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A new extragalactic distance indicator based on the surface brightness profiles of dwarf elliptical galaxies

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ABSTRACT

We present evidence for a correlation between the curvatures of the surface brightness profiles of dwarf elliptical (dE) galaxies and their intrinsic luminosities (for objects with similar stellar populations), based on both Local Group (LG) and Fornax cluster (FC) galaxies. As profile shapes are invariant with distance, this correlation can be used as a distance indicator. A comparison between the LG and FC dEs yields a distance of $13.8^{+2.2}_{-1.8}$ Mpc for the FC.

Key words: galaxies: clusters: individual: Fornax – galaxies: distances and redshifts – galaxies: fundamental parameters – Local Group – distance scale.

1 INTRODUCTION

Bothun, Caldwell & Schombert (1989) found that dEs with exponential profiles exhibit little variation in scalelength (r_0). Invoking r_0 as a distance indicator, for that subset of dEs with approximately exponential profiles, they derived relative distance estimates for the Virgo, Fornax and Centaurus clusters. Ichikawa, Wakamatsu & Okamura (1986) and Binggeli & Cameron (1991), however, suggested that the *shapes* of the surface brightness profiles of dEs might provide a distance indicator. By adopting a seldom-used parametrization to describe profile curvature, we confirm these suggestions in this paper.

2 PROFILE PARAMETRIZATION

We find that Sérsic's (1968) generalization of de Vaucouleurs's (1958) $r^{1/4}$ and exponential laws provides a good description of the profiles of most dEs. This generalized profile law can be written

$$\sigma(r)=\sigma_0 \exp\left[-\left(\frac{r}{r_0}\right)^n\right], \qquad (1)$$

in which r is the reduced radius ($\sqrt{r_{\rm major}r_{\rm minor}}$), $\sigma(r)$ is the surface brightness in linear units of luminous flux density at r, σ_0 is the central surface brightness and r_0 is the angular scalelength. For a recent reappraisal of Sérsic's parametrization, see Caon, Capaccioli & D'Onofrio (1993) but note that, in common with Davies et al. (1988), n in our paper corresponds to Sérsic's n^{-1}. Converting the law into the standard logarithmic units of surface brightness (mag arcsec^{-2}), the central surface brightness becomes $\mu_0=-2.5\log_{10}\sigma_0$, whence

$$\mu(r)=\mu_0+1.086\left(\frac{r}{r_0}\right)^n, \qquad (2)$$

enabling values of μ_0 and r_0 to be obtained by linear regression when the optimum value of n has been derived (see Section 3). The analytical solution

$$2\pi\int_0^\infty \sigma_0 r \exp\left[-\left(\frac{r}{r_0}\right)^n\right]\mathrm{d}r=\frac{2\pi\sigma_0\Gamma\left(\frac{2}{n}\right)r_0^2}{n} \qquad (3)$$

then yields an estimate of the total luminous flux within the pass-band concerned.

3 THE DATA AND THE REDUCTIONS

Of the five brightest ellipticals in the LG, four objects were of interest to this study. M32 was excluded because it is known to be severely tidally truncated by M31, and as a consequence exhibits a surface brightness profile similar to those of classical ellipticals (see e.g. Wirth & Gallagher 1984). Surface photometry has been published for the remaining objects, NGC 205, 185 and 147 and Fornax, by Hodge (1963, 1973, 1976), de Vaucouleurs & Ables (1968), Hodge & Smith (1974), Price (1985), Kent (1987), Peletier (1993) and Lee, Freedman & Madore (1993a). We have selected photometry from amongst these sources. When more than one profile had been published for a particular galaxy, preference was given to those profiles derived from B-band CCD observations. The adopted profiles are depicted in Fig. 1. The profile of NGC 205 is from Peletier (1993). That of NGC 185 is a composite of Lee et al.'s (1993a) for $r<46$ arcsec and Kent's (1987) r_{TG}-band (Thuan & Gunn 1976) profile for the outer regions [as Lee et al. (1993a) found no detectable $(B-V)$ or $(V-R)$ colour gradient at $r>30$ arcsec]. Kent's r_{TG} profile of NGC 147 was also used, as Hodge (1976) found no colour gradient for this galaxy. The transformation $B=r_{TG}+1.21$ was found to be appropriate both for the outer parts of NGC 185 and for NGC 147, on the basis of the colour information presented by Lee et al. (1993a) and Hodge (1976) respectively. Eskridge's (1988) star-count study of Fornax provided a relative intensity profile, which we sampled at 14 points and normalized with the central part of de Vaucouleurs & Ables's photometric profile. Note that the shapes of the inner parts of the star-count profiles by Hodge & Smith and Eskridge are more consistent with the photometry by de Vaucouleurs & Ables than with Hodge & Smith's own surface photometry.

