The Luminosity Function of Globular Clusters as an Extragalactic Distance Indicator

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Abstract. The absolute magnitude \( M^* \) of the peak of the globular cluster luminosity function (GCLF), approximated by a Gaussian, can be calibrated independently in the Galaxy and M31 through RR Lyr stars and Cepheids, respectively. They yield, in perfect agreement, \( M^*_B = -6.93 \pm 0.08 \) and \( M^*_V = -7.62 \pm 0.08 \). Application of these values to the GCLFs in the Leo Group (\( n = 2 \)), the Virgo cluster (\( n = 8 \)), and the Coma cluster (\( n = 2 \)) gives distances which agree with the best determinations from other methods. However, the corresponding distance of the Fornax cluster (\( n = 7 \)) is significantly underestimated, and the distances of several field galaxies are inconsistent. A second parameter, like the width of the GCLF or the color of the peak, is apparently needed to control differences in the GC formation history.

1. Introduction

Extragalactic GCs, discovered in M31 by Hubble (1932), took a role in distance determinations when Racine (1968) proposed the bright end of the GCLF to be used as a “standard candle”. First applications of this tool provided reasonable distances to M87 (Sandage 1968, de Vaucouleurs 1970), yet it was soon realized that the results were sensitive to the GC population size, and that the luminosity \( M^* \) of the turnover point of the bell-shaped GCLF is a much more stable standard candle. This required, however, that one had to sample at least four magnitudes into the GCLF which became feasible only with the advent of CCDs. The first application of the new method to a giant E galaxy (M87; van den Bergh, Pritchet, & Grillmair 1985) was followed by many papers such that \( M^* \) magnitudes are now available for about two dozen full-size galaxies (for reviews e.g. Harris 1991, Whitmore 1997).

Of course distances from the turnover of the GCLF require also an absolute, local calibration of \( M^* \). This became available as sufficient data of complete and objective samples of the GCs in the Galaxy and M31 accumulated which could be combined with a reliable calibration of RR Lyr star luminosities and the Cepheid distance of M31, respectively (Sandage & Tammann 1995).
The calibration of $M^*$ is discussed in Section 2. The resulting distances of 23 E galaxies and one spiral are compared with external evidence in Section 3, the main purpose being to test the stability of $M^*$ as a standard candle. The conclusions are in Section 4.

2. The calibration of the GCLF

2.1. The Galactic GCLF

A list of the 100 Galactic GCs, which an external observer would observe, has been compiled by Secker (1992). Their $B, V$ magnitudes, horizontal-branch magnitudes, extinction values, and metallicities have been compiled by Sandage & Tammann (1995, Table 1); the individual sources are given there. The absolute magnitudes $M^*_B$ and $M^*_V$ are calculated from Sandage’s (1993) RR Lyr star calibration

$$M_V(RR) = 0.94 + 0.30([Fe/H]),$$

which is based on the observed position of the blue edge of the RR Lyr instability strip and the requirements of pulsation theory.

The peak of a Gaussian LF, calculated from equation (1), depends only on the mean metallicity of the sample, which is in this case $<[Fe/H]>= -1.35$. Changes of the slope of the metallicity term in equation (1) affects only the width of the LF to some extent. Calibrations of RR Lyr stars agree amazingly well at a metallicity of $[Fe/H] = -1.35$ as seen in Table 1. The Galactic calibration involving proper motions tend to give somewhat fainter RR Lyr luminosities (Fernley et al. 1998, Tsujimoto 1998), but the results still agree with the adopted value of $M_V(RR, -1.35) = 0.54$ to within $\lesssim 1$ sigma.

|                     | $M^*_B(B)$  | $M^*_V(V)$  |
|---------------------|------------|------------|
| blue edge + pulsation theory | $-6.90 \pm 0.11$ | $-7.60 \pm 0.11$ |
| Baade-Becker-Wesselink | $-6.90 \pm 0.11$ | $-7.60 \pm 0.11$ |
| Hipparcos            | $-6.90 \pm 0.11$ | $-7.60 \pm 0.11$ |
| Hipparcos            | $-6.90 \pm 0.11$ | $-7.60 \pm 0.11$ |
| review               | $-6.90 \pm 0.11$ | $-7.60 \pm 0.11$ |
| adopted              | $-6.90 \pm 0.11$ | $-7.60 \pm 0.11$ |

