THE ASTRONOMICAL JOURNAL VOLUME 88, NUMBER 6 JUNE 1983

STRUCTURE AND STELLAR CONTENT OF DWARF ELLIPTICAL GALAXIES

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Received 20 January 1983; revised 22 February 1983

ABSTRACT

A small number of low-luminosity elliptical galaxies in the Virgo cluster and around other prominent galaxies have been studied using photoelectric and photographic techniques. The color-magnitude relation for ellipticals now extends from $M_v = -23$ to -15, and is linear over that range with a slope of 0.10 in $U-V$ per visual magnitude. Galaxies which are known to contain a large number of young stars ("extreme cases") are from 0.10 to 0.20 mag bluer in $U-V$ than the lower envelope of the dwarf elliptical color-magnitude relation. This difference can be accounted for if the dwarf elliptical galaxies are young, but do not contain the massive blue stars that probably exist in the young populations of the extreme cases. Surface brightness profiles of the dwarfs have revealed some interesting distinctions between themselves and the brighter E's. In general, their intensity profiles are shallower than those of the bright E's, meaning they are of lower mean density. These mean densities are also a function of the total luminosity. Unlike the bright E's, the surface brightnesses near the centers are also a strong function of the total luminosity. The presence of a nucleation, which can be as much as 2 mag brighter than what the outer envelope would predict, does not appear to depend on any other measurable property of the galaxies. The variation in surface brightness profiles at the same total luminosity is suggestive that the low-luminosity dwarfs formed in more than one way. The flattening distribution of the dwarfs is like that of the bright ellipticals, and is also similar to the flattening distribution of field irregular galaxies.

I. INTRODUCTION

Recently formed stars have been known for some time to be present in the dwarf E galaxies N185 and N205, two of the companions to M31. This was first noticed by Hubble, subsequently studied by Baade (1951), Hodge (1963a, 1973), and more recently by Gallagher and Hunter (1982). Several authors have also noticed that N205 is rather blue for its luminosity as well. Interestingly, this is also true of two other dwarf ellipticals (dE's) that are companions to large spiral galaxies. Faber (1973) and Burstein (1979) showed that N4627 (near N4631) is too blue on their color-line strength sequence. N1531 (near N1530) is quite blue in $U-V$ for its luminosity, as is shown later in this paper. Three of these galaxies have strong Balmer absorption in their spectra, a phenomenon often seen in S0 galaxies such as N5102. The presence of the hydrogen lines in these galaxies is now taken to be evidence of recent star formation, rather than of low mean metallicity.

The number of known dwarf ellipticals that are companions to spiral galaxies and thus have a nearby reservoir of gas from which they might draw upon to make stars is small. A much larger collection of low-luminosity galaxies is available for study in the Virgo cluster region. These objects have smooth light distributions, are apparently of lower surface brightness than the dE's just mentioned, and have relatively (not absolutely) bright nuclei. They have been described by Reaves (1956, 1977) and were called "nucleated" dwarfs by Romanishin, Strom, and Strom (1977), but for lack of any reason not to do so, will be referred to as dE's here. These galaxies populate the entire Virgo region, some near spirals, some near ellipticals, some isolated within the cluster. Also, there are similar galaxies near other prominent giant galaxies, as described below.

Are the four dE's mentioned above rare cases of extreme star formation, due to the accretion of gas from their environment? The intent of this paper is to measure the colors of many dE's and compare the observed colors with those expected from the color luminosity relation among brighter ellipticals. A steepening of the slope (becoming blue too fast) would possibly indicate that another parameter besides metallicity is changing among the lower luminosity dwarfs.

This paper presents new photoelectric and photographic photometry on dwarf ellipticals.

II. THE DWARFS

The selection of dE's for photometric observations was made by searching photographic plates for objects which appeared like those exhibited in Fig. 1 (except for N4472 DW10). The plates were kindly supplied by A. Oemler and P. Schechter. They were primarily of blue emulsions (IIa-O or IIIa-J) taken with the Las Campanas 100-in. telescope which has a plate scale of 10.94 arcsec mm^{-1}. The plate sizes and fields are: 14″ by 14″ J