The FC galaxy profiles were all taken from the B-band CCD observations of Caldwell & Bothun (1987). We digitized all 17 of the dE profiles presented in their paper, as well as nine of their E (classical elliptical) profiles. Although their seeing conditions were not documented, it is clear from the profiles of the nucleated dwarfs that they must have experienced sub-arcsecond seeing, perhaps as good as 0.6 arcsec.

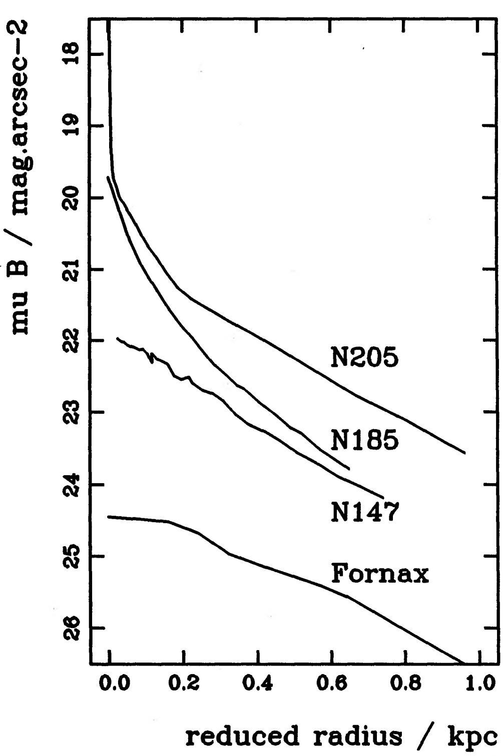

Figure 1. B-band surface brightness profiles of LG dEs after corrections for distance (which introduce large uncertainties into the relative r/kpc scales of the four profiles) and external absorption. Absorption and distance estimates were taken from Lee, Freedman & Madore (1993b) and Buonnano et al. (1985), using $A_B=4.2\,E(B-V)$ from Seaton (1979).

The LG and FC profiles were parametrized using the same procedure. This involved incrementing n from 0.2 to 3.0 in steps of 0.01, and attempting to fit a straight line to $\mu(r)$ as a function of r^n. Isophotes fainter than $\mu_B=26.0+A_B$ (where A_B is the line-of-sight absorption at B) were excluded, as were nuclei (when present), but the surrounding core regions were included. By nuclei, we mean sharp discontinuous central peaks, of which NGC 205's (see Fig. 1) is a good example. NGC 205's nucleus, which corresponds to that region within $r<20$ arcsec, arises because the young stars within this region have not yet had enough time to disperse and make the colour distribution look smooth (see e.g. Peletier 1993). The weightings applied to the profile data points are discussed in Section 4. χ^2 was evaluated for each fit, and the r_0- and μ_0-values corresponding to the best fit were adopted along with the optimum n-value. The total apparent B magnitudes (m_B) were then estimated by means of equation (3), which in the cases of the LG objects yielded absolute B magnitudes (M_B) after corrections for line-of-sight absorption and distance. The parameters computed for LG galaxies are listed in Table 1, whilst those for FC galaxies are listed in Table 2.

4 THE LUMINOSITY-n CORRELATION

Both LG and FC galaxies appear to exhibit a correlation between luminosity and n (see Fig. 2), in which the two loci have been superimposed by shifting the FC locus in magnitude space. In the absence of a larger galaxy sample, the correlation can be approximated by a straight line: $M_B=an+b$, in which the coefficient a is best determined from the FC locus and the constant b provides an absolute distance calibration through the four LG objects. The best least-squares straight-line fit to all of the FC galaxies was found to be $m_B=3.639(\pm0.448)n+13.08(\pm0.40)$ (the errors having been determined by bootstrap resampling with 10^5 realizations), for which the rms scatter is 0.88 mag. Particularly as a variety of relevant statistical tests all suggest only a 2–10 per cent probability that the dispersion about the line is normal, it is possible that the four most discrepant FC dEs in Fig. 2 (G14 and NG 60, 63 and 102) may be deviant, either because their mass-to-light (M/L) ratios are atypical of the galaxy sample, or/and because they are foreground or background galaxies that do not actually lie within the cluster. NG 63 [the only one of the four outliers whose colour

Table 1. Adopted distance moduli and reddening terms, together with the n-values and absolute magnitudes [extrapolated by means of equation (3) and corrected for absorption] derived from the B-band profiles of the LG dEs.