The calibration of Sandage (1993) at the specific metallicity seems secure within a few $0''01$. The corresponding peak magnitudes of the Galactic GCLF are therefore repeated here from Sandage & Tammann (1995)

$$M^*_B(Galaxy) = -6.90 \pm 0.11, \quad \sigma_M = 1.07 \pm 0.11 \quad (2)$$

$$M^*_V(Galaxy) = -7.60 \pm 0.11, \quad \sigma_M = 1.07 \pm 0.11 \quad (3)$$

2.2. The GCLF of M31

The LF of Secker’s (1992) unbiased sample of 82 GCs in M31 peaks at apparent magnitudes of $m^*_B = 17.75 \pm 0.11$ and $m^*_V = 16.98 \pm 0.11$ (Sandage & Tammann...
1995). This translates into

\[ M_B^*(M31) = -7.01 \pm 0.20, \quad \sigma_M = 0.89 \pm 0.10 \]  
\[ M_V^*(M31) = -7.70 \pm 0.20, \quad \sigma_M = 0.89 \pm 0.10 \]

with a true M31 modulus of \((m-M)^0 = 24.44 \pm 0.15\) (Madore & Freedman 1991) and a mean reddening of the GCs of \(E(B-V) = 0.08\) (Sandage & Tammann 1995).

A purist may want to base the GC distance scale on Pop II stars exclusively instead of involving Cepheids. In that case it may be noted that according to Pritchet & van den Bergh (1987a) the RR LyR stars in M31 have \(<m_B>_{RR} = 25.68 \pm 0.06\), which gives with \(<B-V>_{RR} = 0.26\) (Hawley et al. 1986) \(<m_V>_{RR} = 25.42 \pm 0.06\). Adopting [Fe/H] = -0.6 from Pop II giants in M31 (Mould & Kristian 1986) implies \(M_V(RR) = 0.76\) from equation (5). The resulting apparent M31 modulus of \((m-M)_{AV} = 24.66\) is the same as that from Cepheids to within 0.02. Alternatively Holland (1998) finds from fitting the red-giant branches of M31 GCs a true modulus of \((m-M)^0 = 24.47 \pm 0.07\) which is only insignificantly larger than the Cepheid distance.

### 2.3. The combined GCLF of the Galaxy and M31

Noting the perfect agreement of the independent calibrations of equations (2), (3) and (4), (5) we have made a joint Gaussian fit to the absolute magnitudes of the GCs in the Galaxy and M31, resulting in

\[ M_B^*(adopted) = -6.93 \pm 0.08, \quad \sigma_M = 1.02 \pm 0.08 \]  
\[ M_V^*(adopted) = -7.62 \pm 0.08, \quad \sigma_M = 1.02 \pm 0.08 \]

(cf. Sandage & Tammann 1995, 1996).

### 3. Applications of the calibrated GCLF

#### 3.1. The Leo Group

For two galaxies of the Leo group (cf. Humason, Mayall, & Sandage 1956) the turnover point \(m^*\) of the GCLF has been determined (Table 2). The assigned errors are our estimates. The resulting distance is based on equation (6).

| galaxy      | \(m_B^*\) | Source                   |
|-------------|-----------|--------------------------|
| NGC 3377/79 | 23.30 ± 0.40 | Pritchet & van den Bergh 1985 |
| NGC 3379    | 23.00 ± 0.40 | Harris 1990              |

mean: \(23.15 \pm 0.28\)

\[ (m-M) = 30.08 \pm 0.29 \quad (10.4 \text{ Mpc}) \]
The best distance of the Leo group is obtained from the three members whose Cepheids have been observed with HST (Table 3). The moduli are corrected by $+0.05$ for the long/short exposure effect of the WFPC2 (cf. Saha et al. 1996).

Table 3. The Cepheid distances of the Leo group

| galaxy    | $(m - M)$   | Source                   |
|-----------|-------------|--------------------------|
| NGC 3351  | 30.01 ± 0.19| Graham et al. 1997       |
| NGC 3368  | 30.37 ± 0.16| Tanvir et al. 1995       |
| NGC 3627  | 30.22 ± 0.22| Saha et al. 1998         |

mean: 30.20 ± 0.12 (10.9 Mpc)

The distance modulus difference of 0.10 ± 0.35 between Tables 2 and 3 is fortuitously small.

3.2. The Virgo cluster

Different values of $m^*_B$ and $m^*_V$ of bona fide members of the Virgo cluster (cf. Binggeli, Sandage, & Tammann 1985) are compiled in Table 4. The values have been corrected for the small Galactic absorption according to Burstein & Heiles (1984). The $g$ magnitudes of Cohen (1988) and the $R$ magnitudes of Ajhar et al. (1994) were transformed into $V$ magnitudes following Whitmore (1997). No (precarious) attempt was made to correct $m^*_B$ into $m^*_V$.

