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FAMILIES OF ELLIPSOIDAL STELLAR SYSTEMS AND THE FORMATION OF DWARF ELLIPTICAL GALAXIES

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ABSTRACT

Core radii and central surface brightnesses of bulges and elliptical galaxies are measured using CCD photometry obtained with the Canada-France-Hawaii Telescope (scale = 0"22 pixel^{-1}; seeing = 0"45–1"0 FWHM). The correlations between core parameters are derived and compared for ellipticals, bulges, dwarf spheroidal galaxies, dwarf irregular galaxies, and globular clusters. The results are as follows.

1. The data confirm the existence of well-defined correlations between the core parameters of elliptical galaxies. More luminous ellipticals have larger core radii r_c and lower central surface brightnesses μ_{0V}. Galaxies with larger core radii have larger central velocity dispersions. The small, bright core of M32 is normal for a galaxy of $M_B = -15.2$. Radio ellipticals and brightest cluster galaxies satisfy the correlations.

2. The bulges of disk galaxies are basically similar to elliptical galaxies. Their cores have slightly smaller r_c and brighter μ_{0V} than ellipticals of the same luminosity, because their nonisothermal profiles rise more rapidly toward the center and because they often contain extra nuclei superposed on their cores.

3. There is a large discontinuity between the parameter correlations for bright ellipticals, including M32, and those for dwarf spheroidals. Seven dE's in the Local Group and three in the Virgo Cluster have core parameters which are correlated, but not as in ordinary ellipticals. More luminous dE's have larger r_c and *brighter* μ_{0V}. The Virgo dE's have nearly the same average luminosity as M32, but their cores are larger and lower in surface brightness by factors of $\gtrsim$500 and $\gtrsim$5000, respectively. Dwarf spheroidals also have smaller velocity dispersions than comparable ellipticals.

4. A fair comparison between dE's and dwarf irregular galaxies can be made because exponential and isothermal brightness profiles are similar for $r \lesssim r_c$. Dwarf spheroidals and dwarf spiral and irregular galaxies are found to have essentially identical parameter correlations. This implies a closer kinship between dE and dS + Irr galaxies than between dE's and giant ellipticals. These results support suggestions that dwarf spheroidal galaxies are dwarf spirals or irregulars that have lost their gas or processed it into stars long ago.

5. There is also a large difference between the parameter correlations for globular clusters and those for other ellipsoidal stellar systems. Some of these differences may be due to relaxation in globulars. However, it appears that bulges and ellipticals, dwarf spheroidals, and globular clusters are three remarkably different kinds of stellar systems.

Subject headings: clusters: globular — galaxies: formation — galaxies: photometry — galaxies: structure

I. INTRODUCTION

The observed correlations between the core parameters of bulges and elliptical galaxies are fundamental scaling laws that provide important input for theories of galaxy formation. These correlations are rederived here using high-resolution surface photometry obtained with the Canada-France-Hawaii Telescope (CFHT) (Kormendy 1985*a*, hereafter Paper I). An RCA CCD camera used at the Cassegrain focus gave a scale of 0"22 pixel^{-1}. The seeing was excellent; the Gaussian dispersion of a star profile ranged from 0"20 to 0"45, with a median value of 0"33. This is a significant increase in resolution over previous work and allows me to derive core parameters with much improved confidence. This paper reports the first results of the above program; a complete discussion will follow when more galaxies are measured (Kormendy 1985*b*).

The best known core parameter relation is the observation by Faber and Jackson (1976) that more luminous ellipticals have higher central velocity dispersions σ: $L \propto \sigma^n$, $n \approx$ 4–6. Subsequently, Faber (1980) and Kormendy (1982, 1984) showed that L, σ, core radius r_c, and central surface brightness μ_{0V} are all correlated; in particular, more luminous ellipticals have larger r_c and fainter μ_{0V}. Bulges and ellipticals show no obvious differences in their core parameters (see the above papers and Kormendy and Illingworth 1983). In § III I compare the parameter correlations for elliptical galaxies, bulges, dwarf spheroidal galaxies, disks, and globular clusters. This leads to the surprising result that ordinary and dwarf elliptical galaxies do not form a continuous sequence. Rather, bulges and ellipticals, dwarf spheroidals, and globular clusters appear to be three very distinct kinds of stellar systems. Dwarf spheroidal galaxies are most closely related to dwarf irregular galaxies and may have evolved from them.