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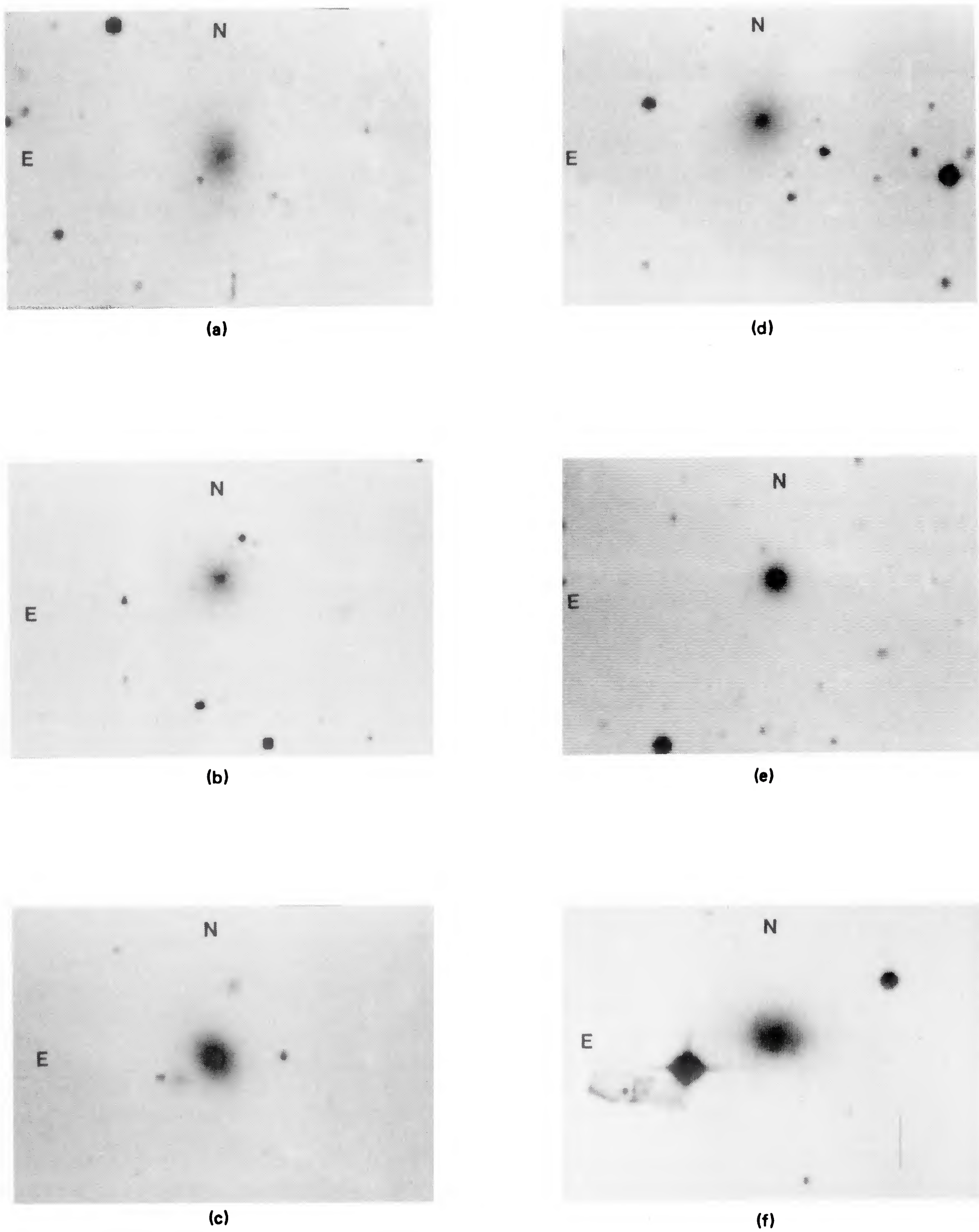

FIG. 1. Images of six of the dwarf galaxies in this study. These pictures are taken off of the television monitor of an image processing system. The original plate was a IIa-O emulsion and a GG385 filter. The plate scale is indicated by a line that is 30 in. long. The intensity scales of the pictures are not all equal, so that some of the lower surface brightness objects could be better displayed. The galaxies shown are N4472 DW1, DW3, DW6, DW8, DW9, and DW10.

of M87, 20″ by 20″ O of N4472, 14″ by 14″ J of N4594, 14″ by 14″ J of N3115, and 20″ by 20″ of N5846. An additional plate of the entire central region of the Virgo cluster was also used, this being a Palomar Schmidt 098-04 plate. Lastly, a preliminary selection of dwarfs from the Palomar Sky Survey prints was made early in this project so that a few could be observed at CTIO as a feasibility test. Consequently, one of the objects from this group was not of the nucleated types (see below).

All of the objects on the Las Campanas plates which had low surface brightnesses and smooth light distributions regardless of their flattening were catalogued. Figure 1 shows images of six of the N4472 field dwarfs. These images were produced by scanning the original plate with the PDS microdensitometer and displaying the resultant raster scans on the television monitor of an image processing system. The monitor screen was then photographed with a 35-mm camera. Linear interpolation in the display was used to avoid the visual discomfort caused by square stars, and the intensity range of each image was set so that the galaxy stands out well against the background.

The positions of the centers were measured using the Yale PDS as a measuring engine and were transformed to 1950 epoch coordinates using the measured positions of local SAO standards. Photoelectric photometry was successfully obtained for most of these objects, but photographic photometry was extracted for nearly all of them. Five of the dE's around M100 (Sandage 1972) were also observed photoelectrically, as was N5206, a galaxy that is probably a member of the N5128 group ($v = 385$ km s^{-1}, from a spectrum of the author's).

III. PHOTOELECTRIC PHOTOMETRY

This section will describe the *UBV* photoelectric photometry obtained of the dE's in this study. The Mark II computer photometer was used on the 1.3- and 2.1-m telescopes at Kitt Peak with an extended S-20 photocathode. The ultraviolet filter of the *UBV* system was blocked with $CuSO_4$.

With the 1.3-m, the chopping secondary mode was used, throw distances being sufficiently large to ensure that only blank sky was being observed in the second beam, but not so large that the secondary looked off of the primary. The 2.1-m observations required the telescope itself to be moved to blank sky areas. The aperture sizes used were 24″.3 and 35″.6; diameters which roughly corresponded to the D(0) values of the galaxies. Typically 15 standard stars from Landolt's (1973) lists were observed each night in all filters. Additional pairs of red and blue stars were observed at different zenith distances to calculate the extinction coefficients.

Since the dE's were too faint to be seen in the TV guider, the telescope coordinates were zeroed on bright offset stars before moving the telescope to the position of the galaxies. The coordinates are nominally accurate to 2″, and the telescope setting is comparable, but it is still possible that larger centering problems have occurred and that the derived magnitudes are consequently affected. The colors are less likely to be affected by centering errors, since color gradients are expected to be small. The Kitt Peak observations were reduced in the standard manner, as were the observations of a few galaxies obtained with the Yale telescope at CTIO.

IV. PHOTOGRAPHIC PHOTOMETRY

To compare the photometry of the dE's with that for the more luminous E's, the magnitude systems must be equivalent. A commonly used system is the V_{26} system of Sandage and Visvanathan (1978), which measures the total amount of visual light contained within 2.5 times the radius at which the B surface brightness falls to 25 mag s^{-2} [D(0)]. To correct aperture measurements of magnitudes to this system, a curve of growth showing the increase of total magnitude with diameter must be available. Judging from the differences in appearance of the dE's in this survey with the more luminous E's, the curve of growth used by Sandage and Visvanathan is probably inappropriate for the dE's. Besides, D(0) values for the dwarfs are unavailable in the literature and so must be measured. Therefore, the integrated photographic magnitudes were measured using the same plates on which the galaxies were selected for photoelectric observations.

