Published in "The Extragalactic Distance Scale", eds. M Livio, M. Donahue and N. Panagia, Cambridge University Press 1997.

GLOBULAR CLUSTERS AS DISTANCE INDICATORS

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Abstract. The globular cluster luminosity function (GCLF) for bright elliptical galaxies can be approximately represented as a Gaussian distribution, with a mean value M^0_V = -7.21 ± 0.26 mag and a width σ = 1.35 ± 0.05 mag. Most of the uncertainty in M^0_V is due to the Cepheid distance scale to the Virgo cluster used to determine the zeropoint. The intrinsic dispersion in M^0_V is $\approx$ 0.12 mag for bright ellipticals, making it competitive with the best distance indicators. The value of M^0_V appears to be nearly universal, with only a weak second-order dependence on luminosity clearly demonstrated and other second-order dependencies possible at about the 0.1 - 0.2 mag level (*e.g.* Hubble type, color, and environment). The Hubble Space Telescope provides a significant improvement in our ability to measure M^0_V, with limiting magnitudes for one orbit observations more than two magnitudes beyond the turnover in the GCLF for galaxies in the Virgo cluster. Historical estimates of the Hubble constant based on the GCLF have been surprisingly stable for nearly 30 years, with a mean H_0 = 72 km s^{-1} Mpc^{-1}. At present the best estimate can probably be determined using seven galaxies in the Fornax cluster, yielding a value of H_0 = 82 ± 13 km s^{-1} Mpc^{-1}. Several hundred high quality GCLF's should be published in the next few years, making globular clusters one of the most important distance indicators during the next decade.

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1. INTRODUCTION

The perfect standard candle would have the following attributes. 1) It would be extremely bright so that it could be seen at high redshift. 2) It would always have exactly the same absolute magnitude (*i.e.* zero dispersion). 3) It would be found in great numbers in all types of galaxies. No single distance indicator has all these attributes, hence the proliferation of methods discussed at this conference.

One of the principle advantages of globular clusters (hereafter: GCs) is that they are very bright, overshadowed only by supernovae and entire galaxies as distance indicators. In addition, they are seen in both population I and II objects (*e.g.* spiral and elliptical galaxies), providing cross calibration between methods which are primarily available for one population type (*e.g.* Cepheid variables for population I). On the negative side they probably represent the extreme in terms of the dispersion in the value of the magnitude for a single object, which is $\approx$ 1.4 mag. However, this is largely irrelevant since a typical spiral galaxy has roughly a hundred globular clusters, an elliptical galaxy roughly a thousand, and a cD galaxy often over ten thousand globular clusters. Hence, in principle, the mean of the distribution can be estimated with uncertainties $\approx$ 0.14 mag (*i.e.* 1.4 - $\sqrt{}$100) for spirals, 0.04 mag for ellipticals, and 0.014 mag for cD galaxies. The intrinsic dispersion of M^0_V is $\approx$ 0.1 mag making it competitive with the best of the distance indicators. At present the limiting factors are the local calibrators, the question of universality, and, for the estimate of the Hubble constant, the effects of peculiar velocities.

From an observational standpoint the GCLF has several advantages over many of the other distance indicators. For example, only a single exposure is needed to make the measurement rather than a series of perhaps a dozen separate observations spread over several weeks or months, as required for Cepheids, RR Lyrae variables, novae, and supernovae. Another advantage is that the most precise measurements can be made in the one galaxy where the question of whether the galaxy is a foreground or background object is not an issue, namely cD galaxies. This is one of the primary difficulties with population I methods. Finally, the number of high-quality GCLF's is rapidly increasing, thanks in part to the fact that the surface brightness fluctuation method of distance estimation requires identifying and removing globular clusters from their images (*e.g.* Tonry, Ajhar, Luppino 1990, Ajhar, Blakeslee, & Tonry 1994).

For these reasons it seems certain that the use of the GCLF to determine distances will become increasingly important in the coming decade. The plan for this paper is to review the current situation and provide an updated compilation of high quality GCLF measurements for bright elliptical galaxies (Section 2), examine the primary uncertainties and estimate the errors (Section 3), take a brief look at theoretical considerations (Section 4), make an estimate of the Hubble constant based on new observations in the Fornax cluster (Section 5), and summarize the discussion and suggest future directions (Section 6).

There are already excellent reviews on the general characteristics of globular clusters in galaxies beyond the local group (Harris 1991) and the use of globular clusters for measuring distance (Jacoby et al. 1992, van den Bergh 1992). These references can be used to backtrack earlier reviews (*e.g.* Harris & Racine 1979). An article by Harris (1996) at this conference provides more detail about GCLFs in spirals and dwarf ellipticals while a recent review by Larson (1996) covers the formation of globular clusters. The current review will focus on the past five years with special attention on GCLFs in bright ellipticals.

2.1. A brief history

The history of the measurement of distances using globular clusters can be broken into four eras.

The measurement of the brightest globular clusters in M87 by Baum (1955) and Racine (1968) launched the first era. Ironically, given the recent history of the distance scale question, Sandage (1968) found H_0 = 75 km s^{-1} Mpc^{-1} using the first-ranked globular cluster in M87 while de Vaucouleurs (1970) found H_0 = 50 km s^{-1} Mpc^{-1}. It was clearly recognized that size-of-sample effects introduced large uncertainties in these estimates.

During the 70s, deeper photographic observations allowed comparisons of the bright side of the luminosity function (*e.g.* Hanes 1977, 20 galaxies in the Virgo cluster down to V $\approx$ 21.6 mag; Strom et al. 1981, 1700 clusters in M87 to B $\approx$ 23.5 mag), eventually leading to the development of sophisticated maximum-likelihood techniques for comparing distributions (*e.g.* Hanes & Whittaker 1987, Seeker & Harris 1993). While this dramatically improved the accuracy (in fact Hanes & Whittaker argue that "there is no need to strive for much deeper levels"), the results were still sensitive to the unknown width of the distribution which was not well constrained by the data.

The availability of CCD detectors in the 80's opened the third era, with the number of measured GCLF increasing rapidly (*e.g.* van den Bergh, Pritchet, & Grillmair 1985, Bridges, Hanes, & Harris 1991, Harris et al. 1991, Ajhar, Blakeslee, & Tonry 1994, Blakeslee & Tonry 1996, Kohle et al. 1996). Some of these observations reached the turnover or just past the turnover, providing more secure measurements by allowing a determination of the peak of the distribution.