II. DERIVATION OF CORE PARAMETERS: SEEING CORRECTIONS

Previous derivations of the parameter correlations depended critically on how the brightness profiles were corrected for

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seeing. In particular, they depended on the assumption that cores are nearly isothermal. Schweizer (1979, 1981) has emphasized that with typical good seeing ($\sigma_* \approx 0''.6$), only a few galaxies are conclusively resolved. In most galaxies, the apparent cores could really have been very centrally peaked light distributions blurred by seeing (Schweizer 1979, 1981). The adopted seeing corrections are then valid if the isothermal assumption is correct, but otherwise they can be very wrong. Doubts therefore remained about the validity of the parameter correlations derived in Kormendy (1982, 1984). Also, the photographic photometry used (Kormendy 1977; King 1978) turns out in many cases to be inaccurate (Young *et al.* 1978; Lauer 1985*a*; Kormendy 1985*b*). This is a problem inherent in photographic work on small objects with large dynamic range. The present CCD photometry establishes the core parameter relations with galaxies that are well resolved and pushes the limits below which r_c and μ_{0V} still depend on assumptions to much smaller galaxies. The present results therefore supersede those of Kormendy (1982, 1984).

Core parameters are derived as follows. Since some profiles are isothermal and others are not (Paper I), I will not use fitting functions. Instead, I use the apparent central surface brightness $\mu_{0,\mathrm{app}}$ and the apparent core radius $r_{c,\mathrm{app}}$ at which the surface brightness has fallen by a factor of 2 from $\mu_{0,\mathrm{app}}$. Subsequent seeing corrections are calculated as in Schweizer (1981). They are based on a King (1966) dynamical model with log $(r_t/r_c) =$ 2.25; this fits overall profiles reasonably well and is sufficiently similar to the observed profiles (isothermal or not) near the center. Schweizer (1981) convolved the above model with Gaussian point-spread functions that had exponential wings of slope 2 mag arcsec^{-1} beyond $r = 2\sigma_*$. The resulting corrections (Fig. 1) are approximately valid for a variety of observations and were used in previous work. More accurate corrections have been calculated here, based on the star profile observed at the CFHT. This is Gaussian out to 1.5 mag arcsec^{-2} below the central brightness and has power-law wings $I(r) \propto r^{-3.8}$ below 2 mag arcsec^{-2}. The adopted corrections are shown in Figure 1; they are slightly larger than those obtained by Schweizer because the wings of the PSF are brighter. They have been used to derive true core radii r_c and central surface brightnesses μ_{0V} illustrated in the next section. In Figures 2 and 3 the sizes of the seeing corrections are indicated by the sizes of the symbols. Large symbols represent galaxies that are very well resolved ($r_{c,\mathrm{app}}/\sigma_* > 5$), so seeing corrections are small and the profile shape is well determined. Intermediate symbols are for galaxies with moderate but still well-defined corrections of $\lesssim 50\%$ ($3 < r_{c,\mathrm{app}}/\sigma_* \leq 5$). Small symbols show galaxies which are poorly resolved ($r_{c,\mathrm{app}}/\sigma_* \leq 3$) and still dependent on the isothermal assumption. In extreme cases these are little better than upper limits.

Other parameters come from the following sources. Photometry of dwarf ellipticals in the Local Group is by Hodge (1971 and references therein, 1976, 1982), Hodge and Smith (1974), and Demers, Beland, and Kunkel (1983). Central velocity dispersions are from Faber and Jackson (1976), Malumuth and Kirshner (1981), Kormendy and Illingworth (1983), Davies *et al.* (1983), Aaronson (1984), and Tonry (1984). Distances within the Local Group are from a variety of sources based mostly on color-magnitude diagrams. Distances beyond 5 Mpc are based on group velocities and a Hubble constant of 50 km s^{-1} Mpc^{-1}; present results are therefore directly comparable with Kormendy (1982, 1984). The derivation of r_c and μ_0 for dwarf spiral and irregular galaxies is discussed in § III*b*. The photometry is from the following sources: LMC, SMC, IC 1613, and the generic large disk, Freeman (1970); NGC 6822, Hodge (1977), GR 8, de Vaucouleurs and Moss (1983); WLM, Ables and Ables (1977); Sextans A, Ables (1971); and LGS-3, Schild (1980). Photometric parameters for globular clusters are from Peterson and King (1975) and Peterson (1976), with distances and reddenings from Harris and Racine (1979). Velocity dispersions of globular clusters are from Illingworth (1976), Cudworth (1976*a*, *b*, 1979*b*), Da Costa *et al.* (1977), Gunn and Griffin (1979), and Pryor *et al.* (1985). Some checks of these observations are available: measurements of individual stars in 47 Tuc by Mayor *et al.* (1984) and by Da Costa and Freeman (1984) give σ in agreement with Illingworth's (1976) value from the integrated spectrum, and Gunn and Griffin's (1979) more accurate σ from individual stellar velocities confirm a measurement from proper motions by Cudworth (1979*a*).