All of the dE's on all of the plates were scanned with the Yale PDS microdensitometer with an aperture corresponding to 2″.2, with additional measurements using 0″.1 pixel size being made of the dwarfs in the M87 and N4472 fields. The bright galaxies on the plates were scanned to aid in setting the photometric zero points, and in determining the characteristic curve.

These plates had a continuous wedge impressed on a blank part of the plate. To derive the characteristic curve, the change in intensity with distance from the dark edge must be known. To find this, the following technique was used. The wedge was assumed to be linear in log I with distance. Raster scans of galaxies of different brightnesses were converted to intensities using a guess for the ratio log I/dx in forming the characteristic curve. These scans were then photoelectrically calibrated and the surface brightness of the local sky values were checked for dependences on the magnitudes of the calibrating sources. The photometric aperture measures of the bright ellipticals, the dwarf E's, and the spot photometry of N3115 by Strom *et al.* (1978) were used in the calibrations. The slope of the wedge that gave the most consistent sky brightnesses for all ranges in calibrating magnitudes was 3.1 in units of log $I/100$ mm. This is in fair agreement with the values of 2.9 found by Schommer for IIa-D plates (private communication 1981), but not very close to 2.6 as found by Jacoby (private communication 1981). There is also a hint in my data that the slope of the wedge for the IIa-O plates is different from that of the IIIa-J plates.

The 3.1 value was adopted, with a cautionary note that the D/I transformation is uncertain to a large degree. Fortunately, this has little effect in the total magnitudes derived, but the surface brightness profiles are quite sensitive to it.

After converting the densities to intensities, and removing star images, the individual plates were calibrated using the photometry of the dwarfs on those plates. The photometry of NGC 3115 and NGC 4486 was included in the calibrations for the appropriate plates. All of the available photoelectric calibrations for a plate were averaged, and the derived mean sky brightness (in mag arcsec^{-2}) was assumed to be appropriate for the whole plate.

An ellipse-fitting program located the isophotal contours of the galaxy, specifically the radius at which a B surface brightness of 25 was reached. The magnitude within 2.5 times this radius was then computed by integrating the surface-brightness profile. Individual magnitudes are accurate to 0.05 mag, not including the effects of a possible error in the D/I transformation.

Plates were not available for several of the galaxies. V_{26} magnitudes were obtained directly from the photoelectric aperture magnitudes for these galaxies, by using the remarkable relation between the surface brightnesses and the total magnitudes, described in the next section.

V. THE COLOR-MAGNITUDE DIAGRAM

Table I presents all the new data on the dE's. Column 1 is the designation. Unless a proper name exists, the galaxy is referred to by a particular number in a field; for example, M87 DW1 is the first dwarf in the sample in the M87 field. The chart numbers for the M100 dwarfs refer to the chart given in Sandage (1972). Column 2 gives the 1950 coordinates of the objects. Column 3 gives the aperture size in arcseconds, and refers to the magnitude quoted. Columns 4–6 are the photoelectric V, $B-V$, and $U-B$ measurements with their corresponding errors. Column 7 is the observed photographic magnitude (V_{26}), and column 8 is the ratio of minor to major axes derived from the ellipse-fitting program.

TABLE I. Photometric properties of the dwarf ellipticals.

Object	R.A.	Dec.	Ap	V		B-V		U-B		V_{26}	ϵ
M87 DW 1	12 29 30.8	12 9 56	35.6	14.88	0.02	0.87	0.03	0.26	0.04	14.75	0.85
M87 DW 3	12 29 40.5	12 20 14	35.6	16.16	0.03	0.77	0.05	0.24	0.08	15.90	0.70
M87 DW 6	12 28 43.9	12 36 28	39.0	15.28	0.03	0.87	0.03	0.34	0.05	15.16	0.93
M87 DW 7	12 26 51.6	12 43 39								14.90	0.90
M87 DW 8	12 29 20.2	12 45 27	35.6	15.75	0.03	0.87	0.05	0.21	0.08	15.48	0.72
M87 DW 10	12 29 29.0	12 53 43								16.26	0.55
M87 DW 11	12 29 19.6	12 55 57	35.6	15.21	0.02	0.83	0.03	0.19	0.05	14.03	0.68
M87 DW 12	12 28 47.7	12 53 15	39.0	16.96	0.07	0.72	0.10	0.12	0.15	16.90	0.70
M87 DW 22	12 25 39.9	10 34 30	35.6	15.18	0.02	0.85	0.03	0.21	0.04	14.65	
M87 DW 27	12 23 1.4	13 30 19	35.6	16.29	0.04	0.93	0.06	0.27	0.10	16.03	
M87 DW 28	12 21 54.6	13 30 44	35.6	15.14	0.02	0.92	0.03	0.10	0.04	14.58	
M87 DW 31	12 31 35.1	13 0 58	35.6	15.93	0.04	0.84	0.06	0.15	0.09	15.57	
N4472 DW 1	12 25 57.5	7 36 6	35.6	15.79	0.03	0.80	0.04	0.34	0.07	15.17	0.64
N4472 DW 2	12 26 26.6	7 48 13	35.6	16.63	0.07	0.91	0.10	0.35	0.20	16.15	0.90
N4472 DW 4	12 28 28.7	7 59 54	35.6	16.59	0.04	0.69	0.06	0.27	0.09	16.30	1.00
N4472 DW 5	12 26 9.1	8 4 53	39.0	16.92	0.05	0.69	0.07	0.05	0.11	16.70	0.83
N4472 DW 6	12 25 22.4	8 22 7	35.6	14.72	0.01	0.77	0.02	0.21	0.03	14.39	0.81
N4472 DW 7	12 27 4.8	8 12 32	39.0	15.92	0.03	0.84	0.05	0.48	0.10	15.11	0.82
N4472 DW 8	12 27 33.0	8 21 03	35.6	15.13	0.02	0.79	0.03	0.44	0.06	14.89	0.96
N4472 DW 9	12 24 46.0	8 29 33	39.0	16.28	0.04	0.79	0.05	0.13	0.08	15.84	1.00
N4472 DW 10	12 29 42.0	8 19 00	39.2	15.24	0.04	0.66	0.05	0.17	0.08	13.67	0.80
IC783 CH 2	12 20 39.0	15 51 16	35.6	14.67	0.01	0.82	0.01	0.33	0.02	13.96	
M100 CH 3	12 21 20.0	15 50 29	35.6	15.37	0.02	0.79	0.04	0.18	0.05	14.85	
N4328 CH 1	12 22 20.0	15 55 42	35.6	14.39	0.01	0.86	0.01	0.23	0.02	13.63	
M100 CH 5	12 22 20.0	15 58 30	35.6	16.45	0.04	0.74	0.04	0.18	0.06	16.25	
M100 CH 6	12 20 56.0	15 45 11	39.0	15.34	0.02	0.87	0.02	0.30	0.03	14.82	
N4594 DW 1	12 36 39.1	-11 26 38	35.6	16.56	0.05	0.62	0.05	0.00	0.07	16.81	0.69
FIELD DW 5	12 40 30.0	3 56 00	39.2	14.10	0.02	0.87	0.02	0.31	0.05	13.24	
N3115 DW 1	10 3 13.5	-7 44 7	58.6	13.45	0.01	0.87	0.01	0.26	0.02	12.76	0.79
N5846 DW 1	15 2 11.1	1 28 47	35.6	16.11	0.03	0.90	0.05	0.35	0.10	15.58	0.90
N5846 DW 2	15 3 6.1	1 29 31	36.2	16.58	0.04	0.86	0.06	0.34	0.11	16.53	0.97
N5846 DW 5	15 3 18.9	2 5 50	35.6	16.22	0.03	0.82	0.04	0.22	0.06	16.00	0.89
N5206	13 30 36.0	-47 52 00	29.8	14.11	0.01	0.85	0.02	0.37	0.03	14.02	

