-5	-1.80	0.15	S	12
		NGC 6822		
NGC 6822-VII	-1.95	0.15	S	13
		WLM		
WLM-1	-1.52	0.08	CMD	14
		Aquarius		
Aquarius-1	+1.0[b]	0.5	C	15

12 of the GCs in their catalogue as possibly being associated with NGC 205. They give metallicities for six of these. Da Costa & Mould (1988) give the metallicity for five of these plus an additional one (Hubble VII/330-056), giving a total of seven clusters with metallicities available. We have decided to adopt the Barmby et al. (1999) list of 12, but have removed Hubble V/324-051 as it is relatively blue and has a spectrum with strong Balmer lines. Da Costa & Mould (1988) also note that it may be a young cluster. For the total number of GCs associated with NGC 205 we adopt 11 $\pm$ 6.

3.6. M33

Three subpopulations of clusters may be present in M33. The blue clusters follow the disk rotation, the red ones show no evidence for rotation and have a large line-of-sight velocity dispersion, while intermediate coloured ones have intermediate kinematic properties. The blue subpopulation are thought to be young and the red ones forming an old spherical halo (Schommer et al. 1991). Sarajedini et al. (1998) summarise the evidence that the halo clusters in M33 formed over a long time span. Christian & Schommer (1988) identify 27 likely candidates for true globular clusters in M33 on the basis that they have $B-V > 0.6$. Mochejska et al. (1988) list 51 GC candidates, while Chandar et al. (1999) list 60 stellar clusters, 49 of which they refer to as ‘populous’, meaning that they had a shape similar to that expected for globular clusters. However, we have not included these populous clusters in the metallicity distribution as it is not clear which objects are genuine GCs. The total number of GCs has been estimated by R. Chandar as part of her thesis on M33 to be 70 $\pm$ 15 (Chandar 1999), which we list in Table 1.

3.7. The Large Magellanic Cloud

The Large Magellanic Cloud (LMC) GC system contains a population of genuine old ($\sim$ 10 Gyr) globular clusters and a class of young ($\leq$ 3 Gyr) clusters (van den Bergh 1994b). The only exceptions to this rule appear to be ESO 121-SC03 which has an age of around 9 Gyr (Dutra et al. 1999) and three GCs recently found to have ages of around 4 Gyr (Sarajedini 1998).

Suntzeff et al. (1992) reviewed thirteen *bona fide* old clusters (meaning clusters of similar age to Galactic globular clusters) which can be found in the Large Magellanic Cloud, giving spectroscopic metallicities for all but one, for which we have derived a metallicity from its $B-V$ colour. Geisler et al. (1997) conducted a search to find more old clusters in the LMC and concluded that “there are few, if any, genuine old clusters in the LMC left to be found.” However Dutra et al. (1999) present spectroscopic evidence that NGC 1928 and NGC 1939 are also old globular clusters in the LMC taking the census up to 15. Olsen et al. (1998) produced CMDs for five of the old globular clusters (NGC 1754, NGC 1835, NGC 1898, NGC 2005 and NGC 2019), and claim that the metallicites they derive from the CMDs are more accurate than the earlier spectroscopic determinations.

It is not clear whether the young (i.e. $\leq$ 3 Gyr) LMC clusters will eventually evolve into *bona fide* GCs. Here we have decided not to include them in our compilation. Thus we adopt the 15 old GCs and the 4 intermediate aged ones to give a total GC system of 19, which could perhaps be as high as 35.

3.8. The Small Magellanic Cloud

The Small Magellanic Cloud (SMC), like the LMC has both old and intermediate aged globular clusters. However unlike the LMC it has several (at least 7, Mighell et al. 1998) GCs between the ages of 3 and 10 Gyr. There is only one old globular cluster (NGC 121) with an age of $\sim$ 11 Gyr. We include this GC plus the 7 intermediate aged GCs. Spectroscopic metallicities exist for six of them (Da Costa & Hatzidimitriou 1998), for the other two we estimate [Fe/H] from their colours.

3.9. Sagittarius

The Sagittarius dwarf has four globular clusters (Ibata et al. 1995) which were previously thought to be members of the Galactic GC system (as described in Sect. 3.3). We have metallicities for all of these. One of them (NGC 6715/M54) is the second brightest globular cluster in the Milky Way and is located close to the centre of Sagittarius. This has led to the idea that it might actually be the nucleus of Sagittarius, as discussed in Mateo (1998); however we will include it as a globular cluster.