Table 4. $m^*$ values of the Virgo cluster

| Galaxy     | $m^*_B$     | $m^*_V$     | $m^*_B - m^*_V$ | Source |
|------------|-------------|-------------|----------------|--------|
| NGC 4365   | 25.18 ± 0.16(2) | 24.47 ± 0.21(1) | 0.71 ± 0.26   | (1)    |
| NGC 4374   | 24.12 ± 0.30(1) | 24.25 ± 0.30(1) | 0.13 ± 0.24   | (2)    |
| NGC 4406   | 24.70 ± 0.11(1) | 23.85 ± 0.21(2) | 0.85 ± 0.24   | (3)    |
| NGC 4486   | 24.82 ± 0.11(2) | 23.74 ± 0.06(5) | 1.08 ± 0.13   | (4)    |
| NGC 4552   | 23.70 ± 0.30(1) | 24.18 ± 0.20(1) | 0.48 ± 0.14   | (5)    |
| NGC 4636   | 24.65 ± 0.14(1) | 24.93 ± 0.21(1) | 0.28 ± 0.10   | (6)    |

straight mean: 24.84 ± 0.12 24.93 ± 0.21

$(m - M)$: 31.77 ± 0.14 31.65 ± 0.13

$\Rightarrow (m - M) = 31.70 ± 0.10$ (21.9 Mpc)

Sources: (1) Harris et al. 1991; Secker & Harris 1993; Forbes 1996a (2) Ajhar et al. 1994 (3) Harris et al. 1991; Ajhar et al. 1994; Cohen 1988 (4) van den Bergh et al. 1985; Harris et al. 1991; Cohen 1988; McLaughlin et al. 1994; Whitmore et al. 1995; Elson & Santiago 1996a,b (5) Kissler et al. 1994 (6) Harris et al. 1991. – The values in parentheses in columns 2 and 3 give the number of independent determinations.
The distance moduli in $B$ and $V$ in Table 4 follow from equation (3) and (5). The former is marginally larger than the latter. The weighted mean GCLF modulus of the Virgo cluster is $(m - M) = 31.70 \pm 0.10$.

Independent distance determinations of the Virgo cluster are as follows:

Cepheids at the distance of the Virgo cluster are difficult objects even for HST. There are now three bona fide cluster members and two outlying members with Cepheid distances from HST. The wide range of their distance moduli, corresponding to 14.9 to 25.5 Mpc, reveals the important depth effect of the cluster. Four of the galaxies have been chosen from the atlas of Sandage & Bedke (1988) because they are highly resolved and seemed easy as to their Cepheids. They are therefore expected to lie on the near side of the cluster. In contrast NGC 4639 has been chosen as parent to SN 1990N and hence independently of its distance; correspondingly this distance is expected to be statistically more representative. A straight mean of the distances is therefore likely to be an underestimate. Indeed the mean Tully-Fisher (TF) distance modulus of the five galaxies is $0.02 \pm 0.16$ (corresponding to 10% in distance) smaller than the mean cluster distance of a complete and fair sample of TF distances (Federspiel et al. 1998).

A preliminary Cepheid distance of the Virgo cluster is obtained by taking the Cepheid distance of the Leo group of $(m - M) = 30.20 \pm 0.12$, based now on three galaxies with Cepheids from HST, and to step up this value by the modulus difference of $\Delta(m - M) = 1.25 \pm 0.13$ (Tammann & Federspiel 1997) between the Leo group and the Virgo cluster. The corresponding result is shown in Table 5.

Table 5. The Virgo cluster modulus from various methods excluding the GCLF

| Method      | $(m - M)_{Virgo}$ | Hubble type | Source |
|-------------|-------------------|-------------|--------|
| Cepheids    | 31.45 ± 0.21      | S           | 1      |
| Tully-Fisher| 31.58 ± 0.24      | S           | 2      |
| SNe Ia      | 31.52 ± 0.20      | E, S        | 3      |
| $D_n - \sigma$ | 31.85 ± 0.19       | S0, S     | 4      |
| Novae       | 31.46 ± 0.40      | E           | 5      |
| Mean:       | 31.61 ± 0.09      |             |        |

Sources:
1. See text.
2. Federspiel et al. (1998).
3. See text.
4. A reasonably tight $D_n - \sigma$ relation of S0 and spiral galaxies in the Virgo cluster has been published by Dressler (1987). The zeropoint calibration rests on the distance of the Galactic bulge (7.8 kpc) and the Cepheid distances of M 31 and M 81 (Sandage & Tammann 1988, Tammann 1988).
5. Pritchet & van den Bergh (1987b) found from six novae in Virgo cluster ellipticals that they are $7.02 \pm 0.14$ more distant than the apparent distance modulus of M 31 of $(m - M)_{AB} = 24.58 \pm 0.10$ from Cepheids (Madore & Freedman 1991) and Galactic novae (Capaccioli et al. 1989). Livio (1997) found from a semi-theoretical analysis of the six Virgo novae $(m - M)_{Virgo} = 31.35 \pm 0.35$. A low-weight mean of 31.46 is adopted.
A good Virgo cluster distance comes from the relation between the 21cm line width of inclined spirals and their luminosity (the so-called Tully-Fisher relation). Because the method, calibrated by 20 local galaxies with Cepheid distances, can be applied to a complete sample of Virgo spirals the result is exceptionally immune to selection effects which systematically lead to an underestimate of all distances (the ever-present Malmquist effect of magnitude-limited samples). The resulting distance modulus is shown in Table 5.