The faint limiting magnitude of the Hubble Space Telescope now makes it possible to routinely reach two or three magnitudes

beyond the turnover at the distance of the Virgo cluster (*e.g.* Whitmore et al. 1995, Elson & Santiago 1996a, b, Forbes 1996a, b), hence opening the fourth era. Even the Coma cluster is within our reach, although only barely if we wish to reach past the peak of the luminosity function (Baum et al. 1995). The primary improvements that can be expected from HST observations are; more accurate determinations of the peak and width of the GCLF, higher precision color measurements which may be necessary for separating red (metal rich) and blue (metal poor) clusters, the opportunity to increase the number of local calibrators using HST observations of Cepheids in galaxies as distant as the Virgo and Fornax clusters, and a determination of the degree to which the GCLF is universal.

2.2. HST observations

The Hubble Space Telescope (HST) provides several advantages over ground-based telescopes for measuring the GCLF. The first is the ability to reach more than two magnitudes past the turnover for single orbit observations in the Virgo cluster. Another important advantage is the ability to differentiate the globular clusters, which are barely resolved at the distance of the Virgo cluster, from both foreground stars and background galaxies. Finally, the excellent spatial resolution makes it possible to use very small apertures which reduces the effect of the galaxy background, resulting in higher precision observations right into the core of the galaxy where the density of clusters is highest. Figure 1 shows an example of an HST image of a portion of M87 (Whitmore et al. 1995). The large improvement over the ground-based observations (*i.e.* the objects labeled "C" from Couture, Harris, & Allwright 1990) is readily apparent.

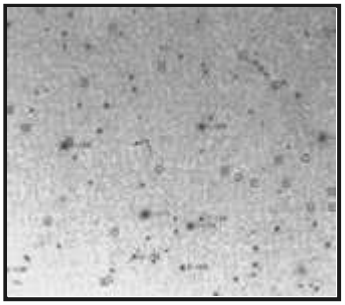

Figure 1. A portion of the M87 field from Whitmore et al. (1995) showing how much deeper HST observations are compared to ground-based. The objects labeled "C" are from the ground-based observations of Couture et al. (1990). The squares show clusters with luminosities near the peak of the luminosity function while the circles show clusters roughly 1.5 mag past the peak.

It is interesting that the first study using HST observations to attempt to determine the Hubble constant using the GC's was the most difficult to date. Baum et al. (1995) attempted to measure the turnover in the GCLF for the non-central elliptical galaxy NGC 4881 in the Coma cluster, with a distance modulus roughly 3.7 magnitudes fainter than the Virgo cluster. They were unable to see any turnover in the distribution, and therefore only quote an upper limit for the Hubble constant of $H_0 = 67$ (+7, -67) km s^{-1} Mpc^{-1}. However, this is somewhat misleading since they clearly see the bright end of the distribution, so very low values of H_0 are not possible. If we assume a GCLF similar to M87 (Whitmore et al. 1995), a value of $M^0_V = -7.21$ mag (Section 3.1), and use the bright half of the distribution to estimate the total number of clusters, we find the value of m_V at 5% of the distribution yields a positive detection of $H_0 = 72 \pm 13$ km s^{-1} Mpc^{-1}, rather than an upper limit. It is not unexpected that the turnover was not seen, since the 50% detection threshold was at $m_V = 27.3$ mag while the peak is predicted at a value $m^0_V \simeq 27.8$ mag for this value of H_0. In addition, the observations were made before the WFPC2 was cooled, hence the number of hot pixels is very large. While Baum et al. attempt to take these limitations into account, the observations are clearly pushing the limit of this particular dataset. It should be possible to observe roughly one magnitude deeper by using the WFPC2 after the cooldown and by using spatial dithering to flatten the background and remove hot pixels.

The HST observations of M87 by Whitmore et al. (1995) reached more than 2 magnitudes beyond the turnover of the GCLF. With over 1000 clusters in the sample this currently represents the best GCLF available for any galaxy, providing statistical accuracies roughly a factor of two smaller than any previously measured galaxy, including the Milky Way and M31 which have

much smaller populations. A Gaussian profile with m^0_V = 23.72 ± 0.06 mag and σ = 1.40 ± 0.06 mag provide a good fit to the data, leading to an estimate for the Hubble constant of H_0 = 78 ± 11 km s^{-1} Mpc^{-1}. The color distribution is strongly bimodal, with peaks near *V* - *I* = 0.95 mag and 1.20 mag. This raises the question of whether the red and blue clusters have the same value of M^0_V.

Elson & Santiago (1996a, b) observed fields in M87 roughly 2.5' from the center. Although their samples are smaller (146 and 220 clusters), their results are consistent with those of Whitmore et al. (1995). In particular, Elson & Santiago (1996b) find a bimodal color distribution with even sharper peaks at *V* - *I* = 0.92 mag and 1.23 mag. They find that the red clusters are roughly 0.3 magnitudes fainter than the blue clusters (see Section 3.2.3 for a discussion).

Forbes et al. (1996) and Forbes (1996a, b) have used HST to study GCs in 14 elliptical galaxies with kinematically-distinct cores. The GCLF of three galaxies (NGC 4365 in either the Virgo cluster or possibly the Virgo W' cloud, and NGC 4278 and NGC 4494 in the Coma I Cloud) have been determined and used to produce estimates of the Hubble constant in the range 72 - 80 km s^{-1} Mpc^{-1}. However, questions concerning membership and peculiar velocities of these clouds limit the reliability of these estimates.

Whitmore et al. (1996), as part of their study of candidate young and intermediate-age globular clusters in merger remnants, find that the old, metal-poor population of globular clusters in most galaxies have remarkably constant colors with mean values of *V* - *I* = 0.95 mag (*i.e.* the Milky Way, M31, ellipticals with narrow color distributions, the blue peak of ellipticals with bimodal color distributions, and the old populations in merger remnants). Following the suggestion by Zepf and Ashman (1993), they argue that the red clusters found in some ellipticals (*e.g.* M87) are metal-rich GC's formed in a second episode of cluster formation, presumably during a merger event. This may be important for distance measurements since red and blue clusters may have slightly different values of M^0_V. They also find that the bright wing of the GCLF for five galaxies observed with HST is remarkably constant, with a scatter of just 0.1 mag, indicating that fairly good distance estimates can be determined as long as the completion limit reaches $m_V \approx$ -8 mag. This is similar to the conclusion of Hanes & Whittaker (1987). For HST, with a limiting magnitude around m_V = 29 mag, this implies a distance modulus of 37 mag and a distance of 250 Mpc. Elson, Santiago, & Gilmore (1996) have shown that globular clusters can be seen out to a distance modulus of 39 mag in the Hubble Deep Field.

