THE SPECIFIC GLOBULAR CLUSTER FREQUENCIES OF DWARF ELLIPTICAL GALAXIES FROM THE HUBBLE SPACE TELESCOPE

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ABSTRACT

The specific globular cluster frequencies (SN) for 24 dwarf elliptical (dE) galaxies in the Virgo and Fornax Clusters and the Leo Group that were imaged with the Hubble Space Telescope are presented. Combining all available data, we find that for nucleated dE (dE, N) galaxies, which are spatially distributed like giant elliptical galaxies in galaxy clusters, SN(dE, N) = 6.5 ± 1.2 and SN increases with Mv, while for nonnucleated dE (dE, noN) galaxies, which are distributed like late-type galaxies, SN(dE, noN) = 3.1 ± 0.5 and there is little or no trend with Mv. Thus, the SN values for dE galaxies are, on average, significantly higher than those for late-type galaxies, which have SN ≤ 1. This suggests that dE galaxies are more akin to giant elliptical galaxies than to late-type galaxies. If there are dormant or stripped irregular galaxies hiding among the dE population, they are likely to be among the nonnucleated dE galaxies. Furthermore, the similarities in the properties of the globular clusters (GCs) and in the spatial distributions of dE, N galaxies and giant elliptical galaxies suggest that neither galaxy mass nor galaxy metallicity is responsible for the high values of SN. Instead, most metal-poor GCs may have formed in dwarf-sized fragments that merged into larger galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: nuclei — galaxies: star clusters

1. INTRODUCTION

There are several distinct classes of galaxies with smooth surface brightness profiles and absolute magnitudes fainter than Mv = −18. Brighter than Mv = −15, most dwarf elliptical (dE) galaxies have central nuclei that are unresolved from the ground at the distance of the Virgo Cluster. However, there are quite a few dE galaxies in this luminosity range that have no sign of a nucleus. Within the Virgo and Fornax Clusters, the nonnucleated dE (dE, noN) galaxies form an extended population, with a spatial distribution similar to the spiral and irregular galaxies rather than to the bright elliptical galaxies and the rest of the dE galaxies (Ferguson & Sandage 1989). A possible explanation for the difference is that the nonnucleated dE galaxies are stripped or harassed dwarf irregular (dI) galaxies (see, e.g., Lin & Faber 1983 and Moore, Lake, & Katz 1998). The most popular alternative scenario for dE formation (see, e.g., Dekel & Silk 1986) is that they formed in one monolithic collapse and subsequently ejected their interstellar medium via supernova winds. To distinguish these scenarios, we require an observational probe of the earliest and most important episodes of star formation in dwarf galaxies. Globular cluster (GC) systems may provide such a probe.

The specific globular cluster frequency (SN), the number of clusters normalized to a galaxy with Mv = −15, is correlated with Hubble type such that it increases from late-type spiral galaxies to early-type spiral and elliptical galaxies, suggesting a correlation with the size of the bulge component (Harris 1991a). The empirical variation of SN from early to late types suggests a simple test for whether dE galaxies are more closely related to giant elliptical (E) galaxies or to irregular galaxies (Harris 1991b). If part of the E family, they should have SN ~ 2–5; if part of the late-type disk galaxy family, we expect SN ≤ 1. Finally, one might expect that nucleated dE (dE, N) galaxies will have higher values of SN than nonnucleated dE galaxies do.

We have begun a Hubble Space Telescope (HST) snapshot survey in order to study the properties of the GCs and nuclei of dE galaxies. In this Letter, we present results on SN for 24 galaxies in the Virgo and Fornax Clusters and the Leo Group. Table 1 lists the galaxies’ names and morphological types from photographic catalogs. This sample represents all the data suitable for determining SN that was taken during HST cycle 6. We assume distance moduli of 31.2 for the Virgo Cluster, 31.4 for the Fornax Cluster, and 30.3 for the Leo Group. When presenting an uncertainty of an average quantity, we quote the standard deviation of the mean. The observations and analysis are summarized in § 2. We present the results of the specific frequencies in § 3 and discuss some implications in § 4. The data will be more fully presented in Miller et al. (1998, hereafter Paper II).

2. OBSERVATIONS AND DATA REDUCTION

Wide Field Planetary Camera 2 (WFPC2) snapshot images are taken in the F555W (2 × 230 s) and F814W (300 s) bands passes with the galaxies centered on chip WF3. The procedures for object detection and classification, aperture photometry, and photometric calibration are similar to those used by Miller et al. (1997). From these data, we can determine the (V − I) colors of GC candidates down to a completeness limit of V ≈ 25.

