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ON THE ORIGIN OF GLOBULAR CLUSTERS IN ELLIPTICAL GALAXIES

S. DJORGOVSKI[1] AND BASILIO X. SANTIAGO[2]
Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125
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ABSTRACT

We correlate the estimated total numbers of globular clusters in elliptical galaxies (N_{gc}), and the numbers per unit luminosity (S_N), with a variety of observed properties of the host galaxies, using multivariate statistical analysis. The number of globular clusters scales roughly as L_{bol}^2, and the 3/2 power of dynamical mass: bigger galaxies were more efficient in producing globular clusters. Both N_{gc} and S_N are correlated with the so-called fundamental plane of elliptical galaxies, suggesting that the processes which determine global properties of ellipticals also largely determine their globular cluster content, although a considerable residual scatter remains. We find that the redder (presumably more metal-rich) galaxies tend to have more globular clusters, implying that a dissipative formation mechanism was involved. We also find that galaxies which have more anisotropic velocity distributions tend to have more clusters, suggesting that mergers may have been important in the production of globular clusters. The data are consistent with the picture of formation of ellipticals and their globular cluster systems primarly through dissipative merging, much of which may have happened at the early epochs.

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

1. INTRODUCTION: DATA AND METHODS

Globular clusters are among the oldest known objects in the universe, interesting both in their own right, and as fossils of galaxy formation. Excellent reviews of the subject of globular cluster *systems* were given by Harris (1988, 1991). The purpose of this study was to investigate the correlations between the estimated total numbers of clusters N_{gc} and their number per unit luminosity S_N with a variety of properties of their host galaxies. To date, only the simplest monovariate correlations have been explored, for example, with the visual luminosity. Much more can be done with the available data on elliptical galaxies and multivariate statistical analysis techniques. We consider elliptical galaxies only, including a couple of S0 galaxies; we deliberately exclude gas-rich and low surface brightness dwarf galaxies. This leaves us with a relatively homogeneous family of objects. Our procedures and results will be documented in detail in a full paper to follow (Santiago & Djorgovski 1992). Here we summarize and discuss our principal results.

We used the data on N_{gc} and S_N for elliptical galaxies, as compiled by Harris (1991); logs of these quantities are used in the correlations (our N_{gc} is Harris's N_{tot}). We selected only the galaxies with error bars smaller than 50% in N_{gc} and S_N, for which we also have adequate data on galaxy properties, leaving us with a sample of 24 objects (the results do not change substantially if we retain galaxies with larger error bars in N_{gc} and S_N). We use modern data on elliptical galaxies from several sources. The effective radii R_e, absolute magnitudes M_e, and mean surface brightness $\langle\mu\rangle_e$ are from Faber et al. (1989, hereafter 7S), and from a recently recalibrated version of the data by Djorgovski & Davis (1987); the results for the two samples agree very well. Multicolor photometry is from Persson, Frogel, & Aaronson (1979) and de Vaucouleurs et al. (1991, hereafter RC3). The central velocity dispersions σ and Mg_2 line strength index are from 7S. Several quantities related to the velocity anisotropy include normalized ratios of the rotational speed and velocity dispersion $(V_m/\sigma)^*$ from a compilation maintained by one of us (SD); isophotal shape parameter a_4/a from Bender et al. (1989); ellipticity gradients $\nabla\epsilon$ and isophotal twist rates $\nabla\Theta = \log(\Delta PA/\Delta \log r)$ derived from the surface photometry by Djorgovski (1985); and X-ray luminosities from Canizares, Fabbiano, & Trinchieri (1987).

This abundance of data calls for statistical methods which go beyond the simplest monovariate regression techniques. Multivariate techniques have been used very profitably in studies of systematics of galaxy properties (cf. the reviews by Djorgovski & de Carvalho 1990a; Djorgovski 1992a, b, and references therein). Many of the global properties of elliptical galaxies are correlated in a statistically two-dimensional manifold, the so-called fundamental plane (FP). The set of bivariate correlations implied by the FP contains valuable information about the formation of elliptical galaxies. To the best of our knowledge, properties of their globular cluster systems have never been examined in this context.

We use principal component analysis (PCA; see Murtagh & Heck 1987), and multivariate fits which optimize Pearson and Spearman correlation coefficients, r and s, for example, by searching for optimal combinations of two or three galaxy properties which correlate with N_{gc} or S_N. We generally avoid least-squares fits, since the error bars are not always well known. The selection effects in this sample are also poorly understood, and error bars for N_{gc} and S_N (and sometimes other quantities as well) are often quite large. Thus, this study should be regarded only as exploratory, and the results primarily as qualitative.

