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THE ABUNDANCE DISTRIBUTION AND LUMINOSITY FUNCTION OF GLOBULAR CLUSTERS IN NGC 1399

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ABSTRACT

Integrated Washington photometry has been obtained for the globular cluster system of NGC 1399, the central elliptical galaxy in the Fornax cluster. A new integrated metallicity index, $C-T_1$, is defined which is about 3 times more sensitive to metal abundance than the previous such Washington index. Abundances accurate to 0.3 dex are derived for $\sim$150 of the brightest globular clusters. The clusters have a broad, flattened abundance distribution, with a mean metallicity of [Fe/H] $= -0.85 \pm 0.1$, 0.75 dex more metal-poor than the halo. A significant fraction of the clusters have an approximately solar abundance, while virtually no clusters exist with [Fe/H] < -2.

The luminosity function is also determined for $\sim$600 clusters to a limiting magnitude of $T_1 \sim 23.75$ (50% completeness limit). The luminosity function clearly shows a turnover at $T_1 = 23.0 \pm 0.15$ or $V = 23.45 \pm 0.16$. Matching this luminosity function with that for the globular cluster system of the Galaxy and M87 yields a distance modulus of 31.0 ± 0.25 for Fornax, 0.5 ± 0.2 mag closer than Virgo. A Hubble constant of 66 ± 14 km s^{-1} Mpc^{-1} is derived assuming a canonical value for the Local Group Virgocentric infall velocity. Alternatively, solving for this infall velocity gives a value of 236 km s^{-1}.

Subject headings: abundances — clusters: globular — luminosity function — galaxies: abundances — galaxies: distances

I. INTRODUCTION

Globular cluster systems (GCSs) offer unique opportunities to investigate the oldest stellar components of galaxies. A detailed knowledge of the properties of the GCS of a galaxy can provide important clues to its formation and subsequent chemical and dynamical evolution (e.g., Mayall 1946; van den Bergh 1969; Strom *et al.* 1981, hereafter S81). Abundance information, in particular, is a powerful tool. It can be used, for example, to investigate distinct cluster populations (Zinn 1985) and to search for abundance gradients and differences with the background galaxy light (S81).

Evidence is becoming increasingly favorable for the use of GCSs as accurate distance indicators as well. The recent study by Harris (1988, hereafter H88) is particularly convincing in this regard: he presents the results of an extensive CCD survey of the GCSs associated with four elliptical galaxies in the Virgo Cluster, including the "anomalous" M87 system, and demonstrates that all four luminosity functions (LFs) have the same turnover and the same Gaussian shape. Hanes and Whittaker (1987) have recently argued that one can obtain a distance estimate accurate to 15% using globular cluster LFs, even when the data fail to reach the turnover luminosity by as much as 1 mag.

The NGC 1399 GCS is a particularly interesting one. This galaxy is the central, dominant elliptical galaxy in the Fornax cluster. Such galaxies are found to have the most populous GCSs known (Harris and Smith 1976; Harris, Smith, and Myra 1983). Dawe and Dickens (1976) first detected the NGC 1399 GCS. Hanes and Harris (1986) followed this with a more extensive photographic study, where they showed that the NGC 1399 GCS was indeed very populous, with perhaps the highest specific frequency of any galaxy known. Given its proximity, the NGC 1399 GCS thus provides a very large sample of nearby clusters, comparable to its more famous and better studied northern hemisphere counterpart—M87 in Virgo. Despite these intriguing characteristics, however, a deep CCD study of the NGC 1399 GCS has been lacking. The initial results of such an investigation are presented here.

II. OBSERVATIONS AND REDUCTIONS

NGC 1399 was observed on three nights in 1987 December with the CTIO 4 m RCA No. 1 prime focus CCD system. The nights were of excellent photometric quality. Data were obtained for a $3' \times 5'$ field centered on the galaxy, plus three surrounding galaxy frames and a comparison field located some 2° north of the galaxy. Results are presented here only for the central and comparison fields. The seeing was 1".2 for the central frame from which the LF was derived.