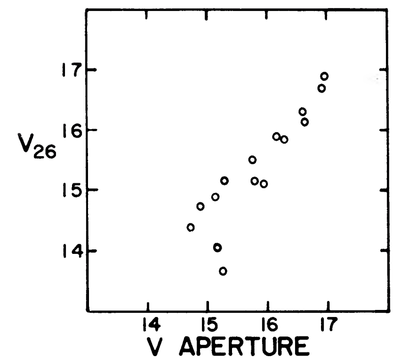

FIG. 2. The observed photoelectric visual magnitudes contained within an aperture of 35″.6 is plotted against the derived photographic V_{26} magnitudes for those galaxies in the Virgo cluster that have both observations. This plot reveals implicitly the dependence of average surface brightness on total luminosity for these galaxies.

These are only accurate to within 0.05, due to the low signal-to-noise of the galaxy images. Those objects without listed axial ratios are those for which V_{26} magnitudes had to be found by the relation between aperture magnitude and V_{26}. Figure 2 shows V_{26} plotted against photoelectric magnitude taken with a diaphragm of diameter 35″.6 for those galaxies that have both pieces of data. A nice relation is evident, so the V_{26} magnitude may be found for the galaxies for which plates were not available by simply looking on the graph for the V_{26} value that corresponds to the measured aperture magnitude.

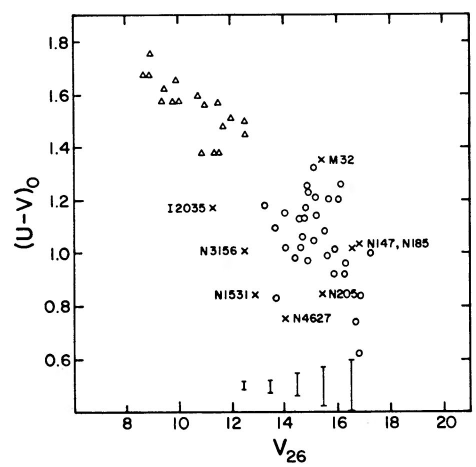

FIG. 3. The color magnitude relation for bright elliptical galaxies in the Virgo cluster (triangles) and the dwarf galaxies in this paper (open circles). $(U-V)_0$ is plotted against V_{26} for the distance modulus of the Virgo cluster. The apparent magnitudes of those galaxies not at the Virgo distance modulus (taken to be 31.7) were changed by an amount appropriate to the distance modulii differences between them and Virgo. The additional galaxies plotted are IC 2035 and NGC 3156, both of them S0s with Balmer line spectra, NGC 1531, NGC 4627, and the dwarf E companions to M31 (all plotted as Xs). The average errors in $(U-V)$ for each faint magnitude interval are displayed at the bottom of the plot.

Figure 3 is the graph of the data, with $(U-V)_0$ plotted against V_{26}. Included are all of the dE's in this survey, the bright ellipticals observed with the same system (described in Caldwell 1983) combined with the V_{26} of *SV*, the local group dE's, and cases of known star formation in early-type galaxies, to be referred to as "extreme cases." These additional galaxies are IC 2035 and NGC 3156, both of them S0's with Balmer line spectra (Caldwell 1982), and NGC 1531 and NGC 4627, described above. The average errors in $(U-V)$ for each faint magnitude interval are displayed at the bottom of the plot. The photometry for M32, N147, and N185 is taken from Sandage (1972). For N205, the large aperture measurement (250″) of de Vaucouleurs (1958) is plotted. The photometry of N4627 and N1531 is taken from the Second Reference Catalog (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), while that of IC 2035 is the transformed value from Sandage and Visvanathan (1978). NGC 3156 was observed in Caldwell (1983). The apparent magnitudes of those galaxies not at the Virgo distance modulus (taken to be 31.7) were changed by an amount appropriate to the distance modulii difference between them and Virgo. The distance moduli were calculated assuming a uniform Hubble flow and $H_0 = 50$ km s^{-1} Mpc^{-1}. A distance of 5 Mpc was assumed for N5206.