III. PARAMETER CORRELATIONS

a) Bulges and Elliptical Galaxies

Figure 2 shows the observed correlations between r_c, μ_{0V}, σ, and M_B for bulges and elliptical galaxies. More luminous galaxies are found to have larger cores of lower surface brightness and higher central velocity dispersion. Least-squares fits of straight lines to the data for ellipticals give:

$$\mu_{0V} = 2.12 \log r_c + 17.48, \text{ i.e.,} \tag{1}$$

$$I_{0V} \propto r_c^{-0.85} ; \tag{2}$$

$$I_{0V} \propto L^{-0.83} ; \tag{3}$$

$$r_c \propto L^{1.06} ; \tag{4}$$

$$\sigma = 321 r_c^{0.22} \text{ km s}^{-1} . \tag{5}$$

Here $\mu_{0V} = -2.5 \log I_{0V} + \text{constant}$, $M_B = -2.5 \log L + \text{constant}$, and all points were given equal weight. In each case, the abscissa in Figure 2 was taken as the independent variable. If the ordinate is used, the relations are not greatly changed: the five "slopes" become 2.27, −0.91, −1.20, 1.21, and 0.27. The above relations are in reasonable agreement with those of Kormendy (1982, 1984; see also Faber 1980; Lauer 1985*b*). They are also similar in sense to global parameter correlations involving the de Vaucouleurs effective radius r_e and surface brightness B_e (see Kormendy 1980, 1982 for reviews). These are basic scaling laws that theories of galaxy formation and evolution should explain (e.g., Silk and Norman 1981).

It is interesting to note the variety of elliptical galaxies which define the above correlations. The high-luminosity end consists of the brightest galaxies in the clusters A779 (NGC 2832), A2199 (NGC 6166), Coma (NGC 4874 and 4889), Virgo (M87 and NGC 4472), and ZwCl 0844+32 (IC 2402). NGC 6166 is a classic cD galaxy (e.g., Oemler 1976). These galaxies are indistinguishable from other ellipticals except for their higher luminosities and appropriately extreme core parameters. A similar result was found for global parameters describing the main bodies of first-ranked ellipticals, including cD's (see Kormendy 1982 for a review). Of course, parameters that measure cD halos have very different correlations with luminosity (Oemler 1976).

Radio galaxies are also consistent with the parameter correlations. They include NGC 6166 = 3C 338, NGC 4874, IC 2402 = 4C 31.32, M87 = 3C 274, DA 240, and NGC 6251. The same is true for the X-ray sources NGC 6166, M87, and NGC