2. SUMMARY OF THE RESULTS

We performed least-squares power-law fits to N_{gc} as a function of luminosity in different optical and IR bands, U through K. There is no significant trend with the wavelength, fits ranging from $N_{gc} \sim L_U^{2.4\pm0.4}$ to $N_{gc} \sim L_K^{2.2\pm0.4}$. The nonlinearity of these correlations implies directly that the efficiency of globular cluster formation varies systematically among the

[1] Presidential Young Investigator.
[2] CNPq Fellow, on leave from Observatorio Nacional, Brazil.

elliptical galaxies. Assuming that the bolometric corrections are smaller in the IR, the data are consistent with the relation $N_{gc} \sim L_{bol}^2$. Shallower and noisier dependences found in some of the previous studies are probably due to the fact that usually the low surface brightness galaxies (a fundamentally different family of objects), and sometimes disk galaxies as well, were mixed in with the true ellipticals. We also do not see any "excess" of globular clusters around brightest cluster galaxies such as M87: they are simply near the high-luminosity end of this nonlinear correlation. A bivariate combination of R_e and σ which optimizes the correlation coefficients is log R_e + 2.17 log σ, which is within the errors equal to the virial mass, M_{vir} = const. × $R_e \sigma^2$. Our best fit gives the scaling $N_{gc} \sim M_{vir}^{1.4 \pm 0.2}$. The implied dependence of (M/L) on the mass for elliptical galaxies is consistent with that found by Faber et al. (1987) and Djorgovski (1988) from the analysis of the FP.

Figure 1 (top row) illustrates some of the simple monovariate correlations: the previously known correlations of N_{gc} with the optical luminosity, and the correlations with the $(V-K)$ color, which is a good measure of metallicity, and the $(V_m/\sigma)^*$ anisotropy parameter. We already see that redder (more metal-rich) and more anisotropic galaxies tend to have more clusters. The correlations with N_{gc} are generally better than those with S_N, partly because the more luminous galaxies have more clusters, and because many quantities, for example, $(V-K)$ and $(V_m/\sigma)^*$, correlate with the luminosity. Furthermore, the true errors in S_N should be larger, since they include both the errors of N_{gc} and of the luminosity, thus resulting in a larger scatter. However, this is not all, as revealed by the multivariate analysis.

We computed PCA solutions using different subsets of the data, but always including N_{gc}, S_N, and the basic FP variables, R_e, M_e, $\langle\mu\rangle_e$, and σ, and sometimes other quantities. We recover the old result that the FP variables define a statistically two-dimensional set; however, when N_{gc} and S_N are included, a third data dimension appears. When the metallicity-sensitive