The specific globular cluster frequency, SN, is defined as SN = Nc × 100.4(Mv−15), where Nc is the total number of clusters (Harris & van den Bergh 1981). Cluster candidates are selected based on color (0.5 < V − I < 1.5), size (FWHM < 2.5 pixels), and accuracy of photometry [err (V − I) < 0.3 mag]. The net number of cluster candidates for a galaxy, Nc, is the total number of cluster candidates in WF3 minus the expected number of background and foreground objects. The number density of

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background objects is determined from the objects in WF2 and WF4. We must also correct for undetected faint clusters. The luminosity function (LF) of all the cluster candidates is consistent with a Gaussian with $M_V^{\text{avg}} \approx -7.3$ and $\sigma \approx 1.0$. Tests then show that we are detecting 85%–90% of the clusters in Virgo and Fornax (down to $M_V \approx -6$) and ~98% in Leo (down to $M_V \approx -5$). Therefore, we multiply the number of detected GCs for Virgo and Fornax galaxies by 1.15 to correct for this incompleteness.

We also measure the corresponding galaxy luminosity in WF3. After sky subtraction, most point sources and resolved background galaxies are removed from the image. The only cluster candidates that are not excised are the nuclei with $M_V < -10.5$ (see below). Then the total counts remaining in the image are summed and corrected for foreground extinction in order to determine $M_V^\circ$. Uncertainties range between 0.1 mag for the brightest systems to ~0.4 mag for the faintest.

An important problem is the classification of galaxies into nucleated and nonnucleated samples. Our first criterion for classifying nuclei is the projected radial distance, $R_{\text{proj}}$, from the galaxy center as defined by the centroid of the light distribution after removing any central pointlike sources. The uncertainties in the central coordinates are determined by measuring centroids with a range of centering-box widths. These uncertainties yield the offsets of the central objects from the centers measured in standard deviations, $\sigma_{\text{proj}}$. As a further test, we have used Monte Carlo simulations to compute the probability, $P$, that an object as bright as the central cluster candidate would be found within $R_{\text{proj}}$ of the center by chance. In each trial for a given galaxy, $N_c$ artificial clusters are drawn from a Gaussian luminosity function and are given the same exponential radial distribution as measured for that galaxy. Many trials are run to reduce uncertainties due to small numbers. We classify a galaxy as nucleated if the centermost cluster candidate is within $3\sigma_{\text{proj}}$ of the galaxy center and $P \leq 1\%$.

In most cases, the nucleus turns out to be the most luminous GC, but in a few galaxies, it is significantly brighter than the typical GC. With $M_V \lesssim -10.5$, these “clusters” are brighter than any globular cluster in the Galaxy or M31 and comparable to the brightest in M87 (Djorgovski 1993; Battisti et al. 1987; Whitmore et al. 1995). These objects may be more like true nuclei. It is unclear whether nuclei of large galaxies are kinematically and structurally distinct from star clusters or whether they are simply giant versions of the latter (Kormendy & McClure 1993; Carollo et al. 1997). To be conservative, we have chosen not to count nuclei with $M_V < -10.5$ as clusters for the purposes of calculating $S_N^\circ$.

### 3. RESULTS

Table 1 lists our measured values of $M_V^\circ$, $N_c$ (corrected for the faint end of the LF), $S_N^\circ$, $R_{\text{proj}}^\circ$, $\sigma_{\text{proj}}$, by which $R_{\text{proj}}$ differs from the galaxy center, and the probability $P$ of finding the centermost cluster candidate within $R_{\text{proj}}$ by chance for 24 dE galaxies. The galaxies have been split into nucleated and nonnucleated categories based on the criteria mentioned above. In two cases, our classification differs from the ground-based classification. FCC 324 was originally in our nonnucleated sample, but we find that it is nucleated. VCC 9 has a catalog type of dE1N. Its most luminous cluster is close to the center, but with $R_{\text{proj}} = 155$ pc, it is too offset to meet our criteria for being nucleated. Two other galaxies may be intermediate types. VCC 1577 and FCC 48 have their most luminous GC within $3\sigma$ of their centers, but these galaxies do not fulfill the probability test. The central regions of VCC 9 and VCC 1577 are shown in Figure 1.
We have one galaxy, VCC 1254, in common with the ground-based study of Durrell et al. (1996). Adjusting their value to our distance modulus yields $S_N = 6.4 \pm 3.0$. Our result from Table 1 is $S_N = 6.2 \pm 2.2$ and agrees very well with their measurement. Therefore, our method appears reliable.