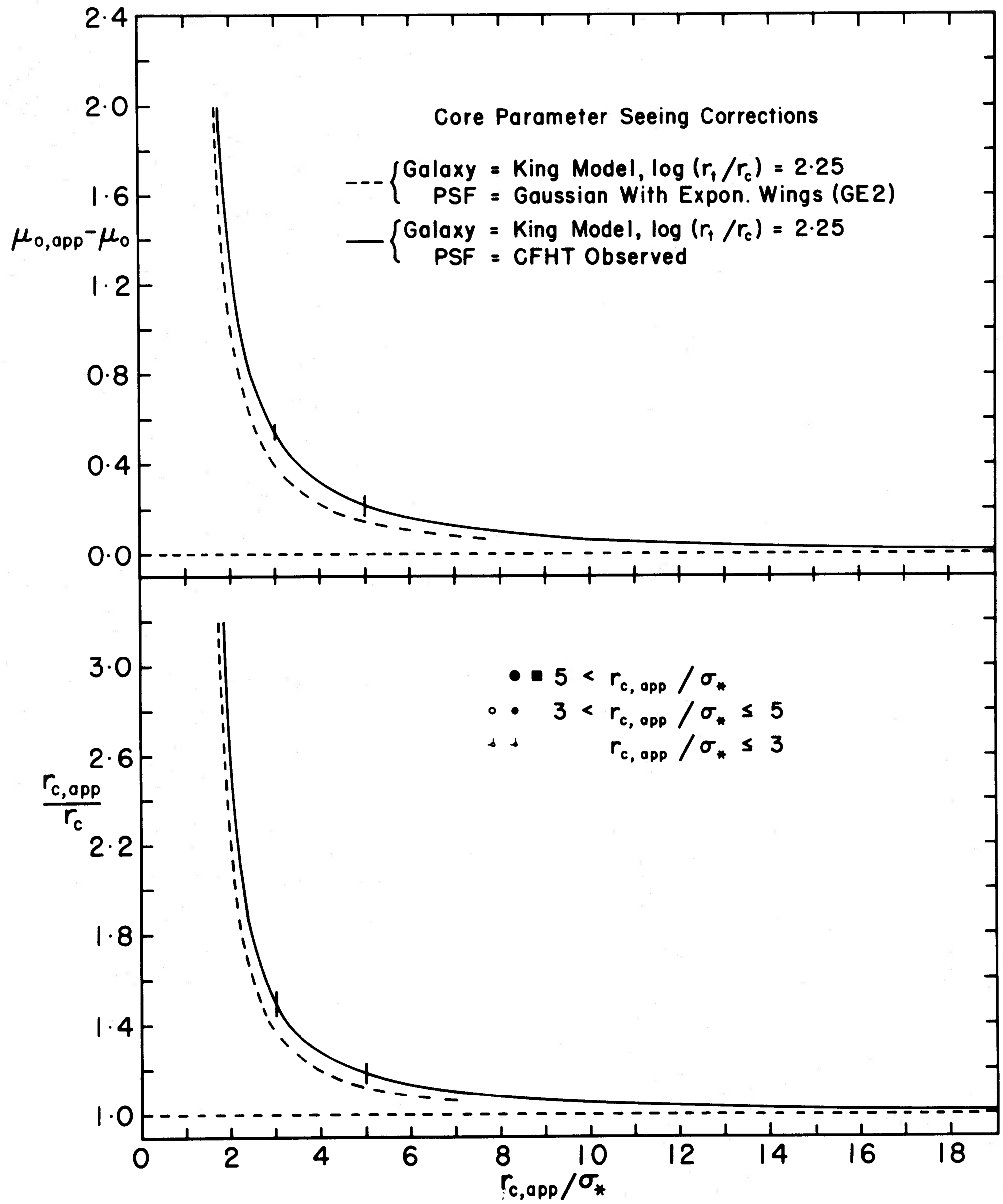

FIG. 1.—Seeing corrections (*solid line*) used to convert apparent core radii $r_{c,\rm app}$ and central surface brightnesses $\mu_{0,\rm app}$ to true values r_c and μ_0. The key shows how symbol sizes are used to indicate small, moderate, and large corrections in Figs. 2 and 3. The dashed line shows corrections from Schweizer (1981) used in previous work (Kormendy 1982, 1984).

4406. Evidently, neither the engines associated with nuclear activity nor hot gas that may condense onto galaxies destroy the correlations.

At the other extreme in luminosity, the well-known small and bright core of M32 is entirely normal for an elliptical of $M_B = -15.2$.

On the other hand, bulges of disk galaxies show small departures from the correlations for ellipticals. Several of the nearest bulges have tiny nuclear star clusters superposed on cores of much larger size. This is well known in M31 (Light, Danielson, and Schwarzschild 1974). The nucleus was fairly well resolved by Stratoscope II and was found to have an axial ratio of 0.63 and a mean core radius of $r_c = 0\farcs42$. In contrast, the bulge of M31 has $r_c = 17''$. My observations of M81, NGC 524, NGC 2841, and NGC 3384 also show such nuclei (Paper I). These are included in the parameter measurements. Not surprisingly, Figure 2 shows that bulges have slightly smaller r_c and brighter μ_{0V} than comparable ellipticals. This is also due to the fact that nonisothermal core profiles rise more rapidly toward the center in bulges than in ellipticals (Paper I). Despite the small