2.3. A compilation and estimate of the intrinsic dispersion in M^0_V

A Gaussian distribution provides a good representation of the GCLF for most galaxies when plotted in magnitude bins (*e.g.* Hanes 1977, Harris 1991, Jacoby et al. 1992; however, see Secker 1992, and Kissler et al. 1994, who argue that a *t* distribution with a shape parameter μ = 5 is a slightly better fit to the Milky Way and M31 GCLFs). Figure 2 shows the data for M87 from Whitmore et al. (1995; see also Figure 7 in Jacoby et al. 1992). The two primary quantities that will be compiled are, m^0_V, the extinction corrected apparent magnitude of the turnover of the GCLF in the Johnson V passband, and σ, the standard deviation or "width" of the distribution.

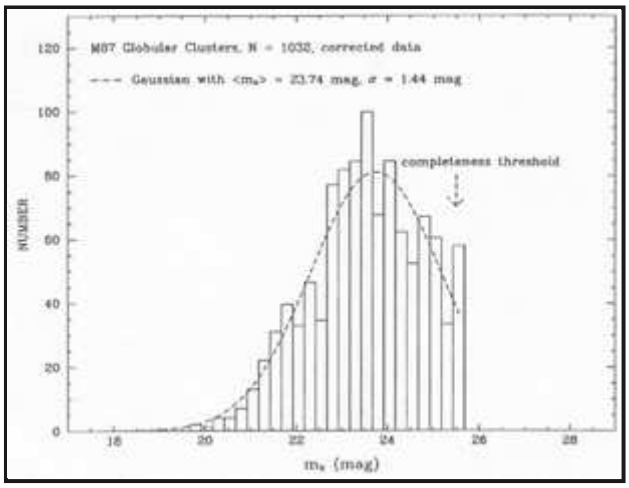

Figure 2. The GCLF for M87 from Whitmore et al. (1995) showing that a Gaussian profile provides a good fit.

Tables 1 and 2 provide a compilation of m^0_V and σ for 18 giant elliptical galaxies deemed of high enough quality to provide estimates with uncertainties less than about 0.3 mag. See H96 for a compilation of GCLFs for spirals and dwarf galaxies, and a plot of M^0_V vs. galaxy, luminosity. Table 1 shows that m^0_V (and therefore M^0_V) is remarkably constant, with a raw scatter of 0.21 mag for the Virgo cluster (0.24 mag if NGC 4365 and NGC 4636 are included), and 0.18 in the Fornax cluster.

Table 1. m^0_V and a for elliptical galaxies in the Virgo and Fornax clusters

	m^0_V	±	σ	±	Reference
Fornax Cluster					
NGC 1344	23.80	0.25 mag	1.35	0.18 mag	Blakeslee & Tonry (1996)
NGC 1374	23.52	0.14	-	-	Kohle et al. (1996)
NGC 1379	23.68	0.28	-	-	Kohle et al. (1996)
NGC 1380	24.05	0.25	1.30	0.17	Blakeslee & Tonry (1996)
NGC 1399	23.81	0.09	-	-	*** weighted mean ***
"	23.90	0.08	-	-	Kohle et al. (1996)
"	23.83	0.15	1.38	0.09	Blakeslee & Tonry (1996)
"	23.85	0.30	(1.4)	-	Bridges et al. (1991)
"	23.45	0.16	1.20	-	Geisler & Forte (1990)
"	24.00	0.20	-	-	Madejsky & Bender (1990)
NGC 1404	24.01	0.14	-	-	*** weighted mean ***
"	24.10	0.20	(1.4)	-	Richtler et al. (1992)
"	23.92	0.20	1.32	0.14	Blakeslee & Tonry (1996)
NGC 1427	23.78	0.21	-	-	Kohle et al. (1996)
weighted mean: (n = 7)	23.80 mag ± 0.18 (scatter) ± 0.07 (m.e.)				
Virgo Cluster					
NGC 4374	24.12	0.3	(1.4)	-	Ajhar et al. (1994)
NGC 4406	24.25	0.3	(1.4)	-	Ajhar et al. (1994)
NGC 4472	23.85	0.08	-	-	*** weighted mean ***
"	23.84	0.11	(1.46)	-	Harris et al. (1991)
"	23.72	0.3	(1.4)	-	Ajhar et al. (1994)
"	23.99	0.3	1.20	-	Cohen (1988)
NGC 4486	23.88	0.07	-	-	*** weighted mean ***
"	23.73	0.06	1.40	0.06	Whitmore et al. (1995)
"	24.14	0.30	-	-	van den bergh et al. (1985)
"	23.99	0.3	1.50	-	Cohen (1988)
"	23.74	0.3	(1.4)	-	Elson & Santiago (1996a)
"	23.99	0.3	1.57	-	Bison & Santiago (1996b)
"	24.20	0.3	1.73	-	McLaughlin et al. (1994)
"	23.92	0.13	(1.46)	-	Harris et al. (1991)
NGC 4552	23.70	0.3	(1.4)	-	Ajhar et al. (1994)
NGC 4649	23.79	0.14	(1.46)	-	Harris et al. (1991)
weighted mean: (n=6)	23.89 mag ± 0.21 (scatter) ± 0.09 (m.e.)				

Table 2. m^0_V and σ for other elliptical galaxies

	m^0_V	±	σ	±	Reference
Leo Group					
NGC 3377/79	22.55	0.40 mag	(1.2 mag)	-	Harris (1990)
NGC 3379	22.20	0.30	-	-	Pritchet et al. (1985)
Coma Group					
NGC 4278	23.23	0.11	1.21	0.09	Forbes (1996a)
NGC 4494	23.05	0.13	1.09	0.11	Forbes (1996a)
"	23.65	0.40	1.4	0.11	Fleming et al. (1995)
Possible Virgo Cluster					
NGC 4365	24.37	0.15	-	-	*** weighted average ***
"	24.20	0.30	1.28	0.15	Forbes (1996a)
"	24.29	0.18	(1.46)	-	Harris et al. (1991)
"	24.68	0.3	(1.4)	-	Ajhar et al. (1994)
NGC 4636	24.18	0.20	-	-	Kissler et al. (1994)

NOTES TO TABLES 1 AND 2

(a) Values of m^0_V have been corrected to $A_V = 0.06$ mag for the Virgo Cluster, based on the average for the galaxies in this sample from Burstein & Heiles (1984). The mean for Fornax was negative, so a value of $A_V = 0.00$ mag has been used, as recommended by Burstein & Heiles.

(b) If no error estimate has been made for m^0_V, a value of 0.3 is assumed in order to compute the weighted mean.