3.10. Fornax, NGC 147 and NGC 185

The Fornax dSph galaxy has five globular clusters, all of which have metallicities available from their CMDs (Buonanno et al. 1998, 1999) and three of which also have spectroscopic metallicities (Dubath et al. 1992). The metallicities listed in Table 3 are the weighted average. The dwarf elliptical NGC 147 has four globular clusters (Minniti et al. 1996), two of which have metallicities available from spectroscopy (Da Costa & Mould 1988). The dwarf elliptical NGC 185 has eight globular clusters (Minniti et al. 1996), five of which have spectroscopic metallicities available (Da Costa & Mould 1988).

3.11. WLM, NGC 6822 and Aquarius

The dwarf irregulars WLM, NGC 6822 and Aquarius have one globular cluster each (Harris 1991 for WLM and NGC 6822, Greggio et al. 1993 for Aquarius). Recently, Hodge et al. (1999) have determined the metallicity of the WLM GC to be [Fe/H] = –1.52 $\pm$ 0.08 from fitting isochrones to its CMD. The metallicity of the NGC 6822 GC from spectroscopy is [Fe/H] = –1.95 $\pm$ 0.15 (Cohen & Blakeslee 1998). The colour of the GC in Aquarius is $B - V$ = 1.15 (Greggio et al. 1993) which corresponds to a metallicity of +1.07 $\pm$ 0.5 (we have set this to a value of +1.0 in Table 3).

3.12. Galaxies with no globular cluster system

No globular clusters have been found in the dwarf irregular galaxy IC 1613 (M_V = –14.7) or the elliptical galaxy M32 (Harris 1991). In the case of the compact elliptical M32, its outer stars, and presumably any GCs, may have been stripped away by interaction with M31. Given its proximity to M31, it is very difficult to form a definitive conclusion on the GC population of M32.

No information has been found in the literature on the GC system of the remaining galaxy in the Courteau & van den Bergh (1999) list, i.e. the dwarf irregular IC 10 with M_V = –16.3. It is more luminous than Fornax and Sagittarius but has no GCs found to date. Such a search may prove fruitful.

Except for Aquarius (at M_V = –11.3), no GCs have been found in any LG galaxy fainter than Fornax and Sagittarius (M_V = –13.1 and –13.8 respectively). This applies to 19 low luminosity galaxies in the Local Group (see Table 1).

4. Properties of the Local Group 'Elliptical'

In Fig. 3 we show the combined metallicity distribution for 387 Local Group GCs with available metallicities. A KMM analysis, excluding the 6 outliers, indicates two peaks at [Fe/H] = –1.55 and –0.64, with the ratio of metal–poor to metal–rich GCs being 2.5:1. This is likely to slightly overestate the ratio; the missing GCs are likely to be found in the central bulge regions (where they are more difficult to observe; Minniti 1995). Elliptical galaxies reveal a range of ratios, but the metal–poor almost always exceed the number of metal–rich ones (e.g. Forbes et al. 1997).

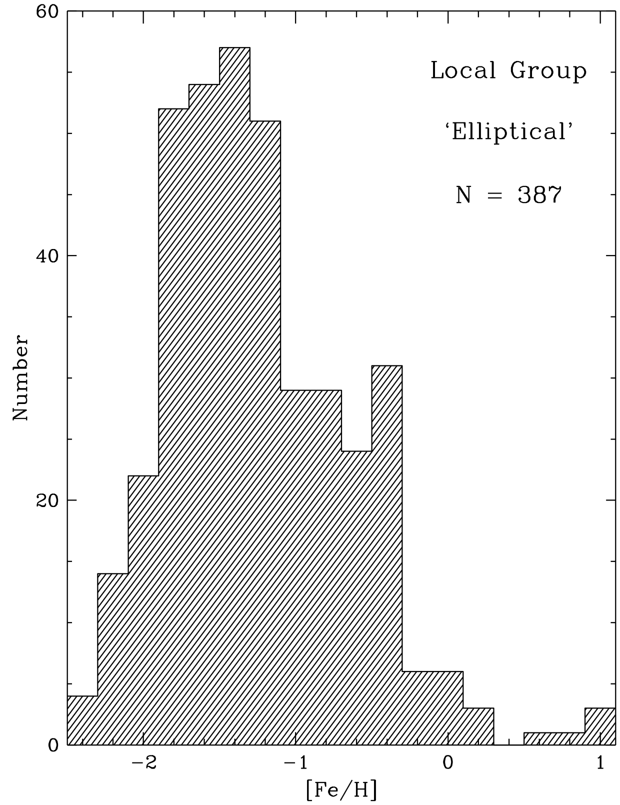

Fig. 3. Metallicity distribution for the Local Group 'elliptical'. The distribution reveals two peaks at [Fe/H] = –1.55 and –0.64.