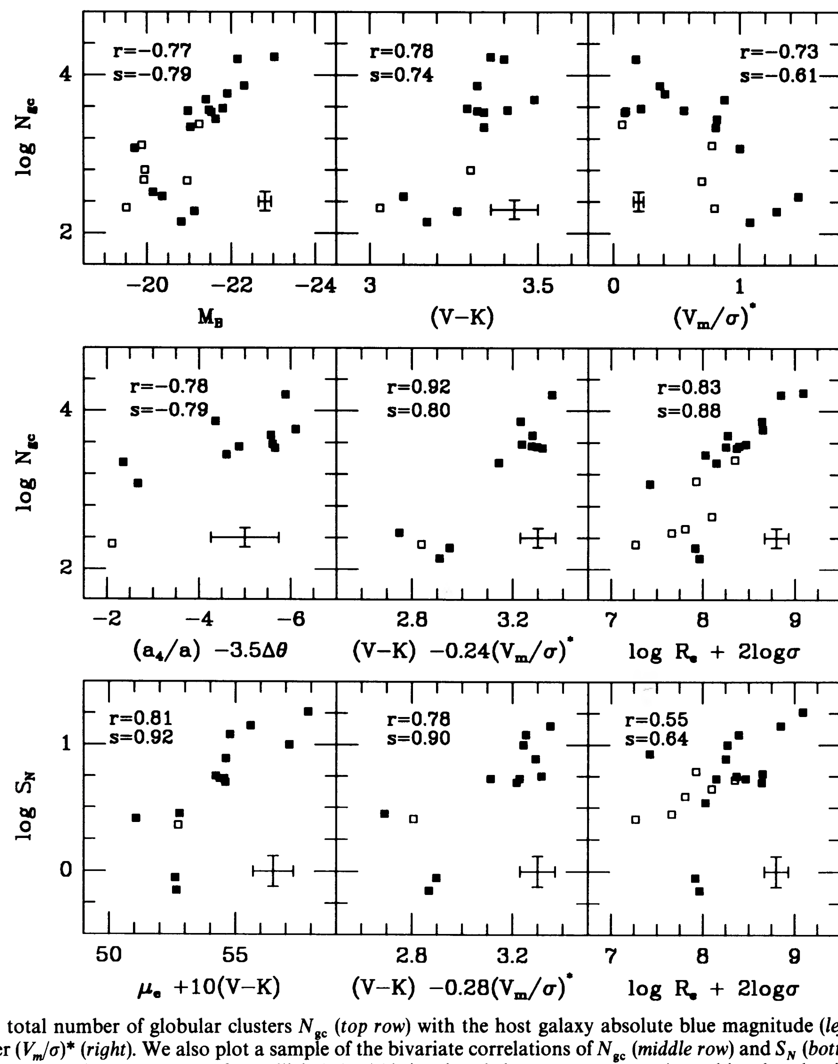

FIG. 1.—Correlations of the total number of globular clusters N_{gc} (*top row*) with the host galaxy absolute blue magnitude (*left*), $(V-K)$ color (*middle*) and the dynamical anisotropy parameter $(V_m/\sigma)^*$ (*right*). We also plot a sample of the bivariate correlations of N_{gc} (*middle row*) and S_N (*bottom row*) with combinations of the mean surface brightness $\langle\mu\rangle_e$, $(V-K)$ color (a measure of metallicity), $(V_m/\sigma)^*$, isophotal shape parameter a_4/a, and isophotal twist rate $\nabla\Theta$. Galaxies with a lower surface brightness, higher metallicity, higher pressure support, boxy isophotes, and larger isophote twists tend to have more globular clusters. The panels on the right show the correlations with the combination of effective radius E_e and central velocity dispersion σ, which should be directly proportional to the dynamical mass for a homologous family of objects. The two discrepant points with a low S_N are NGC 1404 and NGC 1549; when they are omitted from the fits, the correlation coefficients increase typically by several hundredths. Estimated median error bars are shown in each panel, along with the Pearson (r) and Spearman rank (s) correlation coefficients. Galaxies in clusters are plotted as solid squares, and galaxies in poor groups as open squares.

colors, such as $(V-K)$ or $(U-V)$, are added to the FP variables, a weak third dimension also appears (the color data vectors are nearly, but note quite contained in the FP). Some of the residual spread in N_{gc} and S_N can be accounted by their projection to this third axis. It is also known that the parameters which reflect dynamical anisotropies do not correlate well with the FP (Djorgovski 1987). Introducing, for example, $(V_m/\sigma)^*$ to the PCA, also increases the dimensionality of the data set, and again N_{gc} and S_N contain components which project to this axis. In short, much of the dynamical range of the N_{gc} and S_N data vectors is given by their projections in the FP, suggesting that whatever processes determine the global properties of ellipticals as parameterized by the FP variables also largely determine the abundance of globular clusters in them. The remaining spread in N_{gc} and S_N appears to be related to the measures of metallicity and/or velocity anisotropy.

Using the PCA results as a guide, we evaluate a number of bivariate and trivariate solutions, in which N_{gc} or S_N is correlated with a combination of two or three galaxy properties. A number of interesting correlations were found, some of which are illustrated in Figure 1. A consistent picture appears: galaxies with redder colors (i.e., higher metallicities) and more anisotropy [lower $(V_m/\sigma)^*$ or a_4/a, higher $\nabla\epsilon$ or $\nabla\Theta$] tend to have more globular clusters, both in absolute terms (N_{gc}) or at a given optical luminosity (S_N). The best bivariate correlations have a residual scatter which is close to that expected from the error bars. Trivariate correlations offer little improvement because the errors add up. This means that N_{gc} and S_N can be predicted within the measurement accuracy by carefully chosen combinations of two or three observed parameters of their host galaxies.

Finally, we find excellent correlations with the total and "coronal" X-ray luminosities, L_X and ΔL_X, in the sense that galaxies with larger X-ray luminosities also tend to have more globular clusters. Unfortunately, we have only 10 galaxies for which both kind of data are available at this point, and this result should be regarded only as very preliminary. However, it is fully consistent with the trends described above, and the findings by Djorgovski & de Carvalho (1990b) that more anisotropic ellipticals have larger X-ray luminosities.

We see only a hint of the environmental dependence, viz., that cluster galaxies have a higher N_{gc} and S_N at a given luminosity (Harris 1991, and references therein), but the present sample is probably too small to make a definitive statement.