(c) Values of σ in parenthesis indicate cases where an assumed rather than derived value has been used.

(d) A value of $V - R = 0.5$ mag has been used to convert value of M_R from Ajhar et al. (1994).

(e) A value of $B - V = 0.8$ mag has been used to convert value of M_B from Harris et al. (1991), and van den Bergh et al. (1985).

(f) A value of $V - g = -0.15$ mag has been used to convert value of M_g from Cohen (1988).

(g) A ratio of 2/1 for the blue/red clusters has been used to calculate the total values from Elson & Santiago (1996b).

(h) Alternative estimates of m^0_V for the Harris et al. (1991) data, based on maximum likelihood techniques, are available in Secker & Harris (1993).

Part of the observed dispersion is due to measurement uncertainties. Using galaxies with repeat measurements shows that a typical measurement error is 0.16 mag. Another source of uncertainty is the size of the cluster, with some galaxies in the front or back of the cluster. This is especially important for the Virgo cluster due to its large extent. Assuming the Virgo cluster can be modeled as a sphere with 30 radius, and the more compact Fornax cluster with a 10 radius, leads to uncertainties of 0.11 mag (Virgo) and 0.04 mag (Fornax). Subtracting the measurement uncertainty and depth of cluster uncertainty in quadrature (after taking into account the galaxies with multiple measurements) leaves estimates for the intrinsic dispersion of 0.13 mag (Virgo) and 0.11 mag (Fornax). These values compare well with even the best distance estimators (*e.g.* Cepheids with 0.10 mag dispersion, Jacoby et al. 1992). The intrinsic dispersion may be even smaller if it turns out that red and blue clusters have slightly different values of M^0_V (see Ashman, Conti, & Zepf 1995 and Elson & Santiago 1996b), requiring a small correction depending on the ratio of red-to-blue clusters.

Using the measured rather than assumed values from Table 1 and 2 leads to a mean value of $\sigma = 1.35 \pm 0.05$ mag, with a scatter of 0.17 mag (NOTE: error estimates derived in this review are 1 sigma uncertainty in the mean, taking external errors into account when applicable; *e.g.* values of M^0_V include the uncertainty in the Cepheid zeropoint). If we restrict the sample to the nine cases where error estimates have been made we find an observed scatter of only 0.10 mag, smaller than the mean predicted

uncertainty of 0.12 mag. It may therefore be best to assume a fixed value of σ when estimating m^0_V, since there is little evidence at present for any real scatter in σ. The near constancy in M^0_V and σ explains why reasonably good distance determinations can be made using just the bright part of the GCLF (Hanes & Whittaker 1987, Whitmore et al. 1996). It should be noted, however, that spiral galaxies appear to have values of σ which are roughly 0.2 mag lower (H96).

3. THE PRIMARY UNCERTAINTIES

Measurement errors in m^0_V are no longer the limiting factor that determines the accuracy when using the GCLF for distance determinations. Typical internal uncertainties are now 0.1 - 0.2 mag, and can be further reduced by averaging several galaxies together. The uncertainties introduced by the following questions generally dominate the calculation.

a. How secure are the "local" calibrators?
b. How universal is the GCLF?
c. How important is interstellar extinction?
d. What is the appropriate velocity for the calculation of the Hubble constant?

While most of these are the same questions that were with us 20 and 30 years ago (see Sandage 1968, de Vaucouleurs 1970, Hanes 1979), the recent increase in the number of high quality GCLFs and the new capabilities provided by HST are making it possible to resolve many of these questions. For example, rather than relying on the Milky Way and M31 for our calibration it is now possible to use Cepheid measurements to directly calibrate the ellipticals in the Virgo cluster.

3.1. Local calibrators

Until recently, the globular cluster systems of the Milky Way and M31 provided the primary calibration for GCLF distance estimates. While a few other local galaxies have also been measured (M33, M81, NGC 4565, NGC 4594; see H96), the data is relatively poor and the errors roughly twice as large, so most studies have not used them. Secker (1992) and Sandage & Tammann (1995) have recently reexamined the use of M31 and the Milky Way as the local calibrator. Secker finds that M^0_V is roughly 0.2 mag brighter in M31 (M^0_V = -7.51 ± 0.15 mag) compared to the Milky Way (M^0_V = -7.29 ± 0.13 mag). Sandage and Tammann (1995), adopting an RR Lyrae calibration for the Milky Way that is roughly 0.25 mag brighter than in general use, find that M^0_V is nearly identical for M31 (M^0_V = -7.70 ± 0.20 mag) and the Milky Way (M^0_V = -7.60 ± 0.11 mag). The mean of all four values is M^0_V = -7.52 ± 0.17 mag where the uncertainty is the scatter in the four values, which provides the best estimate of the accuracy in this case since systematic effects (*i.e.* the RR Lyrae distance scale) dominate the results.

The use of local spirals to calibrate distant ellipticals has always been one of the primary weaknesses of the GCLF method for measuring distances, as will be discussed in the section on universality (Section 3.2.2). A practical concern is that faint GCs are more difficult to identify in nearby spirals since they can be confused with open clusters, and the smaller number and larger angular extent makes them more difficult to differentiate from background galaxies. Reed et al. (1992) suggests that incompleteness at the faint end may be the reason the value of M^0_V in M31 appears to be slightly higher, and the value of σ slightly lower, than the comparable values for the Milky Way.

It is now possible to replace this comparison of "apples and oranges" with a direct calibration of elliptical galaxies using measurements of Cepheid variables in the Virgo cluster galaxies. The primary uncertainty with this method is the possibility that the galaxy with Cepheid measurements might be in the front or back of the cluster. It is therefore important to observe several galaxies in the same cluster. At present there are five galaxies in the Virgo cluster with distance determinations using Cepheid variables (NGC 4321 - Ferrarese et al. 1996 find m - M = 31.04 ± 0.17 mag; NGC 4496A - Saha et al. 1996a find m - M = 31.03 ± 0.14 mag; NGC 4536 - Saha et al. 1996b find m - M = 31.23 ± 0.05 mag; NGC 4571 - Pierce et al. 1994 find m - M = 30.87 mag; and NGC 4639 - Sandage et al. 1996 find m - M = 32.00 ± 0.23 mag). The value for NGC 4639 is nearly a magnitude higher than the other values. We therefore remove the high and low values to obtain our estimate for the Virgo cluster distance modulus of m - M = 31.10 ± 0.14 mag (where the error estimate is the mean of the value for three galaxies [underestimate] and the value for five galaxies [overestimate]). Using the value of m_V = 23.89 ± 0.09 mag from Section 2.3, and an uncertainty of 0.20 mag for the Cepheid zeropoint (Freedman et al. 1994) yields our final value of M^0_V = -7.21 ± 0.26 mag. Keeping all five Cepheid measurements would result in a value of M^0_V which is 0.13 mag brighter. The dominant uncertainty is due to the Cepheid distance determination for the Virgo cluster and the Cepheid zeropoint, both of which should improve in the near future.