Mass is generally conserved in a merger, and so from the total mass of the progenitor galaxies we can estimate the mass of the resulting elliptical galaxy. By adding together the luminosities of all the galaxies in the Local Group we derive a total magnitude of M_V = –22.0. Thus if all galaxies in the Local Group suddenly merged today, without any change in their overall luminosity, we would end up with a highly luminous elliptical of M_V = –22.0.

Of course, not all of the stars in the LG galaxies resemble the old stellar populations found in ellipticals, but they include intermediate and young stellar populations. To generalise, the bulges of the spirals, dwarf ellipticals and spheriodals contain only old stars, whereas the disks of spirals and irregular galaxies contain intermediate and young stellar populations. The detailed star formation histories of LG galaxies are summarised by Grebel (1997).

To crudely correct for this effect, we have separated the LG stars into 'young' and 'old' sub–populations. For the three spirals we use bulge-to-disk luminosity ratios of 0.33, 0.24 and 0.09 for Sb (M31), Sbc (Milky Way) and Sc (M33) respectively (Simien & de Vaucouleurs 1986). The spiral bulges, dE, Sph and dSph galaxies (see Table 1) are included in the 'old' sub–population and all the Irr and dIrr galaxies as 'young'. This gives the luminosity of the 'old' LG stars as 1.1 × 10^{10} $L_\odot$ and the luminosity of the 'young' stars to be 4.2 × 10^{10} $L_\odot$. Assuming a mass-to-light ratio (M/L_V) of 5 for the old sub–population and 1 for the young one gives masses of 5.7 × 10^{10} $M_\odot$ and 4.1 × 10^{10} $M_\odot$ respectively. This suggests that of the stellar mass in the LG is divided fairly evenly between very old and more recently formed stars. In order to 'simulate' the LG elliptical we convert the mass of the 'young' sub–population into a V band luminosity using the old stars mass-to-light ratio (i.e. M/L_V = 5), thus giving it the luminosity that it would contribute to the final elliptical galaxy after the stars had become comparably old. Combining this luminosity with that of the LG old stars gives a total of M_V = –20.9. This luminosity is therefore more relevant for comparison to that of current day ellipticals. In fact, the luminosity will be somewhat brighter than M_V = –20.9, as we have included the intermediate aged sub–population as 'young'.

In Table 5 we list the specific frequency of the LG Elliptical with those for other spiral galaxies. The LG Elliptical has N_{GC} = 692 ± 125, corresponding to S_N = 1.1 ± 0.2 for the total LG luminosity and S_N = 3.0 ± 0.5 for the LG Elliptical using the stellar population corrected luminosity. The former value is comparable to those of the other spiral galaxies in Table 5. The latter value is similar to the lower bound of the range of S_N for ellipticals, i.e. 3–6 (Harris 1991). This suggests it is possible that the ellipticals at the lower bound of S_N are the result of dissipationless mergers of galaxies containing young/intermediate stellar populations.

The total stellar mass of the LG galaxies is 9.8 × 10^{10} $M_\odot$ as calculated above. Comparison with the total (dynamical) mass of the Local Group of 2.3 ± 0.6 × 10^{12} $M_\odot$ (Courteau & van den Bergh 1999) indicates that only about 5% of the LG mass is in stars.

Table 4. Local Group Galaxy Properties. [Fe/H] clusters gives the mean metallicity of the globular cluster system. The specific frequency $S_N = N_{GC} \times 10^{0.4(M_V+15)}$, error based on uncertainty in N_{GC} only.

Name	[Fe/H] clusters	S_N
Milky Way	-1.59, -0.55	0.7±0.1
LMC	-1.58	0.8±0.6
SMC	-1.29	1.2±1.0
Sagittarius	-1.38	12.0±3.0
Fornax	-1.89	28.8±0.0
M31	-1.40, -0.58	1.3±0.2
M33	-1.32	1.9±0.4
NGC 205	-1.48	3.0±1.7
NGC 185	-1.61	4.6±0.6
NGC 147	-2.06	3.6±0.9
NGC 6822	-1.95	0.4±0.4
WLM	-1.52	1.7±1.7
Aquarius	+1.0	30.2±30.2

Table 5. Specific Frequencies of Spiral Galaxies. 1 = Kissler-Patig et al. (1999), 2 = Ashman & Zepf (1998).