Data were obtained on the Washington photometric system (Canterna 1976). For the central field, exposures totaling 2700 s in C, 1800 s in M, and 3600 s in T_1 were obtained. The Washington system was chosen because of its broad bands and its ability to derive accurate abundances efficiently (Harris and Canterna 1977). Photometry of the stellar images was performed (after first removing the smooth background galaxy light empirically through median filtering) using a version of the DAOPHOT/ALLSTAR program (Stetson 1987) kindly provided by C. Pritchet. The instrumental photometry was then transformed to the standard Washington system by means of aperture photometry derived for 34 standards. The

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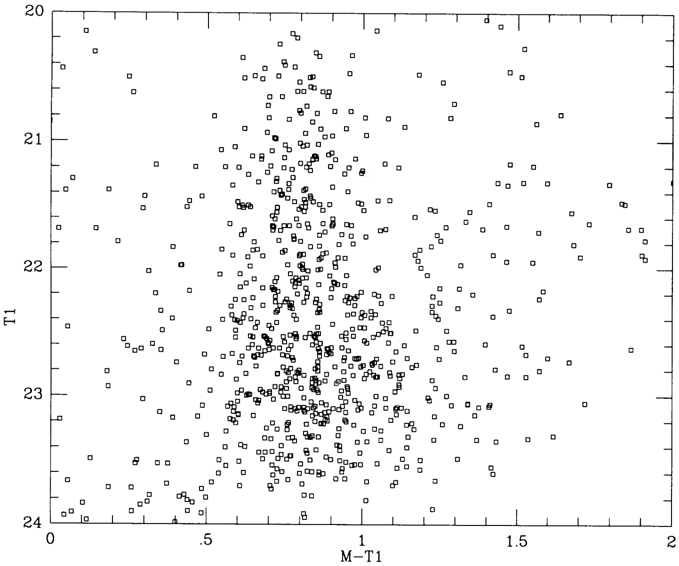

FIG. 1.—T_1 vs. $M-T_1$ color-magnitude diagram for the central NGC 1399 field. Most of the objects at intermediate colors are globular clusters.

rms residuals for the transformation of these standards were 0.027 in $C-M$, 0.008 in $M-T_1$, and 0.013 in T_1.

The T_1 versus $M-T_1$ color-magnitude diagram for the central field is shown in Figure 1. There is a strong enhancement of objects with intermediate colors in the central frame over the comparison field. In particular, there are only four objects in the comparison field with $0.5 < M-T_1 < 1$ and $20 < T_1 < 22$, while 183 are found in the galaxy frame. After background correction, we estimate that ~ 1000 clusters in the central frame alone were detected. Clearly, the NGC 1399 GCS is a very populous one.

In order to investigate the effects of crowding and incompleteness and to determine better the errors (random and systematic) as a function of magnitude, artificial stars were generated with the ADDSTAR routine and photometry obtained for them in exactly the same manner as for the program objects. Twenty stars were added in each of 10 separate trials at a given magnitude, for a variety of magnitudes, ranging from the brightest to the faintest clusters observed.

III. CLUSTER ABUNDANCES

Harris and Canterna (1977) first showed the utility of integrated Washington colors for determining globular cluster abundances. They formed a reddening-free index, Q_{CMT}, analogous to van den Bergh's (1967) Q index for integrated UBV photometry. Hesser and Shawl (1985) found that Q_{CMT} was well correlated with their integrated spectral types for galactic globulars.

However, Q_{CMT} suffers from a rather low abundance sensitivity, varying by only 0.26 mag from the most metal-rich to the most metal-poor Galactic globular clusters. Given this abundance sensitivity, typical errors encountered for the brighter NGC 1399 clusters (~ 0.08 in $C-M$ and $M-T_1$) yield an abundance error of ~ 0.8 dex in Q_{CMT}. This is clearly prohibitive if accurate abundances are desired. In addition, random errors in the M photometry (often the worst) lead to errors in the two color indices, $C-M$ and $M-T_1$, that act in the same sense in the abundance derivation, leading to additive abundance errors for Q_{CMT}, thus increasing the already prohibitive abundance uncertainty.