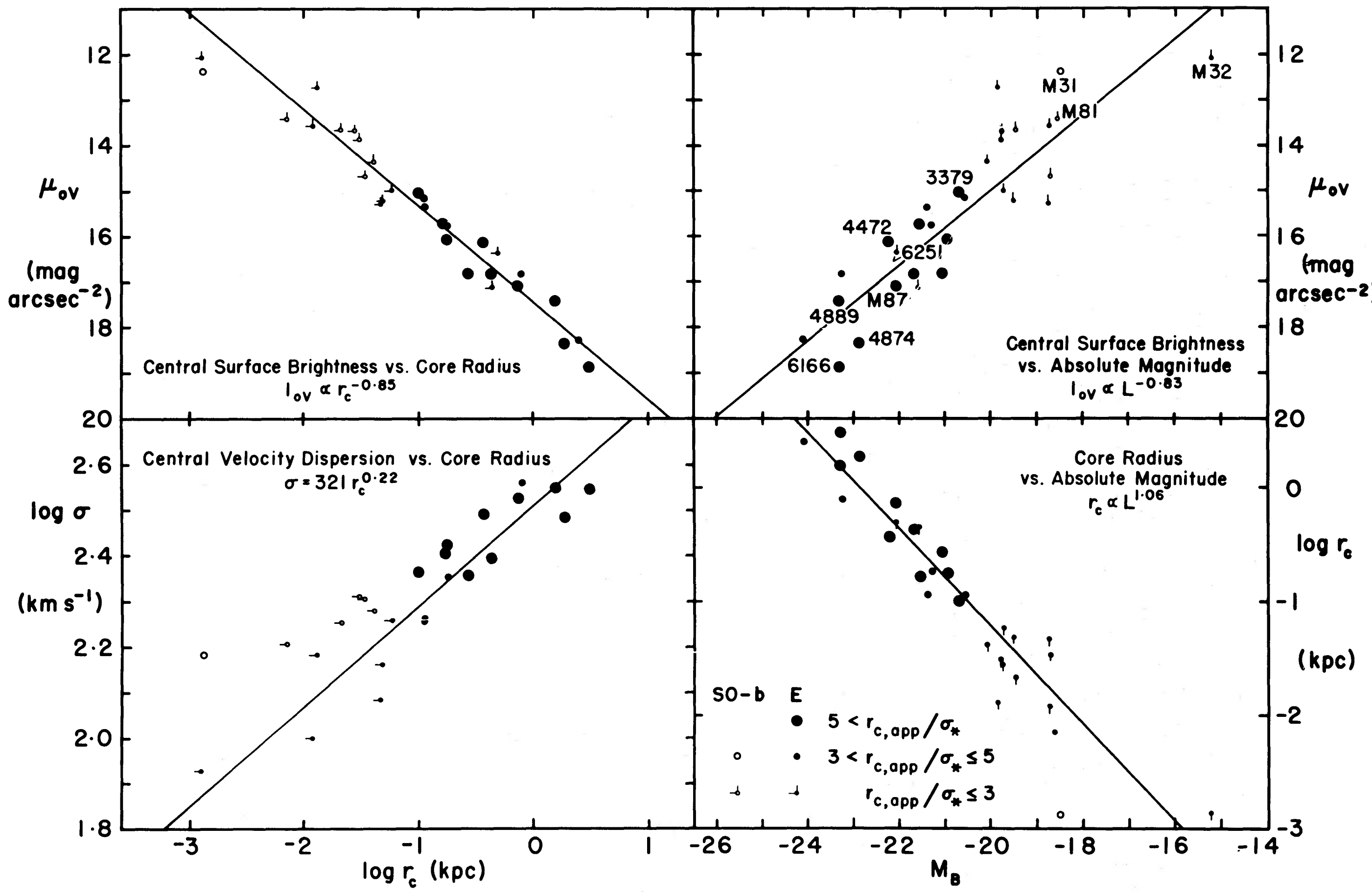

FIG. 2.—Core parameter relations for bulges and elliptical galaxies. Several points are labeled with corresponding NGC or Messier numbers. Open circles for bulges are derived using all of the observed profile, including any nucleus. The straight lines are least-squares fits to the data for elliptical galaxies. M32 is omitted from the regressions because it may be tidally truncated by M31 and hence too faint for its core parameters.

difference, bulges lie close to the low-luminosity ends of the parameter relations for bright ellipticals. On the whole, bulges and ellipticals are very similar.