Name	Type	M_V	S_N	Ref.
LG	E	-22.0	1.1±0.2	Here
LG (Age corrected)	E	-20.9	3.0±0.5	Here
Milky Way	S(B)bc	-20.9	0.7±0.1	Here
M31	Sb	-21.2	1.3±0.2	Here
M33	Sc	-18.9	1.9±0.4	Here
NGC 4565	Sb	-21.4	0.56±0.15	1
NGC 5907	Sc	-21.2	0.56±0.17	1
NGC 253	Sc	-20.2	0.2±0.1	2
NGC 2683	Sb	-20.8	1.7±0.5	2
NGC 3031 (M81)	Sab	-21.1	0.7±0.1	2
NGC 4216	Sb	-21.8	1.2±0.6	2
NGC 4569	Sab	-21.7	1.9±0.6	2
NGC 4594	Sa	-22.2	2±1	2
NGC 5170	Sb	-21.6	0.9±0.6	2
NGC 7814	Sab	-20.4	3.5±1.1	2

5. Spectroscopic metallicities for globular clusters in elliptical galaxies

It is interesting to compare the results of Sect. 4 with ellipticals that have spectroscopically observed GCs. Only two early type galaxies outside of the LG have published *individual* [Fe/H] determinations from spectroscopy. They are NGC 1399 (Kissler-Patig et al. 1998) and M87 (Cohen et al. 1998), which are both cD galaxies with a high specific frequency. In both cases the spectra were taken with the Keck 10m telescope. The GC metallicity distributions for these galaxies are shown in Fig. 4 The number of GCs studied is only a small fraction of the total population, but assuming they are representative, it appears that overall their GCs are slightly more metal–rich on average than the LG elliptical.

We note that in the case of M87, the GC system is clearly bimodal in its optical colours (e.g. Kundu et al. 1999). For the spectroscopic sub–sample of Cohen et al. (1998), the distribution is not obviously bimodal to the eye as displayed in Fig. 4 If we exclude the 14 GCs with extreme metallicities, as done by Cohen et al. (1998), a KMM analysis indicates that a bimodal distribution (with peaks at [Fe/H] = –1.3 and –0.7) is preferred over a unimodal one at the 89% confidence level. If we use the colours of the two peaks from Kundu et al. (1999), i.e. $V - I$ = 0.95 and 1.20, and the improved transformation from Kissler-Patig et al. (1998), we derive values of [Fe/H] = –1.39 and –0.59, which is reasonably consistent with the values from the spectroscopic sample of Cohen et al.

6. Concluding remarks

We have collected together individual metallicity values for globular clusters in the Local Group. Only the three large spirals show the presence of a significant metal–rich (i.e. [Fe/H] ∼ –0.5) population of globular clusters. Most galaxies have a metal–poor population with [Fe/H] ∼ –1.5. The GC systems of the Milky Way and M31 appear to be typical examples of GC systems around spirals.

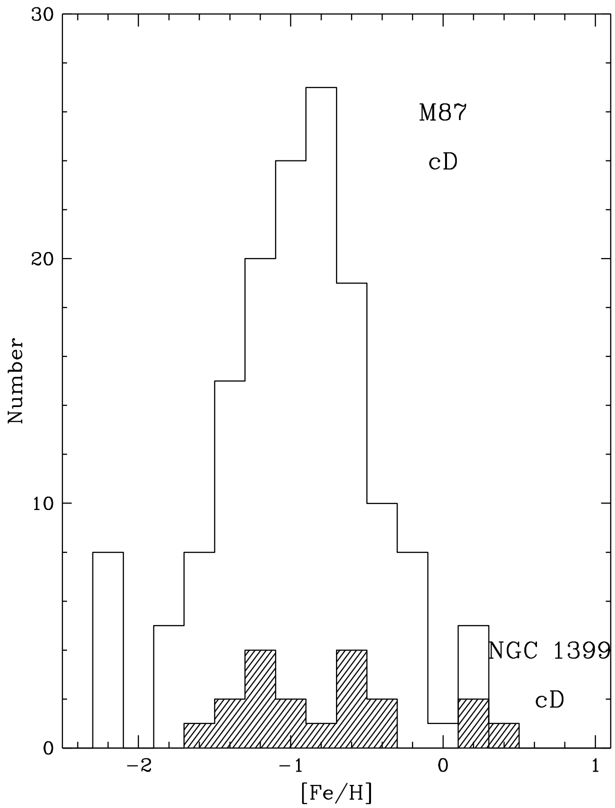

Fig. 4. Metallicity distribution for globular clusters in the cD galaxies M87 and NGC 1399 from Keck spectroscopy (Cohen et al. 1998; Kissler-Patig et al. 1998).