From this diagram, we first note that the color-magnitude relation is linear over 9 mag, nearly a factor of 4000 in mass, assuming M/L is constant. The slope of the relation is about 0.10 in $(U-V)$ per magnitude interval. Second, there are very few galaxies in this group with colors as extreme as the galaxies with known star formation. N4472 DW10 and N4594 DW2 are the only two with color deviations that are commensurate with the extreme cases. The former galaxy shows quite a bit of small-scale structure on a blue plate (Fig. 1). It was selected from the Sky Survey charts and does not have the same appearance as those displayed in the other pictures. N4594 DW2 has one of the fainter apparent magnitudes in this study. A final comment is that the local group dE's bracket the color-magnitude relation for these dE's. If the distance modulus of Virgo is really 31.0 as Mould, Aaronson, and Huchra (1980) find, the local group dE's become 0.7 mag brighter with respect to the Virgo dwarfs. In that case, N185 and N147 fall within the range of colors of the Virgo dwarfs.

Judging from the linearity of Fig. 3, one might suppose that the color-magnitude diagram tells more about the uniqueness of the extreme cases than it does about the dwarfs. But even with its young stars, N185 cannot be considered to be abnormally blue in this diagram. So perhaps there is something in the diagram about star formation in dwarfs after all. The extreme cases, of which some have photographic evidence for young stars, are from 0.2 to 0.1 bluer than the blue ridge line of the dwarfs. N4472 DW10, even with its mottled structure, is only 0.19 bluer than M87 DW11, which has a completely smooth profile. We can presume that the extreme cases as well as N4472 DW10 all have a fair number of OB stars, which are ionizing the interstellar gas (aside of N4472 DW10, all of these galaxies are known to have [O II], Caldwell 1982). A change of 0.19 in the $U-V$ colors of the dwarfs in this paper can be easily accomplished by adding in enough O stars so that the stars contribute 4% of the light in the visual region. This is roughly the amount of visual light contributed by the OB stars to the solar neighborhood "young sequence population" of Gunn, Stryker, and Tinsley (1982). A lack of OB stars would then mean that the dwarf colors should be slightly redder at a given total luminosity than the extreme cases. Thus it is possible that the extreme cases are those in which star formation has occurred recently enough for OB stars to still be alive, whereas the dwarfs in this study, although of a young mean age, no longer have any OB stars.

Sandage and collaborators (1979, 1982) have reported that the spectra of Virgo dwarf ellipticals have Balmer absorption lines which become more prominent as the galaxy luminosity decreases. It seems likely that the interpretation of the dwarf spectra is the same as that of the other galaxies which have Balmer absorption lines: a young population. This is also the interpretation that Sandage (1979) gave to the spectra.

VI. THE STRUCTURE OF THE DWARFS

Figure 4 presents surface brightness profiles of some of the dwarf ellipticals in the M87 and N4472 fields. Surface brightness in V is plotted against log r, where

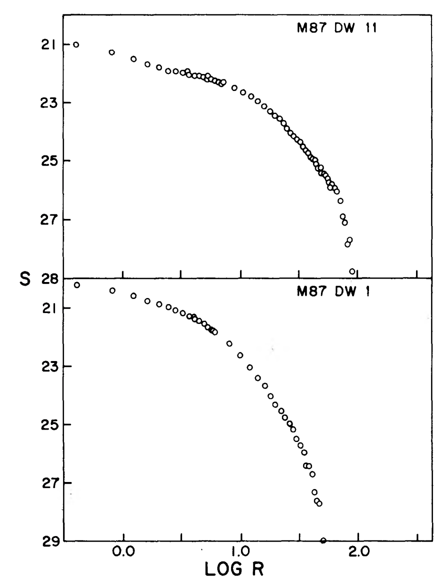

FIG. 4. Surface brightness profiles of some of the dwarf galaxies in this paper. The surface brightness in visual magnitudes per square arcsecond is plotted against the log of the radius, where the radius is the geometric mean of the semimajor and semiminor axes of the isophotal ellipse.