A high-weight Virgo modulus comes also from the seven SNe Ia (excluding the peculiar SN1991T) which give $<m_B> = 12.01 \pm 0.16$ and $<m_V> = 11.96 \pm 0.17$ at maximum. The absolute magnitude of SNe Ia is well calibrated from eight SNeIa with Cepheid distances (Saha et al. 1998). From this the Virgo modulus becomes $(m - M) = 31.46 \pm 0.17$. Four of the seven SNeIa have known $\Delta m_{15}$ values. If they are corrected for $\delta \Delta m_{15}$ and $\delta (B - V)$ (cf. Parodi et al. 1998)) the Virgo cluster modulus becomes $31.52 \pm 0.20$ as included in Table 5.

Table 5 lists also two additional distance determinations of the Virgo cluster. For details the reader is referred to the original literature.

The Virgo cluster modulus from the GCLF and from other methods compares very well, the difference being $\Delta (m - M) = 0.09 \pm 0.13$.

3.3. The Coma cluster

For two Coma cluster members $m_V^*$ values are available from HST observations (Table 6). With the adopted value of $m_V^*$ and equation (7) one obtains the Coma cluster distance as shown in Table 6.

| galaxy     | $m_V^*$  | Source        |
|------------|----------|---------------|
| NGC 4481   | $> 27.3 \pm 0.3$ | Baum et al. 1995 |
| IC 4051    | $27.72 \pm 0.3$   | Baum et al. 1997 |
| adopted:   | $27.72 \pm 0.3$   |               |
| $\Rightarrow (m - M) = 35.34 \pm 0.31$ (117 Mpc) |

The modulus difference Coma-Virgo from four different methods in Table 7 together with the Virgo cluster modulus in Table 5 gives $(m - M) = 35.32 \pm 0.13$ for the Coma cluster. The agreement with the GCLF distance in Table 4 is fortuitously good.

3.4. The Fornax cluster

For seven galaxies in the Fornax cluster $m_B^*$ and/or $m_V^*$ values are available (Table 8). The best independent distance of the Fornax cluster is obtained from its three SNe Ia (SN 1980N, 1981D, and 1992A). They have occurred in early-type galaxies and are therefore likely to lie in the center of the cluster. With the luminosity calibration of eight local SNe Ia through Cepheids (Saha et al. 1998,
Table 7. Independent determinations of the Coma cluster modulus relative to the Virgo cluster

| Method          | Δ(m − M)_{Coma−Virgo} | Source                        |
|-----------------|------------------------|-------------------------------|
| 1st-ranked gal. | 3.34 ± 0.30            | Sandage et al. 1976           |
| 10 brightest gal.| 4.16 ± 0.20            | Weedman 1976                  |
| D_n − σ         | 3.74 ± 0.14            | Faber et al. 1989             |
| TF + D_n − σ    | 3.55 ± 0.15            | D’Onofrio et al. 1997        |
| weighted mean   | 3.71 ± 0.08            | Dekel 1995                    |

\[ + (m − M)_{Virgo} \Rightarrow 35.32 ± 0.13 \]

Table 8. \(m_B^*\) and \(m_V^*\) values of the Fornax cluster

| Galaxy    | \(m_B^*\)       | \(m_V^*\)       | \(m_B^* - m_V^*\) | Source |
|-----------|-----------------|-----------------|-------------------|--------|
| NGC 1344  | 23.28 ± 0.25(1) |                 |                   | (1)    |
| NGC 1374  | 23.52 ± 0.14(1) |                 |                   | (1)    |
| NGC 1389  | 23.68 ± 0.28(1) |                 |                   | (2)    |
| NGC 1399  | 24.38 ± 0.15(2) | 23.86 ± 0.15(2) | 0.48              | (3)    |
| NGC 1404  | 24.72 ± 0.20(1) | 23.84 ± 0.10(5) | 0.88              | (1)(5) |
| NGC 1427  | 23.78 ± 0.21(1) |                 |                   | (2)    |
| straight mean: | 24.55 ± 0.20 | 23.70 ± 0.10 | 0.85 ± 0.22 |        |
| \((m − M)\): | 31.48 ± 0.20 | 31.32 ± 0.10 |                   | (18.6 Mpc) |

Sources: (1) Blakeslee & Tonry 1996 (2) Kohle et al. 1996 (3) Della Valle et al. 1998 (4) Madejsky & Bender 1990; Geisler & Forte 1990; Bridges et al. 1991 (5) Richtler et al. 1992. – The values in parentheses in columns 2 and 3 give the number of independent determinations.