The merger of the Local Group galaxies is expected to form an elliptical galaxy. After the young stellar populations have faded, the resulting galaxy will have $M_V \leq -21.0$. If there is no creation or destruction of globular clusters, this Local Group 'Elliptical' will have about 700 globular clusters. The GC system luminosity function will resemble the 'universal' one. The metallicity distribution will have peaks at [Fe/H] $\sim$ –1.55 and –0.64 with the metal–poor to metal–rich ratio of 2.5:1. These peaks have a similar value to that for the two early type galaxies (M87 and NGC 1399) with available spectroscopically–determined metallicity distributions. The relative population ratio is also similar. After a crude correction for stellar populations, the specific frequency for the Local Group Elliptical is about 3. This value is similar to that for field and loose group ellipticals.

From our 'dissipationless merger simulation' we speculate that the globular cluster systems around low specific frequency ellipticals may be consistent with the simple combination of the progenitor galaxies' globular cluster systems, and with little or no globular cluster formation. However the ellipticals with moderate to high specific frequencies (i.e. S_N = 5–15) require a higher globular cluster to field star ratio. In principle, this could be solved with a dissipational merger (i.e. the creation of new globular clusters from gas as seen in currently merging spirals). However the metal–rich globular cluster populations in these ellipticals are not larger in number than the metal–poor ones, as might be expected for the merger scenario (Forbes et al. 1997). Alternatively, ellipticals and spirals alike, may form the vast bulk of their metal–rich and metal–poor globular clusters during two similar *in situ* formation episodes, as part of a dissipational galaxy collapse process.

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References

Armandroff T.E., Davies J.E., Jacoby G.H., 1998a, AJ 116, 2287
Armandroff T.E., Davies J.E., Jacoby G.H., 1998b, BAAS 193
Ashman K.M., Bird C.M., 1993, AJ 106, 2281
Ashman K.M., Zepf S.E., 1998, Globular Cluster Systems. Cambridge Univ. Press, Cambridge
Ashman K.M., Zepf S.E., 1992, ApJ 384, 50
Barmby P., Huchra J.P., Brodie J.P., Forbes D.A., Grillmair C.J., 2000, AJ 119, 727
Barnes J., Hernquist L., 1992, ARA&A 30, 705
Beasley M.A., Sharples R.M., 1999, preprint (astro-ph/9909230)
Brodie J.P., 1993, In: Smith G.H., Brodie J.P. (eds.) ASP Conf. Series 48, The Globular Cluster-Galaxy Connection. Kluwer, Dordrecht, p. 483
Brodie J.P., Huchra J.P., 1991, AJ 379, 157
Buonanno R., Corsi C.E., Zinn R., et al., 1998, ApJ 501, L33
Buonanno R., Corsi C.E., Castellani M., et al., 1999, AJ 118, 1671
Cardelli J.A., Clayton G.C., Mathis J.S., 1989, ApJ 345, 245
Chandar R., 1999, personal communication
Chandar R., Bianchi L., Ford H.C., 1999, ApJS 122, 431
Christian C.A., Schommer R.A., 1988, AJ 95, 704
Cohen J.G., Blakeslee J.P., 1998, AJ 115, 2356
Cohen J.G., Blakeslee J.P., Ryzhov A., 1998, ApJ 496, 808
Cote P., Marzke R., West M., Minniti D., 2000, ApJ in press
Courteau S., van den Bergh S., 1999, AJ 118, 337
Demers S., Kunkel W.E., Irwin M.J., 1985, AJ 90, 1967
Da Costa G.S., Graham J.A., 1982, ApJ 261, 70
Da Costa G.S., Hatzidimitriou D., 1998, AJ 115, 1934
Da Costa G.S., Mould J.R., 1988, AJ 334, 159
Della Valle M., Kissler-Patig M., Danziger J., Storm J., 1998, MNRAS 299, 267
Dubath P., Meylan G., Mayor M., 1992, ApJ 400, 510
Dubinski J., Mihos J.C., Hernquist L., 1996, ApJ 462, 576
Dutra C.M., Bica E., Clariá J.J., Piatti A.E., 1999, MNRAS 305, 373
Forbes D.A., Hau G.K.T., 2000, MNRAS 312, 703
Forbes D.A., Brodie J.P., Grillmair C.J., 1997, AJ 113, 1652
Geisler D., Bica E., Dottori H., et al., 1997, AJ 114, 1920
Grebel E.K., 1997, Rev. Mex. Astron. Astrofis. 10, 29
Greggio L., Marconi G., Tosi M., Forcardi P., 1993, AJ 105, 894
Harris W.E., 1991, ARA&A 29, 543
Harris W.E., 1996, AJ 112, 1487
Hodge P.W., Dolphin A.E., Smith T.R., Mateo M., 1999, ApJ 521, 577
Huchra J.P., Brodie J.P., Kent S.M., 1991, ApJ 370, 495
Ibata R., Gilmore G.F., Irwin M.J., 1995, MNRAS 277, 781
Karachentsev I.D., Karachentseva V.E., 1999, A&A 341, 355
Kissler-Patig M., Ashman K.M., Zepf S.E., Freeman K.C., 1999, AJ 118, 197