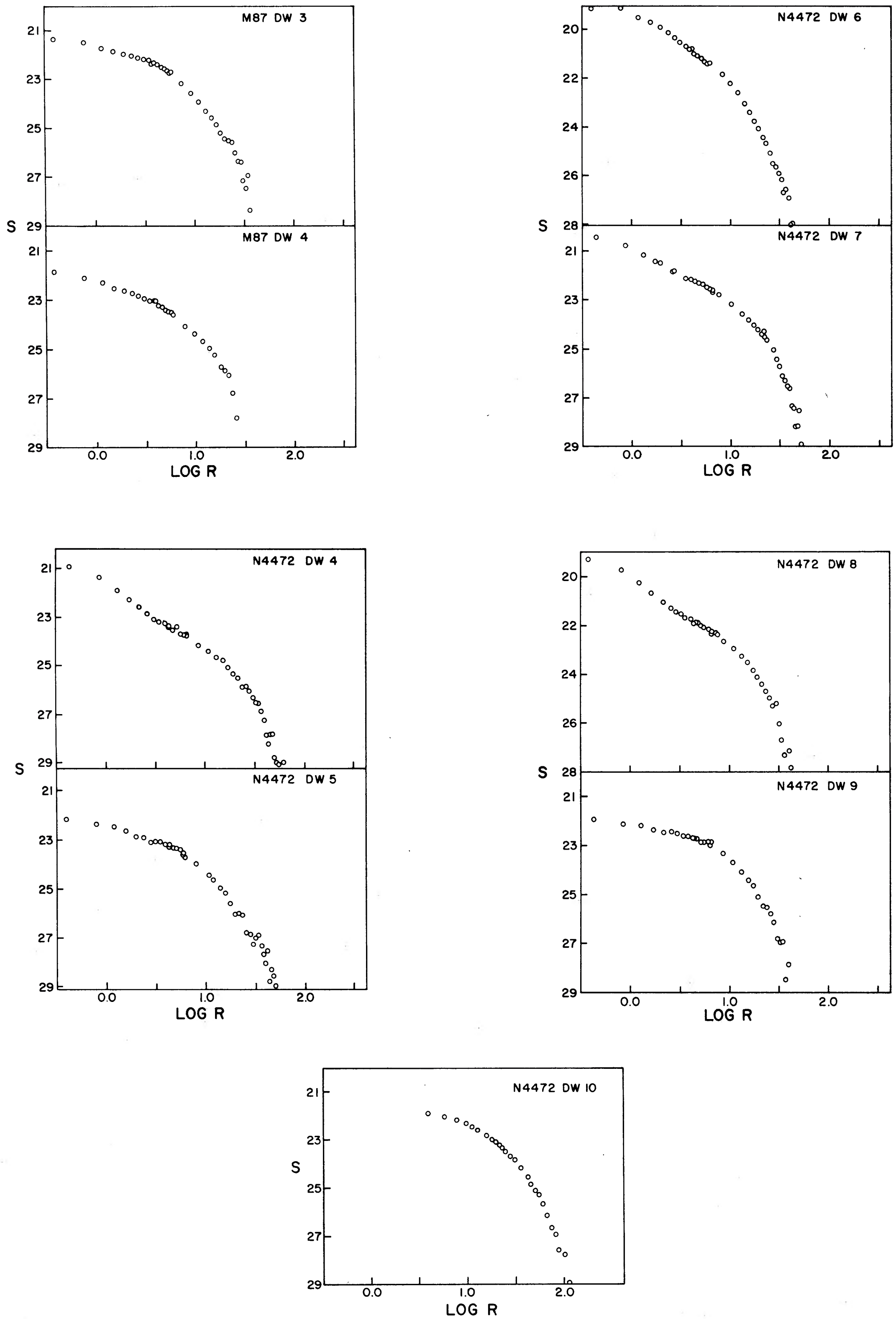

FIG. 4. (continued).

$r = (ab)^{1/2}$, the geometric mean of the semimajor and semiminor axes in arcseconds (subtract 0.99 to convert to log r in kpc). By using the small pixel size PDS raster scans (0″1), the profiles could be followed into the galaxy centers to a radius quite a bit smaller than the radius of the seeing disk on the plates. This was done in order to better display the prominent nuclei in many of these galaxies; seeing would only tend to degrade the contrast between the nucleus and the outer regions. The nuclei are most certainly unresolved in all cases, since the humps begin at about 2″. The envelopes are roughly Hubble profiles, but rarely is the slope -2 in for a large interval in log r. None of the galaxies extends to much greater than 10 kpc.

One of the results of the extensive studies of ellipticals first done by Oemler (1976), and then Strom and Strom (1978a,b,c) was that the intensity profiles of bright ellipticals all have about the same central surface brightnesses, but their limiting radii vary, thus leading to a lower total luminosity for galaxies with smaller radii. In the dwarfs, while the limiting radii still vary somewhat, the central surface brightnesses also change, leading to a strong correlation between average surface brightness and luminosity. The galaxies, however, are a heterogeneous group insofar as their structure is concerned. Striking differences are most evident between M87 DW11 and N4472 DW6, which are of comparable luminosity. The former has a mild nucleation, a broad shoulder in the light profile, and a limiting radius of nearly 100″. N4472 DW6 has a central surface brightness 2 mag brighter, no nucleation, and a limiting radius of only 40″. Its profile is in fact comparable to that of NGC 205 (Hodge 1973), which is again of similar total luminosity.

One question to ask about these galaxies regards the nature of the nucleations. Is there some correlation of the brightness of the nucleus with another physical parameter? To measure the excess light in the nuclei, the galaxy data for log $r > 0.5$ were all fit, to the function

$$I/I_0 = \exp(-(r/\alpha)^2)/(1 + r/\beta)^2$$

(Oemler 1976) which adequately describes the light distributions of bright ellipticals. The brightness expected at the innermost isophote from the fit is then compared

TABLE II. Structural properties.

Name	M_0	contrast	log α	log β	log r_{26}	S (log r =0.5)
M87 DW1	16.46	-0.06	1.43	0.73	1.69	21.19
M87 DW3	17.34	-0.02	1.37	0.78	1.49	22.18
M87 DW6	16.35	-1.23	1.29	0.89	1.63	21.50
M87 DW7	16.35	-0.51	1.60	1.04	1.72	21.97
M87 DW8	16.88	-0.26	1.38	0.84	1.57	21.96
M87 DW10	17.35	0.22	1.30	0.89	1.46	22.68
M87 DW11	15.48	-0.58	1.78	1.21	1.86	21.98
N4472 DW1	16.31	-0.64	1.61	1.15	1.66	22.62
N4472 DW2	17.25	-0.71	1.48	1.07	1.45	23.27
N4472 DW4	17.08	-1.07	1.52	1.11	1.44	23.26
N4472 DW5	18.36	0.16	1.55	0.69	1.40	23.28
N4472 DW6	16.12	-0.54	1.35	0.67	1.74	20.77
N4472 DW7	16.14	-1.25	1.46	1.09	1.67	22.25
N4472 DW8	16.24	-1.76	1.42	1.14	1.70	21.93
N4472 DW9	16.68	-0.10	1.36	1.05	1.55	22.73

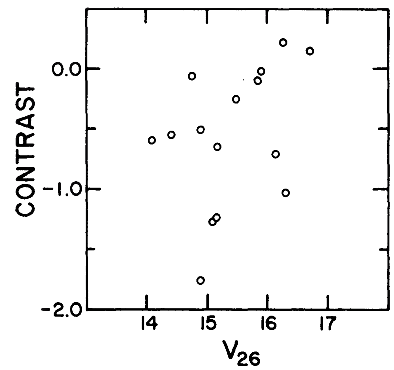

FIG. 5. The excess brightnesses of the nuclei of the dwarfs in the M87 and N4472 fields are plotted against the V_{26} magnitudes.

to the real brightness. Table II contains this contrast value, the reduced magnitude ($M_0 = -2.5 \log I_0$), log α, and log β in arcsecs, the radius inside which V_{26} is computed (r_{26}) and the surface brightness at log $r = 0.5$. From these data there does not appear to be a correlation between excess brightness and luminosity (Fig. 5). This means that the buildup of the central concentration did not simply depend on the amount of exterior material available. The intensity of the nucleus is also not dependent on a radius parameter since the isophotal radii of these galaxies are dependent on the total luminosity, meaning that we are back to the previous test.