Macchetto 1998) one obtains for them a Fornax cluster modulus of \((m − M) = 31.68 ± 0.15\) after full correction for second parameter differences (Parodi et al. 1998).

A different route to the Fornax modulus is through distance determinations relative to the Virgo cluster as compiled in Table 8.

Determinations of the relative distance between the Fornax and Virgo clusters are quite insensitive to selection effects and differences of population size, because one compares more or less comparable galaxies. Therefore the surface brightness fluctuation (SBF) and planetary nebulae (PNe) methods have been included here although they provide in general very unreliable distances. It is known that the bright tail of the luminosity function of the shells of PNe is strongly dependent on the sample (galaxy) size (Bottinelli et al. 1991, Tammann 1993, Méndez et al. 1993, Soffner et al. 1996). The reasons for the generally poor
Table 9. Independent determinations of the Fornax cluster modulus relative to the Virgo cluster

| Method          | $\Delta(m - M)_{\text{Fornax-Virgo}}$ | Source                         |
|-----------------|--------------------------------------|--------------------------------|
| 1st-ranked gal. | 0.44 ± 0.30                          | Sandage et al. 1976            |
| $D_n - \sigma$  | 0.14 ± 0.16                          | Faber et al. 1989              |
|                 | 0.45 ± 0.15                          | D’Onofrio et al. 1997          |
| SB of dwarfs    | 0.28 ± 0.08                          | Jerjen & Binggeli 1997         |
| SBF             | 0.20 ± 0.08                          | Tonry 1997                     |
| PNe             | 0.32 ± 0.10                          | Jacoby 1997                    |
|                 | weighted mean:                        | 0.28 ± 0.06                    |
|                 | $(m - M)_\text{Virgo} \Rightarrow$   | 31.89 ± 0.11                   |

results from SBFs are less clear. Trouble-makers could be, for instance, AGB stars of an admixture of a young population or some very metal-rich stars (cf. Han et al. 1997). In any case, one of the strong objections against the SBF distances is that twelve such distances of galaxies which have provided blue SNe Ia imply a SNe Ia luminosity fully 0.05 fainter than required by the eight Cepheid-calibrated SNe Ia.

Combining the evidence of the Fornax SNe Ia and Table 9 yields a weighted distance modulus of the Fornax cluster of $(m - M) = 31.82 ± 0.09$.

The disagreement of $\Delta(m - M) = 0.47 ± 0.13$ between the distance moduli from GCLF and from independent evidence is blatant. It is clear that in the case of the Fornax cluster the GCLF yields a fallacious distance. The peak of the GCLF of Fornax must be brighter by $\sim 0.05$ than in the cases so far considered.

It should be stressed that all distance determinations of the Fornax cluster considered here involve early-type galaxies (the GCLF, SNe Ia and Table 9). The relatively small Cepheid distance of the giant spiral NGC 1365 (Madore et al. 1998) should therefore not be considered here. This is even more the case as the early-type Fornax galaxies are embedded in a large halo of spiral galaxies whose mean distance seems somewhat smaller than that of the E/S0 galaxies (Tammann & Federspiel 1997).

It may be noted in passing that the distance of the Fornax cluster is important in the present context to test the GCLF as a distance indicator, but it has little relevance for the derivation of $H_0$ because the cluster lies well outside the Virgo complex; its peculiar streaming velocity may therefore be 200–300 km s$^{-1}$, i.e. 20% of the observed mean recession velocity.

### 3.5. Individual galaxies

For six galaxies outside of the Leo group and the big clusters $m_V^*_{V}$ values are in the literature. They are compiled in Table 10.

No useful independent distance information other than the recession velocities is available for the galaxies in Table 10, the exception being NGC 3115 for which the tip of the red-giant branch gives a modulus of $(m - M) = 30.21 ± 0.3$ (Elson 1997) in statistical agreement with the GCLF distance. The individ-
Table 10.  \( m_V^* \) values for individual galaxies

| Galaxy           | \( m_V^* \)     | Source | \( (m - M)_{\text{GCLF}} \) | \( v_{220} \) | \( H_0 \) |
|------------------|-----------------|--------|----------------------------|-------------|---------|
| NGC 4278\(^1\)  | 23.23 ± 0.11    | (1)    | 30.85 ± 0.14               | 542         | 37      |
| NGC 4494\(^1\)  | 23.23 ± 0.12    | (1)(2) | 30.85 ± 0.14               | 1745        | 118     |
| NGC 4565 (Sb!)\(^1\) | 22.63 ± 0.20    | (2)    | 30.35 ± 0.22               | 1662        | 141     |
| NGC 1407\(^2\)  | 23.95 ± 0.30    | (3)    | 31.57 ± 0.31               | 1710        | 83      |
| NGC 1400\(^2\)  | 24.75 ± 0.30    | (3)    | 32.37 ± 0.31               | 475         | 16      |
| NGC 5846\(^3\)  | 25.05 ± 0.10    | (4)    | 32.67 ± 0.13               | 1993        | 58      |
| NGC 3115         | 22.37 ± 0.05    | (5)    | 29.99 ± 0.10               | 483         | 49      |