Hence, the value of M^0_V derived from the Milky Way and M31 (i.e., M^0_V = -7.52 mag) is 0.31 mag brighter than our estimate

of M^0_V for bright ellipticals in the Virgo cluster. This should be considered a tentative result due to the large uncertainties. It is interesting to note, however, that the value is similar to the what has been advocated by Fleming et al. (1995) and Ashman, Conti, & Zepf (1995).

3.2. Universality

In 1958, Sandage wrote "We are, therefore, forced to the conclusion that globular clusters are very poor distance indicators because, at least with the present data, the absolute magnitude apparently vary from galaxy to galaxy". This was based on a comparison between the Milky Way and M31. van den Bergh (1975) came to essentially the same conclusion. As the data improved, these discrepancies went away, and it became more and more evident that the GCLF was actually quite a good distance indicator. For example, Sandage & Tammann (1995) find M^0_V for the Milky Way and M31 agree to within 0.1 mag, well within the statistical uncertainty, and argue that the GCLF is nearly universal.

The question of universality takes four basic forms; 1) luminosity, 2) Hubble type, 3) color, 4) environment.

3.2.1. *Luminosity*

Do bright and faint galaxies have the same value of M^0_V? H96 treats this in some detail, showing that dwarf ellipticals have values of M^0_V which are roughly 0.3 mag fainter than bright ellipticals. One possibility is that fainter clusters can survive in these systems due to the weaker tidal fields. This would predict that values of σ would be larger. While the value of σ for a composite of 8 dwarf ellipticals in Virgo cluster observed by Durrell et al. (1996) is the highest measured value in Table 1 from H96 (σ = 1.48 ± 0.20) the large uncertainty due to the small number of clusters makes this very uncertain. The new HST snapshot survey of 30 dwarf ellipticals (Ferguson et al. 1996) should improve the situation.

The difference in M^0_V for faint galaxies is not actually very important for the distance scale problem, since we are most interested in the bright ellipticals with large populations of GCs needed to provide small statistical uncertainties. The study of the GCLF in dwarf galaxies will primarily be useful for understanding the formation and evolution of GCs.

3.2.2. *Hubble type*

The question of whether spiral and elliptical galaxies have the same GCLF is important since, until recently, the local calibrators were all spirals while the distant galaxies were all ellipticals. This circumstance arose because a more accurate value of M^0_V can be measured for a giant elliptical which has more GCs, fewer point-like sources to be confused with the GCs (*e.g.* open clusters, HII regions, bright stars), and negligible internal extinction. Unfortunately, there are no giant ellipticals in the local group. The measurement of Cepheid variables in galaxies as far as the Virgo cluster is now circumventing this problem (see Section 3.1), but at the price of making the GCLF a secondary distance indicator. The question of universality versus Hubble type is still very important in order to provide a cross check on the Cepheid scale, as well as to gain a better understanding of how GCs form and evolve.

3.2.3. *Color (i.e. metallicity and age effects)*

As the precision of observations has increased it has become clear that many galaxies have bi- or multi-modal color distributions. Recent improvements in spectral synthesis models (*e.g.* Bruzual & Charlot 1993, 1996, Worthey 1994, Fritze-v.Alvensleben & Gerhard 1994) now make it possible to interpret these effects in terms of metallicity and/or age differences. Ashman, Conti, & Zepf (1995) have employed the Worthy (1994) stellar evolution models to show that if spirals and ellipticals have the same mass function (an assumption that needs to be carefully checked, since there are a variety of physical mechanisms that could modify the GC mass function; see Section 4), then spirals should have values of M^0_V which are roughly 0.2 mag brighter than ellipticals due to differences in the mean metallicity of the globular clusters. They also show that the I band is less sensitive to metallicity effects.

The observations of red and blue clusters in M87 (Whitmore et al. 1995, Elson & Santiago 1996a, b) provide some observational evidence for this trend, with a shift of $\approx$ 0.1 mag seen by Whitmore et al. (1995) and a shift of $\approx$ 0.3 mag seen by Elson & Santiago (1996b). These effects, if real, could affect the value of M^0_V at the 0.1 - 0.2 mag level. Correcting for the effect offers the potential of reducing the small dispersion in M^0_V still further.

The discovery of candidate young globular clusters in both merger remnants (*e.g.* Holtzman et al. 1992, Whitmore et al. 1993, Whitmore & Schweizer 1995) and in starburst galaxies (*e.g.* Conti & Vacca 1994, Hunter, O'Connell, & Gallagher 1994, and

Meurer et al. 1995) raises the question of whether M^0_V might be affected by the presence of young and intermediate-age clusters for some galaxies. While very young clusters are easy to identify, since they are up to 6 magnitudes brighter in M^0_V and 0.4 to 1.0 mag bluer in V-I, Whitmore et al. (1996) show that intermediate-age clusters are more difficult to isolate. At an age of 1 - 2 Gyr the clusters have roughly the same colors as old globular clusters, based on the Bruzual & Charlot (1996) models, although they are 1 - 2 mag brighter. Older clusters are redder, and either slightly brighter (2 - 6 Gyr) or slightly fainter (> 6 Gyr) than the old population. Intermediate-age clusters may therefore lead to an estimate for M^0_V which is either slightly too large or too small. It may be possible to minimize this potential problem by selecting galaxies that do not have evidence of recent merger activity (*e.g.* shells and loops), or by using only the blue clusters to determine M^0_V.

3.2.4. *Environment*

There are now enough galaxies with well determined GCLFs to begin to ask whether the environment and the position within the galaxy (*i.e.* the local environment) can affect the GCLF.

Blakeslee and Tonry (1996), using only six galaxies, find tentative evidence for a correlation between M_V and environment. Using the group velocity dispersion as an indicator of environment they find that M^0_V is fainter by about 0.5 mag in the Coma cluster than in the local group. However, the correlation is quite dependent on the observations of NGC 4881 in the Coma cluster (Baum et al. 1995) which are ambiguous (see Section 2.2). In addition, even if the correlation turns out to be real it is quite possible that a difference in M^0_V for different Hubble types is the cause rather than an environmental effect, since the galaxies in the low velocity dispersion environment are all spirals while the other galaxies are ellipticals. Finally, the opposite trend appears to be present for the dwarf ellipticals in the field compared to the dwarf ellipticals in the Virgo cluster (H96).