b) Dwarf Elliptical and Irregular Galaxies

Figure 3 compares the core parameter relations for bulges and ellipticals, dwarf spheroidal galaxies, and globular clusters. The most surprising result of this paper is that there is a large discontinuity between the parameter correlations for ellipticals and for dwarf spheroidals. Seven dE's in the Local Group and three measured so far in the Virgo Cluster have core parameters which are correlated, but not as in ordinary ellipticals. More luminous dwarfs have larger cores of *higher* central surface brightness. A small amount of luminosity overlap emphasizes the well-known diffuseness of the dwarfs. NGC 147 and three dE's measured in Virgo have the same average M_B as M32, but their cores are larger by factors of $\gtrsim 500$ and fainter by factors of $\gtrsim 5000$. Also, preliminary measurements by Aaronson (1983, 1984) imply $\sigma \sim 10$ km s^{-1} in dE's, much smaller than in comparable ellipticals. Plausible measuring errors would only dilute these differences. If I have underestimated the seeing corrections for M32, or if Aaronson's stellar velocity measurements are contaminated by binary stars, then ordinary and dwarf ellipticals are even more different than Figure 3 suggests.

This result differs from the conclusion of Binggeli, Sandage, and Tarenghi (1984, hereafter BST) that dwarf ellipticals fall on the extrapolation toward low luminosity of the parameter relations for giant ellipticals. The BST data are photographic; there appear to be problems with the calibration or dynamic range of the photometry. These problems are shown by their Figure 1, which compares their test measurements of NGC 3379 with the standard profile due to de Vaucouleurs and Capaccioli (1979). The BST measurements deviate below the standard profile interior to $r = 10''$ by amounts which reach 0.6 mag arcsec^{-2} at $r \lesssim 3''$. My measurements show that even the standard profile is too faint near the center by ~ 1 mag arcsec^{-2}. This problem does not affect the photometry below $\sim 19V$ mag arcsec^{-2}; e.g., their measurements of dE's in Virgo agree well with mine. But it has prevented the resolution of the small cores of intermediate-luminosity ellipticals which result in the discontinuity shown in Figure 3.

I therefore conclude that dwarf elliptical galaxies are very different from the sequence of giant ellipticals, including M32. The same conclusion was reached by Wirth and Gallagher (1984) using more global parameters. This result implies a substantial change in goals of theories of galaxy formation. It is no longer necessary to explain how a single process can form giant ellipticals, with their compact cores and deep potential wells, and dwarf spheroidals, with their remarkably low densities.