\(^1\) Coma I cloud (=G13; deVaucouleurs 1975); \(^2\) Eridanus cloud (=G31; deVaucouleurs 1975 does not include NGC 1400); \(^3\) NGC 5846 group (=G50; deVaucouleurs 1960); \(^4\) Velocity corrected for Virgocentric flow (Kraan-Korteweg 1986)

Sources: (1) Forbes 1996b (2) Fleming et al. 1995 (3) Perrett et al. 1997 (4) Forbes, Brodie, & Huchra 1996 (5) Kundu & Whitmore 1998.

The individual Hubble constants \( H_0 \) in the least column of Table 10 resulting from the GCLF distances, as determined from \( m_V^* \) and equation (7), scatter so wildly that the distances are clearly erratic. To be consistent NGC 4565 would have to have a peculiar velocity of \( \sim 1000 \text{ km s}^{-1} \), unparalleled outside of clusters. Also the velocities of NGC 4278 and NGC 4494, having about equal GCLF distances, differ by \( > 1000 \text{ km s}^{-1} \). NGC 1400 is most likely in the foreground of the Eridanus cloud, yet its GCLF distance is \( \sim 0.8 \) larger than that of the cloud member NGC 1407. The conclusion is that the distances in Table 10, with the exception of NGC 5846 and NGC 3115 and possibly NGC 4278 and NGC 1407, are unrealistic. While the peak of the GCLF of NGC 4494 and NGC 4565 seems to be overluminous by \( \sim 1 \) magnitudes, it is underluminous in NGC 1400 by almost 3 magnitudes! These numbers may be somewhat reduced by allowing for peculiar motions, but it is improbable that the discrepancies will disappear.

4. Conclusions

The distances derived from the peak of the GCLF are of highly variable quality. While the method yields excellent distances to the Leo group, Virgo cluster, and also the Coma cluster, the distance of the E/S0 galaxies in the Fornax cluster is off by \( \sim 0.5 \). Even larger discrepancies are found for at least three individual galaxies in clouds. The GCLF peak seems to be brighter than average in Fornax, NGC 4494, and NGC 4565 and much fainter in NGC 1400. It is also somewhat worrisome that the particularly well determined value \( m_V^* \) of the enormous GC population of the giant elliptical M87 (NGC 4486) is brighter by \( \sim 0.35 \) than the mean of six other Virgo cluster members.

There is hence strong evidence that \( M^* \) is variable, but it is by no means clear which parameters govern this variability.

One can exclude the Hubble type as the principal parameter because the calibration from spirals (Galaxy, M 31) provides perfect distances for the E/S0
galaxies in the Leo group and in the Virgo and Coma clusters. Inversely, the GCLF distance of the spiral NGC 4565 is unacceptable.

The available evidence concerning the width $\sigma_M$ of the GCLF is rather inconsistent. Some authors force an adopted $\sigma_M$ on the (partial) observations to determine $m^*$. If the LF is observed well beyond the peak a simultaneous solution for $m^*$ and $\sigma_M$ is possible; in other cases $m^*$ and $\sigma_M$ are correlated. But real differences of $\sigma_M$ are unquestionable. One may compare $\sigma_M = 1.02$ for the Galaxy and M 31 combined versus the well determined value $\sigma_M = 1.40$ for NGC 4486 (Whitmore et al. 1995); but other large E galaxies have small $\sigma_M$, i.e. $\sigma_M \approx 1.1$ for NGC 4278 and NGC 4494 (Forbes 1996b). Yet at present there are too few reliable $\sigma_M$ values to correlate them with the distance deviations.

Unfortunately very little color information is available for the GCLF peak. For the Galaxy and M 31 $m^*_B - m^*_V = 0.69$ is well determined. The peak color of NGC 4486, taken at face value, is much redder and its $m^*_V$ is unusually bright compared with other Virgo galaxies (cf. Table 4). Yet the overluminosity of the Fornax GCLF peak seems to go with a rather blue peak (cf. Table 8).

There are almost certainly metallicity differences, as indicated by color variations in $(C-T_1)$ and $(V-I)$, between the GC systems of different galaxies. The GCs in spirals are more metal-poor than in ellipticals (Ashman & Zepf 1998), but as noted before that does not impair the distance determination of the Leo, Virgo, and Coma ellipticals by means of the calibration in spirals (Galaxy and M 31), although stellar population models suggest that GCs of equal mass are about $0^m 2$ brighter in ellipticals than in their metal-poor counterparts in spirals (Ashman, Conti, & Zepf 1995). The likely merger galaxies NGC 4486 (Whitmore et al. 1995, Elson & Santiago 1996a,b) and NGC 5846 (Forbes 1996b) have bimodal distributions in $(V-I)$, but so do many other galaxies, e.g. NGC 3115 (Kundu & Whitmore 1998). The bimodality is clearly reflected in the GCLF in $V$ of NGC 4486 (Elson & Santiago 1996b) and probably of NGC 3115 (Kundu & Whitmore 1998), but not obviously so in NGC 5846 (Forbes et al. 1996).