A large number of studies have concluded that M^0_V is not a function of position in a galaxy (*e.g.* Grillmair, Pritchet, & van den Bergh 1986, van den Bergh 1992, McLauglin, Harris, & Hanes 1994, Harris & Pudritz 1994, and Forbes 1996a). However, a recent paper by van den Bergh (1996) indicates that the luminosity distribution of globular clusters in the Milky Way depends on cluster size, which is known to correlate with Galactocentric distance. In addition, the clusters in the outer halo (> 10 kpc) with red horizontal branches are fainter than normal clusters by a factor of 10. Many of these are the anomalous clusters such as Pal 1, Pal 12, and Ter 7 which are both very extended and very faint, and would not be picked up by most studies of GC's in external galaxies. It will be important to examine the more recent HST datasets to search for possible trends in ellipticals, but based on earlier results the effects on M^0_V are likely to be quite small.

3.3. Extinction

Extinction from dust in the Milky Way (galactic extinction), and dust in other galaxies (internal extinction), results in relatively minor uncertainties. For example, Sandage & Tammann (1995) advocate a value of $A_V = 0.00$ mag for the galactic extinction in M87 while several other studies use a value from Burstein and Heiles (1984) of $A_V \approx 0.06$ mag (*e.g.* Whitmore et al. 1995). The situation is similar for the Fornax cluster, where values of $A_V = 0.00$ mag, 0.05 mag, and 0.10 mag are commonly used.

Effects of internal extinction are generally negligible since elliptical galaxies, containing very little gas and dust, are used for most GCLF distance determinations. However, for the Milky Way GCs typical values of the color excess, E(B - V), are 0.3 mag (Sandage & Tammann 1995), and 0.1 mag for M31 (Reed, Harris, & Harris 1992). Internal extinction is potentially important if these galaxies are used to set the zeropoint. If we use galaxies with Cepheid variables to calibrate our zero point the uncertainty due to extinction is quite small. For example, Ferrarese et al. (1996) estimate a total color excess E(B - V) = 0.10 mag for the Cepheid measurements in M100, and a combined uncertainty of 0.02 mag in the error budget for absorption in M100 and the LMC (used to define the Cepheid zeropoint).

3.4. Effect of "peculiar" velocities on the calculation of H_0

A determination of the Hubble constant requires an estimate of the distance and of the appropriate "expansion" velocity of a galaxy. Globular clusters share a problem common to several distance indicators, namely they only provide accurate distance estimates out to a few thousand km s^{-1}. Since peculiar velocities of a few hundred km s^{-1} are common for clusters of galaxies (*e.g.* Lauer & Postman 1994), this can introduce substantial uncertainties in our estimate of the Hubble constant. For example, a typical estimate for the Virgocentric infall velocity is 200 km s^{-1} (Han & Mould 1990). This represents an $\approx$ 15% correction to the Virgo velocity. The spread in the different measurements ($\approx$ 70 km s^{-1}) represents a 5% uncertainty in H_0.

One approach to circumvent this problem is to use HST to push out to larger distances. Baum et al. (1995) has shown that it is

difficult but not impossible to reach the turnover of the GCLF at the distance of the Coma cluster ($\approx$ 7000 km s^{-1}). Another technique is to offset from a nearby cluster to a more distant cluster, assuming the relative distances of the two clusters are well known (*e.g.* Freedman et al. 1994). This appears to be the case between the Virgo and Coma clusters, where estimates of $\Delta_{\text{Coma-Virgo}}$(m - M) = 3.71 ± 0.05 mag (van den Bergh 1992, based on 12 studies), $\Delta_{\text{Coma-Virgo}}$(m - M) = 3.71 ± 0.03 mag (de Vaucouleurs 1993, based on 12 studies, with 7 overlapping van den Bergh 1992), and $\Delta_{\text{Coma-Virgo}}$(m - M) = 3.80 ± 0.17 mag (Jerjen & Tammann 1993, based on five studies) are in good agreement. A related technique is to use the relative distance between a single cluster and several more distant clusters, so that any peculiar motions of the distant clusters tend to average out. Jerjen and Tammann (1993) use this technique to estimate the "Machian" velocity of the Virgo cluster based on 15 clusters. The main shortcoming of this technique is that the number of galaxy clusters with accurate relative distance is limited, so adding more clusters may simply add noise in some cases.

It is generally assumed that all the galaxies in a cluster are at the same distance, and the systemic velocity of the cluster can therefore be used as the appropriate velocity for the calculation of the Hubble constant. However, the galaxy may actually be in the front or back of the cluster. For a system as large and ill-defined as the spiral galaxies in the Virgo cluster (*i.e.* with a "radius" in the range 3° - 6°), this may result in a 5 - 10% error in the true distance. In addition, for some studies there may be a tendency to select galaxies which are slightly nearer (*e.g. Cepheids*), since it is easier to resolve the stars in this case. It will therefore be important to observe a number of galaxies and a number of different groups and clusters.

One way to solve this problem is to observe the dominant D or cD galaxy in the cluster, since there is good evidence that these galaxies reside very near the center of the cluster. For example, the position at the center of the extended x-ray halo in the Virgo cluster is good evidence that M87 is at the bottom of the potential well. Another method is to use a very compact cluster such as Fornax. In this case the radius of the cluster is roughly 1°, implying a maximum line-of-sight excursion of about 2% if the cluster is roughly spherical.

3.5. Error estimate

As discussed in Section 2.3, the combination of the intrinsic dispersion in the value of M^0_V and the measurement uncertainty results in internal uncertainties of $\approx$ 0.2 mag. Data for several galaxies can be averaged together reducing the uncertainty still further. Hence, the external errors are generally the limiting factors for distance determinations using the GCLF.

Table 3 provides an estimate of the total error budget for the following three cases: 1) using the Milky Way and M31 for calibration, 2) using Cepheids in the Virgo cluster for calibration, 3) using Cepheids in several groups and clusters to nail down the zeropoint, and ten ellipticals in the range 2,000 - 5,000 km s^{-1} with good sky coverage to average out peculiar velocities. See Section 2 and Section 3 for the discussion of the values in Table 3. Values in parenthesis assume ten galaxies have been averaged together. The value of ± 0.10 mag for the calibration of Method # 3 assumes the uncertainty in the Cepheid distance scale will be reduced by roughly a factor of two in the next few years (*e.g.* more observations in the Virgo and Fornax cluster and a better determination of the distance to the LMC). The table shows that at present, the limiting factors are the zeropoint calibration, peculiar velocities, and for Method # 1, the question of universality. These lead to current uncertainties of $\approx$ 15% in H_0. The estimate for method # 3 shows that within a few years it should be possible to use the GCLF to determine distances for individual ellipticals to $\approx$ 10%, and to determine H_0 to about 7%.