We thus sought an index which is more metallicity sensitive and in which random photometric error does not lead to correlated abundance errors. Such an index is the $C-T_1$ color. Figure 2 presents our abundance calibration for this new index using the Galactic globular cluster photometry of Harris and Canterna (1977) and the [Fe/H] values and reddenings from Zinn (1985) and Armandroff and Zinn (1988). Except for three clusters (NGC 288, NGC 6522, and NGC 6712—shown in parentheses), a line provides a good fit to all of the data. A least-squares regression yields $[Fe/H] = 2.35(C-T_1)_0 - 4.39$, with a correlation coefficient of 0.95. The 48 clusters have a mean standard deviation of 0.19 dex, only slightly more than expected from the errors in the two quantities. Performing the same calculation for Q_{CMT} gives $[Fe/H] = 6.76Q_{CMT} - 4.43$ with $\sigma = 0.15$.

Thus, $C-T_1$ can measure metallicity to 0.2 dex, only slightly worse than Q_{CMT}, but it is about 3 times more metallicity sensitive. We emphasize, though, that the $C-T_1$ index is not reddening-free. The total reddening $E(C-T_1) = 2.0E(B-V)$. However, $C-T_1$ is the preferred index for measuring abundances of clusters in distant galaxies where the reddening is either well known and/or small and nonvariable across the galaxy, as is the case for NGC 1399 [$E(B-V) \leq 0.03$—Hanes and Harris 1986]. The photometric errors in $C-T_1$ (~ 0.1) now imply an abundance error of only 0.3 dex. The $C-T_1$ index has a total range of 0.84 mag, which compares well with that for other integrated photometric abundance indices, such as Q_{39} (Zinn 1980—total range 0.54 mag) and $U-V$ (Reed, Hesser, and Shawl 1988—total range 0.86 mag).

We have thus used the $C-T_1$ index to derive abundances accurate to 0.3 dex for the clusters in NGC 1399. We selected only bright ($T_1 < 22.3$) clusters with good photometry (σ of any index < 0.2). This also ensures a cluster sample contaminated by stars or galaxies at only the few percent level. The abundance distribution for the selected 145 clusters is displayed in

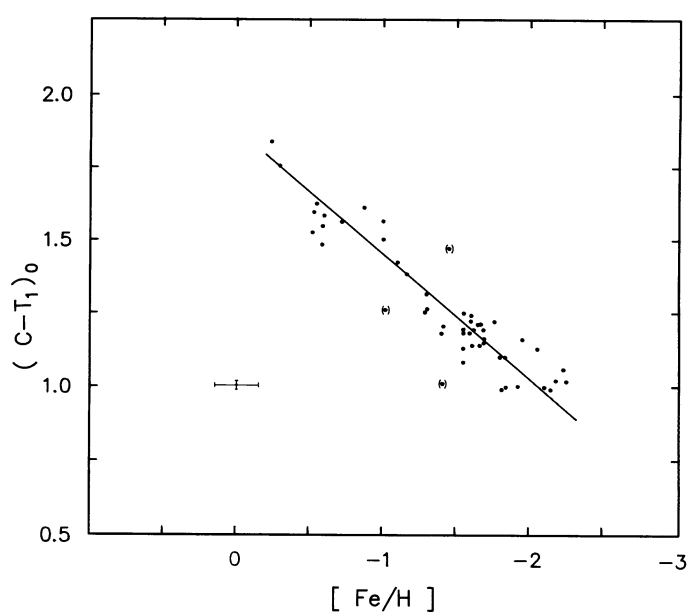

FIG. 2.—Metallicity calibration for the $(C-T_1)_0$ index, using Galactic globular clusters. Note the large range in color.