No clear picture emerges which second parameter governs the peak luminosity $m^*$ of the GCLF, but in view of the many differences of GC systems and their apparently different formation histories and ages it is not too surprising that $m^*$ yields distances which are not reliable in all cases.

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References
Ajhar, E. A., Blakeslee, J. P., & Tonry, J. L. 1994, AJ, 108, 2087
Ashman, K. M., Conti, A., & Zepf, S. E. 1995, AJ, 110, 1164
Ashman, K. M. & Zepf, S. E. 1998, in ‘Globular Cluster Systems’, Cambridge: Cambridge Univ. Press, p. 89
Baum, W. A., Hammergren, M., Groth, E. J., Ajhar, E. A., & Lauer, T. R. 1995, AJ, 110, 2537
Baum, W. A., Hammergren, M., Thomsen, B., Groth, E. J., Faber, S. M., Grillmair, C. J., & Ajhar, E. A. 1997, AJ, 113, 1483
Binggeli, B., Sandage, A., & Tammann, G. A. 1985, AJ, 90, 1681
Blakeslee, J. P. & Tonry, J. L. 1996, ApJ, 465, L19
Bottinelli, L., Gougenheim, L., Paturel, G., & Teerkorpi, P. 1991, A&A, 252, 560
Bridges, T. J., Hanes, D. A., & Harris, W. E. 1991, AJ, 101, 469
Burstein, D. & Heiles, C. 1984, ApJS, 54, 33
Cacciari, C. 1998, private communication
Capaccioli, M., Della Valle, M., Rosino, L., & D’Onofrio, M. 1989, AJ, 97, 1622
Chaboyer, B., Demarque, P., Kernan, P. J., & Krauss, L. M. 1998, ApJ, 494, 96
Cohen, J. 1988, AJ, 95, 682
Dekel, A. 1995, private communication
Della Valle, M., Kissler-Patig, M., Danziger, J., & Storm, J. 1998, MNRAS, 299, 267
deVaucouleurs, G. 1960, ApJ, 131, 585
deVaucouleurs, G. 1970, ApJ, 159, 435
deVaucouleurs, G. 1975, in ‘Galaxies and the Universe’, eds. A. Sandage & J. Kristian, Chicago: Univ. of Chicago Press, p. 557
D’Onofrio, M., Capaccioli, M., Zaggia, S. R., & Caon, N. 1997, MNRAS, 289, 847
Dressler, A. 1987, ApJ, 317, 1
Elson, R. A. W. 1997, MNRAS, 286, 771
Elson, R. A. W. & Santiago, B. X. 1996a, MNRAS, 278, 617
Elson, R. A. W. & Santiago, B. X. 1996b, MNRAS, 280, 971
Faber, S. M., Wegner, G., Burstein, D., Davies, R. L., Dressler, A., Lynden-Bell, D., & Terlevich, R. J. 1989, ApJS, 69, 763
Federspiel, M., Tammann, G. A., & Sandage, A. 1998, ApJ, 495, 115
Fernley, J. et al. 1998, this conference
Fleming, D. E. B., Harris, W. E., Pritchet, C. J., & Hanes, D. 1995, AJ, 109, 1044
Forbes, D. A. 1996a, AJ, 112, 954
Forbes, D. A. 1996b, AJ, 112, 1409
Forbes, D. A., Brodie, J. P., & Huchra, J. 1996, AJ, 112, 2448
Geisler, D. & Forte, J. C. 1990, ApJ, 350, L5
Graham, J. A., et al. 1997, ApJ, 477, 535
Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., & Lattanzi, M. 1997, ApJ, 491, 749
Han, M. et al. 1997, AJ, 113, 1001
Harris, W. E. 1990, PASP, 102, 966
Harris, W. E. 1991, ARA&A, 29, 543
Harris, W. E., Allwright, J. W. B., Pritchett, C. J., & van den Bergh, S. 1991, ApJS, 76, 115
Hawley, S. L., Jeffreys, W. H., Barnes, T. G., & Lai, W. 1986, ApJ, 302, 626
Holland, S. 1998, AJ, 115, 1916
Hubble, E. 1932, ApJ, 76, 44
Humason, M. L., Mayall, N. U., & Sandage, A. R. 1956, AJ, 61, 97
Jacoby, G. H. 1997, in ‘The Extragalactic Distance Scale’, eds. M. Livio, M. Donahue, & N. Panagia, Cambridge: Cambridge Univ. Press, p. 186