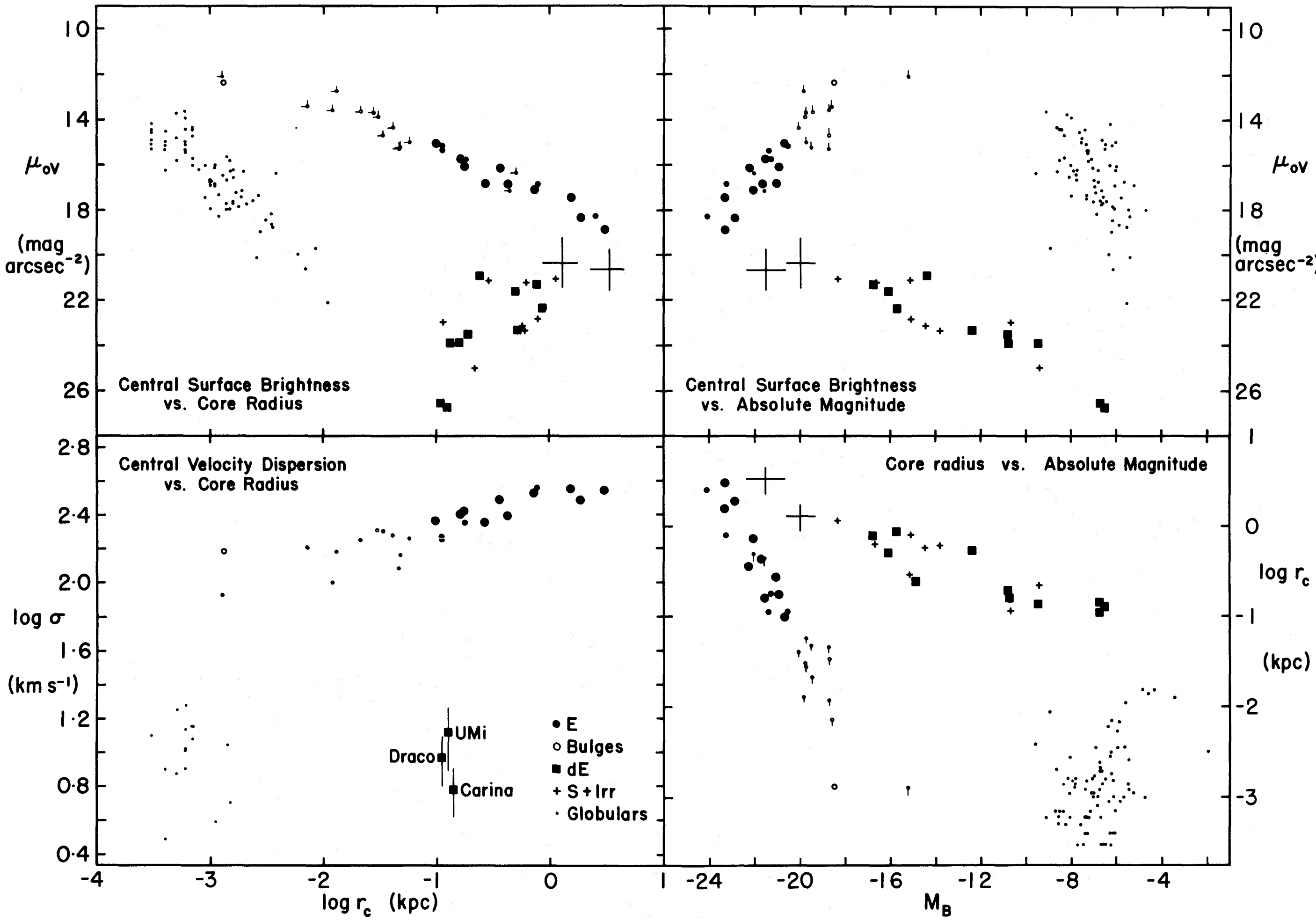

FIG. 3.—Comparison of the core parameter relations for various kinds of stellar systems. Bulges and ellipticals are as in Fig. 2. The dwarf elliptical galaxies are, in order of decreasing luminosity, IC 3349, 12°52, and 13°66 (Virgo Cluster designations from Binggeli, Sandage, and Tarenghi 1984), NGC 147, Fornax, Leo I, Sculptor, Leo II, Draco, Carina, and UMi. Similarly, the dS + Irr galaxies are the generic large disk (two points), LMC, SMC, NGC 6822, WLM, IC 1613, Sextans A, GR 8, and LGS-3. The discrepant globular cluster at upper left (μ_{0V} = 16.38 mag arcsec^{-2}, log r_c = −2.42) is, of course, ω Cen.

Instead, the low-luminosity analog of a galaxy like M87 or NGC 3379 is still more compact (although not more tightly bound) than a giant galaxy. This is potentially easier to explain, since compactness and rotation in small ellipticals (Davies *et al.* 1983) may both result from a greater amount of dissipation during galaxy formation. In eliminating the continuity between giant and dwarf ellipticals, the present results also eliminate a classic argument against mergers as the origin of elliptical galaxies (Tremaine 1981, p. 81), although, of course, they do not prove that any galaxy is a merger remnant. Figure 3 suggests that dwarf spheroidals and ordinary ellipticals were formed in very different ways.

A clue to the origin of dwarf ellipticals is obtained by comparing them with dwarf spiral and irregular galaxies. A fair comparison is possible because "tidally truncated isothermal" profiles of dE's and exponential profiles of dS + Irr galaxies are very similar for $r \lesssim r_c$ (Faber and Lin 1983; BST; present photometry). I can therefore derive a core radius and central surface brightness for an exponential exactly as I did in § II. Figure 3 shows the resulting parameters for dS + Irr galaxies in or near the Local Group. I also illustrate the properties of the generic large disk with two points derived from Freeman (1970). These are averages for 13 and 19 galaxies with exponential scale lengths $\alpha^{-1} > 4$ kpc and $\alpha^{-1} \leq 4$ kpc, respectively, in Freeman's Table 1 (but with $H_0 = 50$ km s^{-1} Mpc^{-1}). The error bars are equal to the observed dispersion in each parameter.