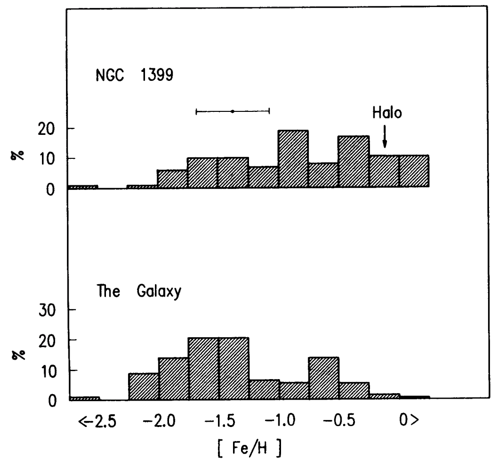

FIG. 3.—Abundance distribution for the globular clusters in NGC 1399 (*above*) and the Galaxy (*below*). The abundance for the NGC 1399 halo is also shown.

Figure 3. This is one of the largest samples of quantitative abundance estimates available for any GCS (note that these results supercede the preliminary analysis presented in Geisler and Forte 1989). For comparison, the distribution for Galactic globulars (121 clusters) using the data of Zinn (1985) and Armandroff and Zinn (1988) is also shown.

In general, the globulars in NGC 1399 cover a range of metallicities similar to those in the Galaxy. However, the shapes of the distributions are quite different. While the Galactic globulars exhibit a bimodal distribution, due to distinct halo and disk subsystems (Zinn 1985), the NGC 1399 distribution is much broader, essentially flat across the whole range of abundances. (Note, however, that the larger abundance errors for the NGC 1399 clusters—0.3 vs. 0.15 dex—would preferentially smooth any peaks.) Second, a greater fraction of the NGC 1399 clusters have abundances near solar. The abundance derived for these clusters is more uncertain, however, as it requires an extrapolation of the calibration. In any case, NGC 1399 does appear likely to contain more metal-rich clusters than does the Galaxy, with the most extreme having [Fe/H] $\sim +0.3$. This also appears to be the case in the two other best studied elliptical galaxies—NGC 5128 (Harris, Harris, and Hesser 1988) and M87 (S81). Third, NGC 1399, like the Galaxy, shows a rather abrupt cutoff at the metal-poor tail. However, this cutoff occurs at a metallicity (~ -2) somewhat higher than that in the Galaxy (~ -2.25).

The mean $(C-T_1)_0$ color of the NGC 1399 globulars is 1.51 ± 0.03 (s.e. of the mean), indicating a mean metallicity of -0.85 ± 0.07. We have also determined the mean colors for the background halo light of the galaxy. We find $(C-T_1)_0 = 1.83 \pm 0.05$, yielding [Fe/H] $= -0.09 \pm 0.12$. Thus, NGC 1399 is similar to M87 and other bright Virgo ellipticals in that the globular clusters are bluer than the halo light at a given radius (S81; Forte, Strom, and Strom 1981; Cohen 1988; Wagner, Richtler, and Hopp 1989). S81 derive a difference in metal abundance of $\sim$0.6 dex between the clusters and the halo light in M87, similar to our value of 0.75 dex for NGC 1399. The mean metal abundance for Milky Way globular clusters is -1.32 ± 0.05 (Armandroff and Zinn 1988). Cohen (1988) finds the median metallicity of M87 globulars to be ~ -0.9 from integrated Gunn photometry, very similar to our value for the NGC 1399 clusters. However, Couture, Harris, and Allwright (1990) find a mean metallicity of -1.1 ± 0.25 for M87 globulars, and Wagner, Richtler, and Hopp (1989) conclude that the NGC 1399 clusters are significantly redder ($\sim$0.1 in the mean in $B-V$) than their M87 counterparts.

IV. THE LUMINOSITY FUNCTION

The first step in deriving a LF is to simply count the number of objects in Figure 1 within different magnitude bins. In order to ensure the purest cluster sample, only objects with intermediate colors were included. Note that the limit of the photometry is $T_1 \sim 23.8$. For a typical globular cluster, this is equivalent to $V \sim 24.3$ or $B \sim 25$.

This raw LF must first be corrected for any systematic errors in the photometry, as well as incompleteness, as determined from the ADDSTAR experiments. Finally, the number of background objects must be subtracted. Our results show that these effects are all only a few percent at $T_1 \sim 23$ (the turnover magnitude that we derive—see below) but become increasingly significant as the limiting magnitude is approached.