Figure 2 shows $\log S_N$ versus $M_V$ for all dE galaxies with measured $S_N$. In the figure, galaxies with $S_N = 0$ have been assigned $\log S_N = 0.0$. There is a clear trend of increasing $S_N$ with decreasing galaxy luminosity for the nucleated galaxies (filled symbols). A weighted least-squares fit to the nucleated galaxies with $M_V < -13.5$ gives a slope of $0.24 \pm 0.04$ (solid line). The nonnucleated galaxies (open and half-filled symbols) do not show such a trend; a fit to these points gives a slope of $0.10 \pm 0.05$ (dashed line). The trend for the nucleated galaxies was seen by Durrell et al. (1996), but our larger sample now indicates that there is a difference in $S_N$ between nucleated and nonnucleated dE galaxies.

At magnitudes fainter than $M_V = -14$, the large fluctuations in $S_N$ caused by small number statistics may blur the distinction between nucleated and nonnucleated galaxies. An extension of the fit to the nucleated galaxies in Figure 2 passes through the points for both the Fornax and Sagittarius dwarfs, the dE galaxies with the highest measured $S_N$. Even though the total extent of Sagittarius is uncertain because of tidal disruption by the Galaxy, M54 is generally thought to be its nucleus (Sarajedini & Layden 1995). Fornax is usually considered nonnucleated, but it has a high $S_N$ like the other dE, N galaxies and a metal-rich GC only $\sim 150$ pc from its center. The triangle labeled “LG dSph” represents the $\sim 12$ nonnucleated Local Group dwarf spheroidals with $S_N = 0$. For now, it may be best to think of the dE, N galaxies as defining the upper envelope to the trend of increasing $S_N$ with $M_V$.

4. DISCUSSION

High-resolution HST images of a large sample of dE galaxies provide an improved estimate of their specific globular cluster frequency and an indication that $S_N$ depends on galaxy type and luminosity. We confirm earlier ground-based estimates of a high $S_N$ for dE galaxies (Durrell et al. 1996). Adjusted to our distances, their sample of nine dE, N and three dE, noN galaxies gives an unweighted mean of $S_N = 5.1 \pm 1.0$. For comparison, our sample gives $5.3 \pm 1.1$. These values are consistent and are significantly higher than the mean for late-type galaxies of $S_N = 0.5 \pm 0.2$ (Harris 1991a). In addition, we find that for our sample, $S_N$(dE, N) = $7.5 \pm 1.8$ and $S_N$(dE, noN) = $2.8 \pm 0.7$. The difference in $S_N$ between dE, N and dE, noN galaxies in Durrell et al.’s sample is much less apparent, probably because of the smaller sample size. The combined sample
with $M_V < -13.5$ shown in Figure 2 yields $S_{\mu}$ (dE, N) = 6.5 ± 1.2 and $S_{\mu}$ (dE, noN) = 3.1 ± 0.5; the $S_{\mu}$ for nucleated dE galaxies is a factor of 2 higher than for nonnucleated dE galaxies.

This result is a further argument against the formation of dE galaxies as a class via the quiescent evolution of dI galaxies. The statistics of $S_{\mu}$ in dI galaxies are not very good, but typical values appear to be around $S_{\mu} = 0.5$ (Harris 1991a). The simple removal of gas from a dI galaxy would result in modest fading. For example, let us consider a galaxy that forms stars at a constant rate for 5 Gyr, whereupon it is stripped of gas and ceases forming stars. In the 5 Gyr after star formation ends, the galaxy fades by ~1.5 mag in $V$. So, if it started with $S_{\mu} = 0.5$, it would end up with $S_{\mu} \approx 2.0$, which is at the low end of the observed range for the dE galaxies. A longer period of fading would result in higher $S_{\mu}$, but the resulting surface brightness would tend to be fainter than measured in bright dE, N galaxies. Similarly, a model in which dE galaxies in general represent the quiescent periods between stochastic bursts of star formation in dI galaxies (Tyson & Scalo 1988) appears inconsistent with the high average value of $S_{\mu}$ measured for dE galaxies. The conclusion is that most bright dE galaxies, and the dE, N galaxies in particular, are not simply faded or dormant dI galaxies.