Romanishin, Strom, and Strom (1977) reported finding no significant differences in color between the nuclei and the surroundings, but one can imagine the difficulty in obtaining photographic colors of what is essentially a 17th mag star embedded in a galaxy. In fact, since the nucleations appear on blue and red plates, we already know that the colors are not extraordinarily blue. Perhaps these nuclei are just tightly bound clusters of stars, whose ages are not significantly different from those of the outer regions of the galaxies. If so, the next observation to make would be to measure the nuclear velocity dispersions and compare it to the halo velocity dispersions. This is an exceedingly difficult project to do, but worthwhile since the brightness contrast of the nucleus would mean the observations would really pertain only to the nucleus, a rare piece of information in any galaxy.

The surface brightness near the centers of the dE's is, as I have said, a strong function of luminosity. Figure 6 shows the surface brightnesses at a radius just outside of the dwarf nucleations ($r = 3''16$) plotted against V_{26}. The bright elliptical data as well as the local group dwarf elliptical and spheroidal data are taken from Sandage and Visvanathan (1978), King (1978), Oemler (1976), de Vaucouleurs (1953), and Hodge (1963b, 1973, 1974). The data for the local group dwarfs are those that would be observed if the galaxies were at the distance of Virgo. A change in the relative distance modulus from the local group to Virgo would result in a movement of the local group galaxies parallel to the line described by the data.

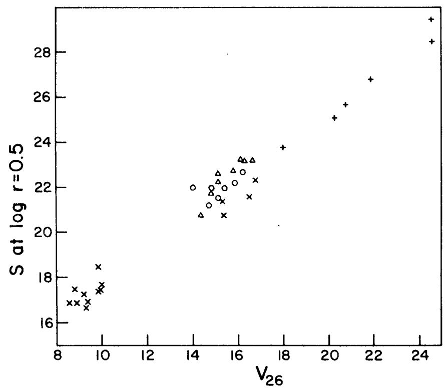

FIG. 6. The surface brightnesses at log $r = 0.5$ are plotted against the V_{26} magnitudes for bright ellipticals (Xs), the dwarfs in this study (circles for the M87 field, triangles for the N4472 field), the local group dwarfs (also Xs), and the dwarf spheroidals of the Milky Way (+).

This is due to the usual cancelling out of the effects of the luminosity decreasing as distance squared and the surface brightness decreasing as radius squared (which increases with distance). In this plot the difference between the local group dE's and the dE's of this study is noticeable. Unfortunately, so is a difference between the M87 and N4472 dwarfs, which is probably due to an error in the intensity calibration of the photographic plates. The dwarf spheroidals of the Galaxy are of course even fainter than these objects, but their central surface brightnesses seem to be near that expected from the extrapolated relation.

Strom (Romanishin, Strom, and Strom 1977, and private communication) has asserted that the low surface brightness dwarfs in Virgo are fossil disk systems: dwarf spirals that have lost their disk gas through a violent event. If the gas fraction in these systems was initally large, the gas then provided much of the gravitational potential in the disk, and its removal would cause the disk stellar system to fatten in order to conserve energy (Biermann and Shapiro 1979). This fattening of the disk would have to be quite dramatic to reproduce the flattenings listed in Table I (see also Sandage 1979). Figure 7 compares the flattening distributions of the dE galaxies in this group with the E's (dashed line) in the study of intrinsic flattenings by Sandage, Freeman, and Stokes (1970). The flattening distribution of the dE's is quite similar to that of the bright E's, but not at all like the uniform distribution that characterizes disk galaxies. Note also that these galaxies occur outside the Virgo cluster, where gas removal mechanisms are expected to be absent. From this fact, Fig. 7, and the assumption that flat galaxies were not discriminated against in the selection process, the best interpretation of the low surface brightness dwarfs is that they are spheroidal and not disk systems. Figure 7 also shows the flattening distribution of the Magellanic irregular galaxies from Fisher and Tully's (1977) paper on the H I content of dwarf galaxies. The distribution is also similar to that of the dwarf E's in this study.

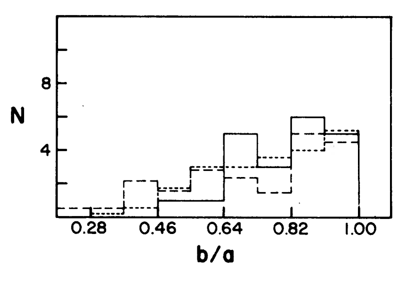

FIG. 7. The number of galaxies in a particular bin of b/a (the flattening) is plotted against the flattening. The solid line is from the data in this study, while the short dashed line is for bright ellipticals and is taken from the work of Sandage, Freeman, and Stokes (1970). The long dashed line is the flattening distribution for the Magellanic irregulars listed in Fisher and Tully (1977).

Finally, Larson (1974) showed in his hydrodynamic collapse models of spherical galaxies that a shallow surface density profile is one result of a galactic wind that purges the interstellar gas early in the formation process. The larger the fraction of total mass in gas that is lost, the shallower is the resultant profile. So the correlation of central surface brightness with total luminosity of the dwarfs in this study could be explained by a scenario wherein the initial total masses of the galaxies were comparable, but a range in final masses was induced by a variation in the efficiency of gas removal. However, this purging process should also severely inhibit the formation of a nucleus, which, in his models, is the result of subsequent infall of material into the center of a galaxy. This is, of course, contrary to what is observed.