Kissler-Patig M., Forbes D.A., Minniti D., 1998, MNRAS 298, 1123
Kissler-Patig M., Brodie J.P., Forbes D.A., Grillmair C.J., Huchra J.A., 1998, AJ 115, 105
Krismer M., Tully R.B., Gioia I.M., 1995, AJ 110, 1584
Kundu A., Whitmore B.C., Sparks W.B., et al., 1999, ApJ 513, 733
Liller W., Alcaino G., 1983, AJ 264, 53
Majewski S.R., 1994, ApJ 431, L17
Mateo M., 1998, ARA&A 36, 435
Mochejska B.J., Kaluzny J., Krockenberger M., Sasselov D.D., Stanek K.Z., 1998, Acta Astron. 48, 455
Mighell K.J., Sarajedini A., French R.S., 1998, AJ 116, 2395
Minniti D., 1995, AJ 109, 1663
Minniti D., Meylan G., Kissler-Patig M., 1996, A&A 312, 49
Olsen K.A.G., Hodge P.W., Mateo M., et al., 1998, MNRAS 300, 6650
Olszewski E.W., 1994, In: Gilmore G., van der Kruit P. (eds.) IAU Symp. 164, Stellar Populations. Kluwer, Dordrecht, p. 181
Olszewski E.W., Schommer R.A., Suntzeff N.B., Harris H.C., 1991, AJ 101, 515
Ortolani S., Bica E., Barbuy B., 1995a, A&A 300, 7260
Ortolani S., Bica E., Barbuy B., 1995b, A&A 296, 680
Reed L.G., Harris G.L.H., Harris W.E., 1992, AJ 103, 824
Sarajedini A., 1998, AJ 116, 738
Sarajedini A., Geisler D., Harding P., Schommer R., 1998, ApJ 508, L37
Schommer R.A., Christian C.A., Caldwell N., Bothun G.D., Huchra J., 1991, AJ 101, 873
Schroder L.L., Brodie J.P., Kissler–Patig M., Huchra J.P., Phillips A.C., 2000, AJ submitted
Simien F., de Vaucouleurs G., 1986, ApJ 302, 564
Suntzeff N.B., Schommer R.A., Olszewski E.W., Walker A.R., 1992, AJ 104, 1743
Toomre A., Toomre J., 1972, ApJ 178, 623
Unavane M., Wyse R.F.G., Gilmore G., 1996, MNRAS 278, 727
Valtonen M.J., Wiren S., 1994, MNRAS 266, 33
van den Bergh S., 1994a, AJ 107, 1328
van den Bergh S., 1994b, In: Smith R.C., Storm J. (eds.) The Local Group. ESO, Garching, p. 3
van den Bergh S., 1998, ApJ 505, L127
van den Bergh S., 1999, preprint (astro-ph/9908050)
Whitmore B.C., 1997, In: Livio M., Donahue M., Panagia N. (eds.) Symp. Series 10 STScI, The Extragalactic Distance Scale. Cambridge Univ. Press, Cambridge, p. 254
Whitmore B.C., Zhang Q., Leitherer C., et al., 1999, BASS 194
Zepf S.E., Ashman K.M., English J., Freeman K.C., Sharples R.M., 1999, AJ 118, 752
Zijlstra A.A., Minniti D., 1999, AJ 117, 1743
Zinn R., 1993, In: Smith G.H., Brodie J.P. (eds.) ASP Conf. Series 48, The Globular Cluster-Galaxy Connection. Kluwer, Dordrecht, p. 38
Zwicky F., 1959, Handbuch d. Physik 53, 373