The low mean $S_{\mu}$ among nonnucleated dE galaxies suggests that any faded dI galaxies that exist in the cluster populations are likely part of this class. A number of the dE, noN galaxies in our sample have $S_{\mu} < 1$, which is consistent with the values measured in dI galaxies. Also, our calculation above shows that faded dI galaxies would have $S_{\mu}$ close to the mean $S_{\mu}$ that we measure for the dE, noN class. A further argument in favor of this possibility is the observation that the nonnucleated dE galaxies brighter than $M_V = -14$ have an extended spatial distribution in the Virgo and Fornax Clusters that is like the spatial distribution of spiral and irregular galaxies. It would be interesting to search for evidence of gas either in or around some of the brighter nonnucleated dE galaxies in these clusters. Also, stripped dI galaxies may still exhibit rotation.

The colors and luminosity functions of the GCs in dE galaxies are also similar to the old, metal-poor GC populations in giant elliptical galaxies (Paper II). Therefore, GCs in both giant E and dE galaxies seem to have formed at similar times, with the same metallicities and with the same efficiencies. It is not obvious why this should be so. The velocity dispersions of typical giant elliptical galaxies are more than 250 km s$^{-1}$, while for dE galaxies typical velocity dispersions are likely to be less than 100 km s$^{-1}$ (Bender & Nieto 1990). Thus, it appears that galaxy velocity dispersion (and thus potential well depth) is not a key parameter. In addition, the metallicities of our dE galaxies, if adequately represented by their colors, are probably less than half solar, while the metallicities for many giant elliptical galaxies exceed solar. Thus, the current metallicity of the galaxy also does not seem to play an important role in driving $S_{\mu}$. How can such similar GCs form in such different parent galaxies?

This can be explained if most GCs are formed in dwarf galaxy–sized “fragments” that later merge into giant elliptical galaxies (Searle & Zinn 1978; Harris & Pudritz 1994). The fact that E galaxies and dE, N galaxies inhabit the densest regions of clusters suggests that the cluster environment is somehow important for GC formation, for example, through stronger interactions, higher external pressures, or higher star formation rates during the epoch of cluster formation (McLaughlin & Pudritz 1996; Elmegreen & Efremov 1997; Harris, Harris, & McLaughlin 1998). These environments would also be prone to the most merging. Additional evidence for this type of scenario is the accretion of the GCs from the Sagittarius dwarf into the halo of the Galaxy. Thus, accretion of GC-rich dwarfs may be a natural explanation for the metal-poor GCs in giant elliptical and spiral galaxies.

Turning to the trend with luminosity, our data suggests that, at least among nucleated dE galaxies, less luminous galaxies have higher $S_{\mu}$. We have investigated several possible explanations for this phenomenon. First, winds may be more efficient at quenching star formation in the lower luminosity dE galaxies. Second, many of the original clusters may have merged into the bright nucleus. A $10^6 M_{\odot}$ cluster moving at 50 km s$^{-1}$ through an isothermal halo will decay from a radius of 3 kpc in less than a Hubble time (Binney & Tremaine 1987). We have calculated that $S_{\mu}$ could decrease by a factor of about 1.5 if the nuclei brighter than $M_V = -10.5$ are merged GCs. However, these nuclei do not appear to be simple conglomerates of GCs. They are on average 0.06 ± 0.02 mag redder in $(V-I)$ than the mean color of the GCs in those galaxies. If this is due to metallicity (Couture, Harris, & Allwright 1990), then the nuclei are about 0.3 dex more metal rich than the GCs. Thus, additional nuclear star formation, perhaps as a result of interactions, may have occurred (also see Durrell et al. 1996).

In summary, we have confirmed earlier estimates of a high globular cluster specific frequency in dE galaxies in nearby clusters of galaxies. Furthermore, we have shown evidence for a difference in $S_{\mu}$ between nucleated and nonnucleated dE galaxies and for a trend in $S_{\mu}$ with luminosity (at least for the dE, N galaxies). The results reinforce the status of dE, N galaxies as the likely low-luminosity tail of the giant E galaxy sequence and suggest that the processes that formed both types of galaxies were related and probably influenced by the cluster environment. The present trends with luminosity and type are tentative and must be confirmed with larger samples. Fortunately, these are relatively inexpensive observations to make with the HST, and we are engaged in an extension of the survey that will observe up to 30 more faint dE galaxies and up to 30 dI galaxies in order to improve the statistical comparisons.

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