VII. CONCLUSIONS

A small number of low-luminosity elliptical galaxies have been studied using photoelectric and photographic techniques. The color-magnitude relation for E's now extends from $M_v = -23$ to -15, and is linear over that range with a slope of 0.10 in $U - V$ per visual magnitude. Galaxies which are known to contain a large number of young stars are from 0.10 to 0.20 mag bluer than the lower envelope of the elliptical color-magnitude relation. This difference can be accounted for by a lack of the most massive stars in a young population. Thus, the Balmer absorption line spectra of the dE's that have been observed by others can be best understood as the signature of a young population that no longer has an upper main sequence of stars.

Intensity profiles of the dwarfs have revealed some interesting distinctions between themselves and the brighter E's. In general, their surface brightness profiles are shallower than those of the bright E's, meaning they are of lower mean density. These mean densities are also a function of the total luminosity. Unlike the bright E's, the surface brightnesses near the centers are also a strong function of the total luminosity. The presence of a nucleation, which can be as much as 2 mag brighter than what the outer envelope would predict, does not appear to depend on any other measurable property of the galaxies. One galaxy, N4472 DW6, has a structure like that of the local group dwarf N205, i.e., unlike the others in this study. This fact is suggestive that the low-luminosity dwarfs formed in more than one way.

An interesting thought concerns the kind of Virgo galaxy typified by N4472 DW10. As a reminder, this galaxy is only a little bluer in $U-V$ than the bluest dwarf ellipticals in this study. No spectrum of this galaxy is available, but it is not too hard to imagine what it probably looks like: emission lines characteristic of H II regions, and a young star absorption line spectrum. That is, if the emission lines are ignored, the galaxy spectrum would probably strongly resemble the dwarf elliptical spectra of Sandage's (1979). Interestingly, the intensity profile of N4472 DW10 is quite similar to that of M87 DW11. Also of note is the fact that the flattening distribution of the dE's is consistent with that of Magellanic irregulars found in the field. A scenario whereby the Virgo dwarf irregular galaxies (estimated to be 10%–20% of the Virgo dwarfs by Sandage 1982) evolve into dwarf ellipticals is therefore plausible, and should be investigated in future studies using the IR colors, H I content as well as the integrated spectra of both kinds of dwarfs.

It is a pleasure to thank Gus Oemler who originally suggested that a study of dwarf ellipticals should form part of my thesis at Yale. I would like to thank the organizers of the conference on dwarf galaxies at Kitt Peak for a most enjoyable meeting which prompted some changes in this text. Bob Schommer and the referee, Jeremy Mould, provided much appreciated critical readings of the text.

REFERENCES

Baade, W. A. (1951). Publ. Obs. Univ. Mich. **10**, 7.

Biermann, P., and Shapiro, S. L. (1979). Astrophys. J. Lett. **230**, L33.

Burstein, D. (1979). Astrophys. J. **232**, 74.

Caldwell, C. N. (1982). Ph. D. thesis, Yale University.

Caldwell, N. (1983). Astrophys. J. **268**, in press.

Crampton, D., Cowley, A., and McClure, R. (1982). Astrophys. J. **260**, 222.

de Vaucouleurs, G. (1953). Mon. Not. R. Astron. Soc. **113**, 134.

de Vaucouleurs, G. (1958). Bull. Lowell Obs. **4**, 105.

de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G., Jr. (1976). *The Second Reference Catalog of Bright Galaxies* (University of Texas Press, Austin).

Faber, S. M. (1973). Astrophys. J. **179**, 731.

Fisher, J., and Tully, R. B. (1977). Astron. Astrophys. **44**, 151.

Gallagher, J. S., and Hunter, D. A. (1981). Astron. J. **86**, 1312.

Gunn, J. E., Stryker, L. L., and Tinsley, B. M. (1981). Astrophys. J. **204**, 649.

Hodge, P. W. (1963a). Astron. J. **68**, 435.

Hodge, P. W. (1963b). Astron. J. **68**, 691.

Hodge, P. W. (1973). Astrophys. J. **182**, 671

Hodge, P. W. (1974). Circular 12, IAU Comm. 28.

King, I. R. (1978). Astrophys. J. **222**, 1.

Landolt, A. U. (1973). Astron. J. **78**, 759.

Larson, R. B. (1974). Mon. Not. R. Astron. Soc. **169**, 229.

Mould, J., Aaronson, M., and Huchra, J. (1980). Astrophys. J. **238**, 458.

Oemler, A., Jr. (1976). Astrophys. J. **209**, 693.

Reaves, G. (1956). Astron. J. **61**, 69.

Reaves, G. (1977). In *The Evolution of Galaxies and Stellar Populations*, edited by R. B. Larson and B. M. Tinsley (Yale Univ. Obs., New Haven), p. 37.

Romanishin, W., Strom, K. M., and Strom, S. E. (1977). Bull. Am. Astron. Soc. **9**, 347.

Sandage, A. R. (1972). Astrophys. J. **176**, 21.

Sandage, A. R. (1979). Annual Report Dir. Hale Obs., p. 621.

Sandage, A. R. (1982). Talk given at the conference on dwarf galaxies at KPNO in Tucson.

Sandage, A. R., Freeman, K. C., and Stokes, N. R. (1970). Astrophys. J. **160**, 831 (SFS).

Sandage, A. R., and Visvanathan, N. (1978). Astrophys. J. **223**, 707.

Strom, K. M., and Strom, S. E. (1978a). Astron. J. **83**, 73.

Strom, K. M. (1978b). Astron. J. **83**, 732.

Strom, K. M. (1978c). Astron. J. **83**, 1293.

Strom, K. M., Strom, S. E., Jensen, E. B., Moller, J., and Thompson, L. A. (1977). Astrophys. J. **212**, 335.