Table 3. Error estimates

	Method # 1	Method # 2	Method # 3
Timeframe:	Current	Current	Future
Calibration:	Milky Way + M31	Virgo Cepheids	Cepheids
Velocities:	Virgo cluster	Virgo cluster	10 distant galaxies
Distance Estimates			
Intrinsic Scatter:	0.12 mag (0.04 mag)	0.12 mag (0.04 mag)	0.12 mag (0.04 mag)
Measurement:	0.16 (0.05)	0.16 (0.05)	0.10 (0.03)
Calibration:	0.17	0.24 mag	0.10
Universality:	0.2		- -
Extinction:	0.05	0.05	0.05
totals:	0.33 mag (0.27 mag)	0.32 mag (0.25 mag)	0.19 mag (0.12 mag)
H_0 **Estimates**			
Velocities:	0.15 mag	0.15 mag	(0.05 mag) (0.05 mag)
totals:	0.37 mag (0.31 mag)	0.35 mag (0.29 mag)	0.20 mag (0.13 mag)

NOTES TO TABLE 3

(a) Values in parenthesis are for an average of ten galaxies.

(b) Total errors are derived assuming uncertainties add in quadrature.

(c) Universality is not relevant for methods # 2 and # 3 since the elliptical galaxies are calibrated directly, rather than using local spirals.

(d) Effects of peculiar velocities are estimated for methods # 1 and # 2 by assuming an uncertainty in the expansion velocity for the Virgo cluster of 100 km s^{-1} (approximate difference between Jerjen & Tammann [1993] and Huchra [1988]; using a mean velocity from the two studies of 1292 km s^{-1}).

4. THEORY (OR LACK THEREOF)

It is often said that the lack of a well established theory explaining the near constancy of M^0_V is one of the shortcomings of the GCLF method for measuring distances. However, even a method that has a solid theoretical basis can have hidden pitfalls when put into practice (*e.g.* the difference between population I and population II Cepheids confused the early distance estimates to M31). The final arbitrator of the success of a method is the empirical data, not the theory. Just because we do not understand the reason for the near universality of M^0_V does not mean there is not a physical mechanism that is responsible.

There are two basic approaches that have been used to try to understand why GCs have a characteristic mass, and therefore a characteristic luminosity since the mass-to-light ratio for GCs are generally similar. The first is to identify some aspect of the initial conditions that preferentially select a certain mass scale for formation (*e.g.* Peebles & Dicke 1968, Fall & Rees 1985, 1988, Kang et al. 1990, Murray & Lin 1992, West 1993, and Kumai, Basu & Fujimoto 1993). One of the difficulties for many of these models is the near constancy of M^0_V over a wide range of metallicities.

The second approach is to assume that proto GC's form over a wide range of scales, but destruction mechanisms destroy clusters outside some preferred range. For example, Fall and Rees (1977) argue that destruction from dynamical friction for high mass clusters, disk shocking for large clusters, and evaporation for small clusters results in a "survival triangle" responsible for the near universality of M^0_V. Similar studies have been done by Aguilar, Hut, & Ostriker (1988), Chernoff and Shapiro (1990), Capaccioli, Piotto, & Stiavelli (1993), Fukushige & Heggie (1995), and Murali & Weinberg (1996).

Observations of young clusters in the ongoing merger NGC 4038 / 4039 by Whitmore & Schweizer (1995) have provided some empirical support for this basic approach. They find that the luminosity function increases as a power law $\Phi(L)dL \propto L^{-1.8}\,dL$. This is similar to the luminosity function found in open clusters (Elson and Fall 1985), as well as giant molecular clouds (Sanders, Scoville, & Solomon 1985), supporting the suggestion by Jog & Solomon (1992) that globular clusters are formed in

giant molecular clouds, or in the cores of postulated supergiant molecular clouds (Harris & Pudritz 1994, McLaughlin & Pudritz 1996; but see also Schweizer et al. 1996).

This might explain the bright end of the GCLF, with the faint end being whittled away by one or more destruction mechanisms. The near universality of M^0_V in the presence of a wide variety of Hubble types, environments, galactocentric positions, and metallicities suggests that the destruction mechanism is more inherent to the clusters themselves (*e.g.* evaporation of stars by two-body relaxation within the cluster) than to their environment. It should be possible to study the process of cluster destruction in detail by observing merger remnants of different ages (*e.g.* Whitmore et al. 1996).

Blakeslee & Tonry (1996) develop a framework designed to determine whether creation or destruction mechanisms are more sensitive to environmental effects. At present the existing database is not able to distinguish these two possibilities from other effects such as a dependence on Hubble type or metallicity (see 3.2.4). With the rapidly increasing number of high-quality GCLFs it should be possible to test these and other theories in the near future.

5. ESTIMATES OF H_0

Figure 3 shows a plot of H_0 determinations using globular clusters over the past 30 years. Perhaps the most interesting aspect of this plot is the relative constancy of both the mean value (H_0 = 72 km s^{-1} Mpc^{-1}) and the scatter (10 km s^{-1} Mpc^{-1}). While it would be silly to use this mean as an estimate of the Hubble constant, in a sense the scatter is probably a reasonable representation of the external errors, since it is dominated by the different assumptions that go into the calculation rather than the observational data themselves. This is probably why the scatter is nearly constant, although the observational precision has improved dramatically over the past 30 years. The quoted uncertainties appear to be relatively good estimates since they roughly match the scatter in the diagram.

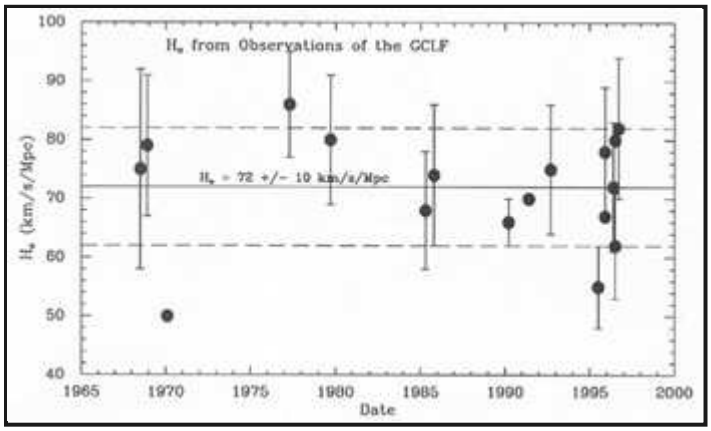

Figure 3. Estimates of H_0 based on the GCLF. Includes Sandage (1968), Racine (1968), de Vaucouleurs (1970, 1977), Hanes (1979), van den Bergh, Pritchet, & Grillmair (1985), van den Bergh (1985), Geisler & Forte (1990), Harris et al. (1991), Jacoby et al. (1992), Sandage & Tammann (1995), Baum et al. (1995), Whitmore et al. (1995), Forbes (1996a, b), Sandage & Tammann (1996), and Whitmore (1996).