3. DISCUSSION

Our basic conclusion is that a basic property of the globular cluster systems in elliptical galaxies, viz., their absolute numbers and numbers per unit galaxy luminosity, are correlated in a nontrivial manner with the properties of their host galaxies. These results can be used to constrain models of the formation and evolution of globular cluster systems in early-type galaxies. They imply immediately that the formation (or survival) of globulars is connected with the formative and/or evolutionary processes of elliptical galaxies themselves. We note that more than one mechanism may be involved, and the observed correlations imply a complex formation history. Several mechanisms for the formation of globulars have been proposed (cf., e.g., Harris 1988, 1991; van den Bergh 1990a; Fall & Rees 1985; Ashman & Zepf 1992). Globular clusters may be pregalactic and accreted onto galaxies; formed along with the old spheroidal components; acquired in mergers of already formed galaxies; formed in dissipative mergers; formed in cooling flows, either pregalactic or recent; formed relatively quiescently in gas-rich galaxies; and destroyed by tidal shocks and evaporation.

Globular cluster formation may be associated with the initial, dissipative formation of spheroidal stellar components of galaxies, whether or not merging was involved (cf. Larson 1988; Fall & Rees 1985, 1988). We find that the principal correlations involving N_{gc} and S_N are those involving the FP variables; these correlations can account for most of the variation of N_{gc} and S_N among the ellipticals. Whichever processes determine the global properties of ellipticals and the FP also largely determine the numbers of globular clusters formed in them. The correlations of the mean metallicities of globular cluster systems with the metallicities and luminosities of their host galaxies (van den Bergh 1975; Brodie & Huchra 1991), the radial color or metallicity gradients in globular cluster systems, correlations found in this work involving the metallicity-sensitive colors, etc., also imply that globular cluster formation in ellipticals is closely related to the dissipative galaxy formation.

This picture, however, does not readily account for the bivariate correlations involving the dynamical or isophotal shape parameters which are generally interpreted as reflecting the velocity anisotropy, $(V_m/\sigma)^*$, $\nabla\epsilon$, $\nabla\Theta$, or a_4/a. We find that the galaxies which are more anisotropic tend to have more globulars. It is generally believed that an increased velocity anisotropy may be a consequence of mergers and dynamical interactions. Dissipationless merging can also decrease the mean surface brightness, and we find trends in which galaxies with a lower mean surface brightness tend to have more clusters.

Schweizer (1987), Ashman & Zepf (1992), and others suggested that at least some globular clusters may form in dissipative mergers. This has been supported by the recent observations of NGC 3597 (Lutz 1991) and NGC 1275 (Holtzman et al. 1992). Larson (1990) suggested that the efficiency of cluster formation may be enhanced in the densest protostellar clouds or cloud cores. Mergers and interactions may be an efficient mechanism for compression of the gas, thus providing an efficient mechanism for cluster formation. This could account for the nonlinear relation we find between the number of clusters and the galaxy luminosity: both the net number of stars and the number of globulars increase as a galaxy grows, but the number of clusters increases faster. This mechanism may have operated early, with the bulk of the clusters formed during an initial epoch of elliptical galaxy formation via dissipative infall merging. There are excellent arguments against the formation of ellipticals *exclusively* through major, late mergers of spirals, including, for example, the differences in S_N (cf. van den Bergh 1990b). However, formation through dissipative infall and early merging of many small, gas-rich fragments is perfectly acceptable.

Zinnecker et al. (1988) and Freeman (1990) suggested that many or all globulars may be former compact nuclei of dwarf galaxies, with their envelopes stripped away in mergers. Ferguson & Sandage (1989) found that nucleated dwarfs are more strongly concentrated toward the globular-cluster-rich, giant ellipticals in Virgo and Fornax clusters. As we have shown, anisotropic, presumably triaxial galaxies tend to have more clusters. Ostriker, Binney, & Saha (1989) argued that such potentials are more effective in *destroying* globulars via tidal shocking. This would appear to be contrary to the observed trends, but one can expand their argument to include nucleated dwarfs: possibly the acquisition of globulars by stripping of nucleated dwarfs can outweigh the loss of clusters by tidal shocks and evaporation. Arguments against this scenario have been presented by van den Bergh (1990a), but it is possible that at least some fraction of the globulars was acquired in this way, perhaps early on.

We conclude that globular cluster formation stimulated by dissipative merging, probably mainly during an early epoch of elliptical galaxy formation, may be the most promising mechanism. Correlations between the properties of globular cluster systems and properties of their host galaxies provide useful constraints for the models of their formation.

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