Figure 4 shows the corrected LF for the NGC 1399 globular clusters. The total sample size is $\sim$600. *A clear turnover near* $T_1 = 23$ *exists and has been surpassed by about 3/4 of a magnitude* before the 50% completeness limit ($T_1 \sim 23.75$) is reached. A Gaussian with $\sigma = 1.2$ (indicated by our data) and peak magnitude = 23.0 provides a reasonable fit to the LF. We note that independent *BV* data by Bridges, Hanes, and Harris (1990) confirm this turnover.

We can now derive the distance to NGC 1399 and the Fornax cluster by fitting the LF to that of a GCS whose distance is known. The assumptions and advantages of this method, as well as convincing support, are presented by H88. We will first use the Galaxy as the comparison GCS. However, we will use the latest value for $(M_V)_{\rm peak}$ of -7.50 ± 0.13 derived by Armandroff (1989) for Galactic globulars, slightly different from Harris's value of -7.6.

The peak magnitude we derive for the NGC 1399 GCS is $T_1 = 23.0 \pm 0.15$ or $V = 23.45 \pm 0.16$. Assuming a reddening $E(B-V)$ of 0.03 (Hanes and Harris 1986), the true distance modulus is $(m-M)_0 = 30.85 \pm 0.22$ or 14.8 ± 1.6 Mpc. Note that the formal error is only about 10%. However, the possible errors associated with matching the GCSs of a relatively isolated spiral and a giant ellipical galaxy at the center of a large cluster of galaxies are difficult to assess.

One would expect a more reasonable comparison to be obtained between the globular cluster LFs of NGC 1399 and

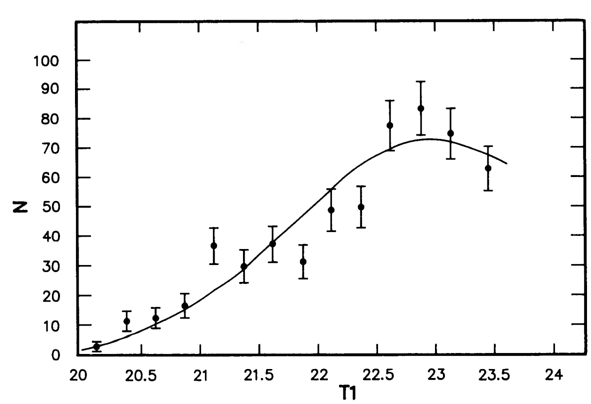

FIG. 4.—The T_1 luminosity function for NGC 1399 globular clusters. The data have been corrected for systematic photometric errors, incompleteness, and background contamination. Root N error bars are shown. The curve is a Gaussian with peak magnitude = 23.0 and $\sigma = 1.2$.

M87, given their very similar luminosities, galactic environments, globular cluster specific frequencies, and possibly even detailed GCS abundance distributions. A relative Fornax-Virgo distance based on globular cluster LFs should minimize any systematic errors in this method. By normalizing our LF to that of H88 for the composite LF of four Virgo ellipticals (including M87, whose LF is very similar to those for the other three galaxies), we find an excellent match between the LFs if Fornax is 0.5 ± 0.2 mag closer in distance modulus. This relative Fornax-Virgo distance is in good agreement with that of Bothun, Caldwell, and Schombert (1989) and Bridges, Hanes, and Harris (1990). However, Dressler *et al.* (1987) and Pierce (1989) find the two clusters to be at virtually the same distance. Using Harris's distance of 31.6 ± 0.22 for Virgo then gives $(m - M)_0 = 31.1 \pm 0.3$ for Fornax. We will take the mean of these two (somewhat) independent determinations and adopt $(m - M)_0 = 31.0 \pm 0.25$ for Fornax, or 15.8 ± 2 Mpc.