Jerjen, H. & Binggeli, B. 1997, in ‘The Nature of Elliptical Galaxies’, ASP Conference Series 116, p. 298
Kissler, M., Richtler, T., Held, E. V., Grebel, E. K., Wagner, S. J., & Capaccioli, M. 1994, A&A, 287, 463
Kohle, S., Kissler-Patig, M., Hilker, M., Richtler, T., Infante, L., & Quintana, H. 1996, A&A, 309, L39
Kraan-Korteweg, R. C. 1986, A&AS, 66, 255
Kundu, A. & Whitmore, B. C. 1998, preprint
Livio, M. 1997, in ‘The Extragalactic Distance Scale’, eds. M. Livio, M. Donahue, & N. Panagia, Cambridge: Cambridge Univ. Press, p. 186
Macchetto, F. D. 1998, this conference
Madejsky, R. & Bender, R. 1990, IAU Symp., 139, 377
Madore, B. & Freedman, W. L. 1991, PASP, 103, 933
Madore, B. F. et al. 1998, Nature, 395, 47
McLaughlin, D. E., Harris, W. E., & Hanes, D. A. 1994, ApJ, 422, 486
Méndez, R. H., Kudritzki, R. P., Ciardullo, R., & Jacoby, G. H. 1993, A&A, 275, 534
Mould, J. & Kristian, J. 1986, ApJ, 305, 591
Parodi, B., Saha, A., Sandage, A., & Tammann, G. A. 1998, preprint
Perrett, K. M., Hanes, D. A., Butterworth, S. T., & Kavelaars, J. J. 1997, AJ, 113, 895
Pritchett, C. J. & van den Bergh, S. 1985, AJ, 90, 2027
Pritchett, C. J. & van den Bergh, S. 1987a, ApJ, 316, 517
Pritchett, C. J. & van den Bergh, S. 1987b, ApJ, 318, 507
Racine, R. 1968, JRASC, 62, 367
Reid, I. N. 1998, AJ, 115, 204
Richtler, T. et al. 1992, A&A, 264, 25
Saha, A., Sandage, A., Labhardt, L., Tammann, G. A., Macchetto, F. D., & Panagia, N. 1996, ApJ, 466, 55
Saha, A., Sandage, A., Labhardt, L., Tammann, G. A., Macchetto, F. D., & Panagia, N. 1998, preprint
Sandage, A. 1968, ApJl, 152, L149
Sandage, A. 1993, AJ, 106, 703
Sandage, A. & Bedke, J. 1988, Atlas of Galaxies useful to measure the Cosmological Distance Scale, Washington: NASA
Sandage, A., Kristian, J., & Westphal, J. A. 1976, ApJ, 205, 688
Sandage, A. & Tammann, G. A. 1988, ApJ, 328, 1
Sandage, A. & Tammann, G. A. 1995, ApJ, 446, 1
Sandage, A. & Tammann, G. A. 1996, ApJ, 464, L51
Secker, J. 1992, AJ, 104, 1472
Secker, J. & Harris, W. E. 1993, AJ, 105, 1358
Soffner, T., Méndez, R., Jacoby, G., Ciardullo, R., Roth, M., & Kudritzki, R. 1996, A&A, 306, 9
Tammann, G. A. 1988, in ‘The Extragalactic Distance Scale’, eds. S. van den Bergh & C. J. Pritchet, San Francisco: ASP, p. 282
Tammann, G. A. 1993, in ‘Planetary Nebulae’, eds. R. Weinberger & A. Acker, Dordrecht: Kluwer, IAU Symp. 155, p. 515
Tammann, G. A. & Federspiel, M. 1997, in ‘The Extragalactic Distance Scale’, eds. M. Livio, M. Donahue, & N. Panagia, Cambridge: Cambridge Univ. Press, p. 137
Tanvir, N. R., Shanks, T., Ferguson, H. C., & Robinson, D. R. T. 1995, Nature, 377, 27
Tonry, J. L. 1997, in ‘The Extragalactic Distance Scale’, eds. M. Livio, M. Donahue, & N. Panagia, Cambridge: Cambridge Univ. Press, p. 297
Tsujimoto, T. 1998, this conference
van den Bergh, S., Pritchet, C., & Grillmair, C. 1985, AJ, 90, 595
Weedman, D. W. 1976, ApJ, 203, 6
Whitmore, B. C. 1997, in ‘The Extragalactic Distance Scale’, eds. M. Livio, M. Donahue, & N. Panagia, Cambridge: Cambridge Univ. Press, p. 254
Whitmore, B. C., Sparks, W. B., Lucas, R. A., Macchetto, F. D., & Biretta, J. A. 1995, ApJ, 454, L73