Figure 3 shows that the core parameters of dwarf spheroidals fall on the faint parts of well-defined parameter correlations for disks. This is true not only for r_c, μ_{0V}, and M_B, but also for the correlation between σ and r_c. Rotation velocities of dwarf irregular galaxies are comparable to the velocity dispersions of dE's. The Tully-Fisher relation for DDO dwarf galaxies (de Vaucouleurs, de Vaucouleurs, and Buta 1983) implies a test-particle circular rotation velocity of ~30 km s^{-1} for $M_B = -15$. For motion in a spherical, isothermal mass distribution, the corresponding velocity dispersion is ~20 km s^{-1}. This is much smaller than σ = 85 km s^{-1} (Tonry 1984) in M32 ($M_B = -15.2$). The extreme dwarf M81 dwA ($M_B \approx -11.0$) has a projected rotation velocity of 2.5 ± 1.0 km s^{-1} and an H I velocity dispersion of ~8 km s^{-1} (Sargent, Sancisi, and Lo 1983). These values are very similar to the velocity dispersions of dwarf spheroidals. Moreover, with rotation velocities comparable to velocity dispersions, we do not expect extreme dwarf irregulars to be very flattened. I therefore conclude that dwarf spheroidal galaxies are more closely related to dwarf spirals and irregulars than to ordinary ellipticals. Lin and Faber (1983) reached the same conclusion from somewhat sparser data. This result supports the hypothesis that dwarf elliptical galaxies are dwarf spirals and irregulars that either lost their gas or converted it all into stars long ago.

Circumstantial evidence for this hypothesis has been accumulating for some time. Einasto *et al.* (1974) noticed that morphological types of dwarf companions of large galaxies correlate with luminosity and distance. Only dE's are found close to parent galaxies; almost all distant companions are spirals or irregulars. The dividing line occurs nearer the parent galaxy for larger companions. Einasto and collaborators suggested that the dE's were stripped of gas by a gaseous halo around the parent galaxy. Strong support for this idea comes from the detection of young stars in dwarf ellipticals (see Mould 1982 and Lin and Faber 1983 for reviews). A range of metallicity in dE's also suggests that there were several generations of star formation (Mould 1982). Faber and Lin (1983) and Lin and Faber (1983) review the evidence and make a strong case that dE's are dwarf irregulars stripped by ram pressure. Since then, Sandage and Binggeli (1984) have discovered a class of very large (diameter ~ 10 kpc), low-surface-brightness dwarfs in the Virgo Cluster. Such objects might also be produced by gas stripping: an irregular containing mostly gas would expand greatly and end up with very low surface brightness. It is noticeable that dE's which fit the parameter correlations for spirals and irregulars reach higher luminosities in Virgo, where ram pressure stripping may be easier, than in the Local Group. Correspondingly faint Sa–c galaxies are lacking in Virgo (Sandage and Binggeli 1984). Have they been converted into nucleated dwarf ellipticals? Many intermediate and late-type small galaxies have nearly exponential disks surrounding bright, tiny nuclei (e.g., NGC 7793—de Vaucouleurs and Davoust 1980). Finally, the apparent discovery by Olszewski and Aaronson (1984) of a distinct subcluster of stars in UMi is most easily understood if the galaxy was once a dwarf irregular. Thus, there are a variety of observations which suggest that dwarf ellipticals are dwarf irregulars stripped of gas. The present results emphasize how similar these types of galaxies are in their overall structure.

c) *Globular Clusters*

The relationship between elliptical galaxies and globular clusters has long been an intriguing problem. When we thought that ellipticals form a continuous sequence from giants to dwarfs, it appeared that lower- and lower-luminosity ellipticals were less and less like the brightest globulars that they were approaching in M_B. With the revision in our ideas about the parameter correlations for ellipticals, it is worth reexamining the question of whether ellipticals and globular clusters are related.

The distribution of globulars in Figure 3 strongly suggests that they are related neither to giant ellipticals nor to dwarfs. A significant correlation is found between μ_{0V} and log r_c. But this correlation and the other parameter distributions are very different from those for ordinary and dwarf ellipticals. It is still possible that the sequence of ordinary ellipticals fainter than M32 converges on the globulars, or that transition cases between Palomar clusters and dwarf ellipticals will be found. However, such transition objects must be very rare. Globulars may differ from galaxies partly because of internal relaxation, but the longest relaxation times are almost 10^{10} yr (Peterson and King 1975). Thus, Figure 3 shows that ellipticals and bulges, dwarf spheroidal galaxies, and globular clusters are three very different kinds of stellar systems. The interesting problem now is to incorporate these results into a believable theory of galaxy formation.

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