Given the distance to the Fornax cluster and its radial velocity (1261 ± 50 km s^{-1}—Dressler *et al.* 1987), we can immediately solve for the Hubble constant, after correcting for the total motion of the Local Group toward the Virgo Cluster (331 ± 41 km s^{-1}—Aaronson *et al.* 1982). A value of 66 ± 14 km s^{-1} Mpc^{-1} is obtained, in good agreement with the value of 64 ± 7 which H88 derives from the GCSs in Virgo [corrected to $(M_V)_{\rm peak} = -7.5$]. Alternatively, we can derive the Virgocentric infall velocity of the Local Group by using Harris's distance to Virgo of 20.9 Mpc and assuming that Fornax does not participate in this flow. We find 236 km s^{-1} for the pattern infall velocity (corrected for a random motion of 81 km s^{-1}—Aaronson, *et al.* 1982). This agrees well with most previous values, e.g., the Aaronson *et al.* value (250 ± 64 km s^{-1}) and that of van den Bergh (1981—252 km s^{-1}).

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REFERENCES

Aaronson, M., Huchra, J., Mould, J., Schechter, P. L., and Tully, R. B. 1982, *Ap. J.*, **258**, 64.
Armandroff, T. E. 1989, *A.J.*, **97**, 375.
Armandroff, T. E., and Zinn, R. 1988, *A.J.*, **96**, 92.
Bothun, G. D., Caldwell, N., and Schombert, J. M. 1989, *A.J.*, **98**, 1542.
Bridges, T., Hanes, D. A., and Harris, W. E. 1990, in preparation.
Canterna, R. 1976, *A.J.*, **81**, 228.
Cohen, J. G. 1988, *A.J.*, **95**, 682.
Couture, J., Harris, W. E., and Allwright, J. W. B. 1990, preprint.
Dawe, J. A., and Dickens, R. J. 1976, *Nature*, **263**, 395.
Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R., Faber, S., Terlevich, R., and Wegner, G. 1987, *Ap. J.*, **313**, 42.
Forte, J. C., Strom, S. E., and Strom, K. M. 1981, *Ap. J. (Letters)*, **245**, L9.
Geisler, D., and Forte, J. C. 1989, *Rev. Mexicana Astr. Af.*, in press.
Hanes, D. A., and Harris, W. E. 1986, *Ap. J.*, **309**, 564.
Hanes, D. A., and Whittaker, D. G. 1987, *A.J.*, **94**, 906.
Harris, H. C., and Canterna, R. 1977, *A.J.*, **82**, 798.
Harris, H. C., Harris, G. L. H., and Hesser, J. E. 1988, in *IAU Symposium 126, Globular Cluster Systems in Galaxies*, ed. J. E. Grindlay and A. G. D. Philip (Dordrecht: Kluwer), p. 205.
Harris, W. E. 1988, in *The Extragalactic Distance Scale* (A.S.P. Conf. Series, Vol. 4), ed. S. van den Bergh and C. J. Pritchet (New York: ASP), p. 231 (H88).
Harris, W. E., and Smith, M. G. 1976, *Ap. J.*, **207**, 1036.
Harris, W. E., Smith, M. G., and Myra, E. S. 1983, *Ap. J.*, **272**, 456.
Hesser, J. E., and Shawl, S. J. 1985, *Pub. A.S.P.*, **97**, 465.
Mayall, N. U. 1946, *Ap. J.*, **104**, 290.
Pierce, M. J. 1989, *Ap. J. (Letters)*, **344**, L57.
Reed, B. C., Hesser, J. E., and Shawl, S. J. 1988, *Pub. A.S.P.*, **100**, 545.
Stetson, P. B. 1987, *Pub. A.S.P.*, **99**, 191.
Strom, S. E., Forte, J. C., Harris, W. E. Strom, K. M., Wells, D. C., and Smith, M. G. 1981, *Ap. J.*, **245**, 416 (S81).
van den Bergh, S. 1967, *A.J.*, **72**, 70.
———. 1969, *Ap. J. Suppl.*, **19**, 145.
———. 1981, *Science*, **213**, 825.
Wagner, S., Richtler, T., and Hopp, U. 1989, preprint.
Zinn, R. 1980, *Ap. J. Suppl.*, **42**, 19.
———. 1985, *Ap. J.*, **293**, 424.

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