Until very recently the best available data set for estimating the Hubble constant was the study of the four Virgo galaxies NGC 4365, NGC 4472, NGC 4486, and NGC 4649 by Harris et al. (1991), and van den Bergh, Pritchet, & Grillmair (1985). These observations, which go roughly one mag past the turnover, led to estimates of H_0 from 55 km s^{-1} Mpc^{-1} by Sandage and Tammann (1995) to 70 km s^{-1} Mpc^{-1} by Harris (1991).

The HST observations of the GCLF in M87 by Whitmore et al. (1995) reach more than two magnitudes beyond the turnover and provide a more secure exclusion of background/foreground objects. The position of M87 in the core of the Virgo cluster is another advantage. The resulting estimates for the Hubble constant range from H_0 = 62 ± 9 km s^{-1} Mpc^{-1} by Sandage and Tammann (1996) to H_0 = 78 ± 11 km s^{-1} Mpc^{-1} by Whitmore et al. (1995).

These two cases, which use the same data sets but result in an 25% spread in H_0, demonstrate that the major uncertainties are in

the precepts made for the calculation (*i.e.* the local calibrators, expansion velocities, and extinction) rather than the intrinsic dispersion in the GCLF (*i.e.* ≃ 6% in distance estimation).

5.1. A new estimate of H_0 using the Fornax cluster

Perhaps the best current estimate of the Hubble constant can be made using the seven galaxies (12 measurements) in the Fornax cluster. The weighted mean from Table 1 yields a value of $m_V = 23.80 \pm 0.07$ mag. The compact size of the cluster makes the uncertainty due to position in the cluster negligible. In addition, the extinction is small ($A_V = 0.00$ mag; Burstein & Heiles 1984). HST observations of GCLFs for several galaxies in the Fornax clusters should supplement this sample in the near future.

The appropriate expansion velocity has not been as well studied for the Fornax cluster as for the Virgo cluster. Using $V_{Fornax} = 1420$ km s^{-1} (Freedman 1996), and $M^0_V = -7.21 \pm 0.26$ mag (Section 3.1), yields a distance modulus m - M = 31.01 ± 0.27 mag and a Hubble constant $H_0 = 89$ km s^{-1} Mpc^{-1}. If we use $V_{Fornax} = 1398$ km s^{-1} (Sandage & Tammann 1993) we find $H_0 = 88$ km s^{-1} Mpc^{-1}, and for $V_{Fornax} = 1338$ km s^{-1} (Jerjen & Tammann 1993) the value is $H_0 = 84$ km s^{-1} Mpc^{-1}.

Another approach is to offset from the Fornax cluster to the Coma cluster, assuming $\Delta_{Virgo\text{-}Fornax}(m - M) = 0.00 \pm 0.15$ mag (see de Vaucouleurs 1993, Jerjen & Tammann 1993, Kohle et al. 1996, Blakeslee & Tonry 1996, Table 1), and $\Delta_{Coma\text{-}Virgo}(m - M) = 3.71 \pm 0.10$ mag (see 3.4), and a velocity of the Coma cluster of 7188 km s^{-1} with an assumed uncertainty due to peculiar velocities of ± 250 km s^1 (Lauer and Postman 1994). This leads to $H_0 = 82 \pm 13$ km s^{-1} Mpc^{-1}. For the present we consider this last estimate the most reliable, since a careful study of the peculiar velocity of the Fornax cluster remains to be done. Again, the main uncertainty is the Cepheid distance to the Virgo cluster and the Cephied zeropoint, both of which should improve in the near future.

6. SUMMARY

6.1. Observing strategies

Recent results suggest the following observational strategies might be useful.

a. Observe two bandpasses (*e.g.* V and I) so that possible systematic effects with color (metallicity and age) can be identified and removed (see Ashman, Conti, & Zepf 1995, and Elson & Santiago 1996b).
b. Observe farther toward the infrared (*e.g.* I band) to minimize possible correlations of M^0_V with metallicity (see Ashman, Conti, & Zepf 1995).
c. For HST observations, use dithered exposures to help remove hot pixels and improve spatial resolution.

6.2. Future Work

What are the key observations likely to be over the next five years?

a. The determination of whether the GCLF is different for spiral and elliptical galaxies. The most straightforward approach would be to use HST to observe spirals and ellipticals in tight groups, or possibly in pairs.
b. A better determination of the zeropoint for the GCLF in bright elliptical galaxies using Cepheid variables in the Virgo, Fornax, and other nearby groups and clusters. This will remove the dependence on spiral galaxies where the GCLF is less well defined.
c. A better determination of the appropriate expansion velocity to use for the estimate of the Hubble constant. While the Jerjen & Tammann (1993) approach is promising, it can be improved using the more extensive data currently available. In addition, the same method should be used for the Fornax cluster and other key groups where Cepheid measurements are available (*e.g.* the Leo group).
d. Observations of the GCLF in a sample of bright elliptical galaxies with good sky coverage in the range 2,000 - 10,000 km s^{-1} (with HST) to minimize the dependence on peculiar velocities.

6.3. Conclusions

a. The GCLF for bright ellipticals turns out to be an excellent distance indicator, much better than might be expected based on current theoretical ideas about the formation and destruction of clusters. The intrinsic dispersion in M^0_V is ≃ 0.12 mag.

b. The value of M^0_V appears to be nearly universal. The current database can begin to support the search for possible (small) second-order correlations of M^0_V with various properties (*e.g.* Hubble type, color, environment).
c. Cepheid variables can be used to determine the GCLF zeropoint for bright ellipticals rather than relying on the Milky Way, M31, and an assumption of universality.
d. HST provides an excellent tool for measuring the GCLF, providing limiting magnitudes roughly two to three magnitudes deeper than ground-based observations.
e. The number of high quality GCLFs will increase dramatically in the next decade, making this one of the most important methods of measuring distances.

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