LG galaxy	$(m-M)$	$E(B-V)$	n_B	M_B
NGC 205	24.42	0.035	0.41	−16.09
NGC 185	23.96	0.19	0.58	−14.72
NGC 147	24.13	0.17	1.06	−14.27
Fornax	20.59	0.03	1.38	−12.56

Table 2. The n-values and extrapolated apparent magnitudes derived from the B-band profiles of the FC galaxies. The G numbers are from Jones & Jones (1980), and the NG numbers are from Caldwell (1987). Nucleated dwarfs are denoted 'dEn', whilst galaxies classified as classical ellipticals by Caldwell & Bothun (1987) are denoted 'E'.

FC galaxy	type	n_B	m_B
NG 1	dEn	0.62	16.03
NG 4	dEn	0.98	16.28
NG 5	dEn	1.08	17.12
NG 22	dEn	1.14	17.15
NG 24	dE	0.52	14.79
NG 35	dEn	1.22	18.35
NG 47	dEn	0.76	15.46
NG 60	dE	1.25	19.08
NG 63	dE	1.80	17.79
NG 69	dE	0.46	14.75
NG 82	dE	1.43	18.78
NG 83	dE	1.48	18.68
NG102	dE	1.18	19.05
G 14	dE	0.85	13.87
G 26	dEn	0.65	15.21
G 43	dE	0.71	16.23
G 72	dE	0.60	15.50
NG 7	E	0.62	14.60
G 8	E	0.36	13.81
G 75	E	0.49	15.03
G 79	E	0.44	14.96
G 84	E	0.36	14.13
G 91	E	0.65	14.48
G 92	E	0.54	15.80
G 104	E	0.72	15.66
G 118	E	0.31	14.74

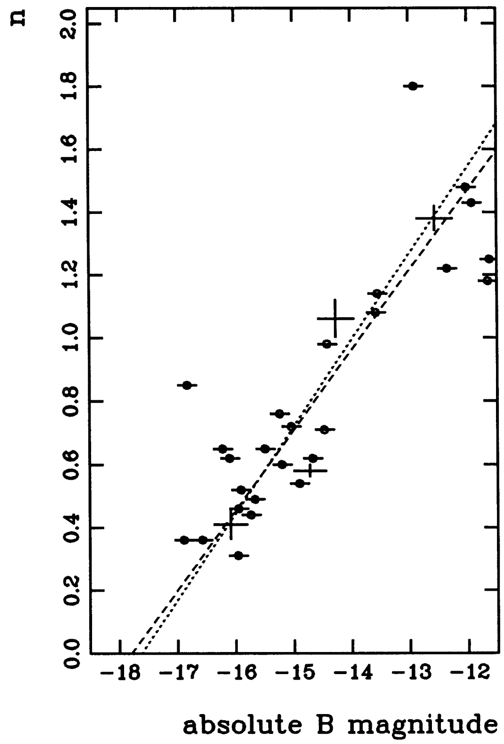

Figure 2. n versus M_B for both LG galaxies (shown with error bars in both axes) and FC galaxies [○ symbols with error bars in magnitude only (± 0.23 mag)]. The dotted and dashed lines represent least-squares fits to all 26 FC galaxies and to the same galaxy sample less the four outliers, respectively. The FC galaxies have been shifted in magnitude space in order to superimpose the LG and FC loci. The dE sequence probably diverges from the classical E ($n \approx 1/4$) one at $M_B \sim -17$.

was measured by Caldwell & Bothun (1987)] has a $(B-V)$ index of 0.48, which is very atypical of our galaxy sample. Furthermore, its large magnitude residual also suggests that it is a foreground object. Interpretation of the magnitude residuals of NG 60 and 102 as due to depth would put them in the background at about twice the distance of the FC. In a forthcoming paper (Young & Currie, in preparation) we will present evidence that G 14 is probably a low-M/L object within the FC rather than a foreground object. Exclusion of these four galaxies reduces the observed rms scatter to 0.47 mag, and the best least-squares fit becomes $m_B = 3.940(\pm 0.313)n + 12.91(\pm 0.25)$.

Of the observed scatter, the depth through the FC can account for ± 0.15 mag (assuming spherical symmetry), and uncertainties in photometric zero-points can account for about ± 0.1 mag. A_B in the direction of the FC is not well known – Burstein & Heiles (1984) obtained negative values for the cluster direction, whilst other authors ignore absorption altogether. In this work we have arbitrarily assumed $\overline{A_B}(\mathrm{FC}) = 0.00^{+0.13}_{-0.00}$ mag. We quantified the error on each profile due to noise and uncertainties in sky determination *individually*, finding $\sigma_{\mu_B}(\mathrm{fit})$ to be typically 0.012 mag at $\mu_B = 21$, 0.011 at $\mu_B = 22$, 0.017 at $\mu_B = 23$, 0.019 at $\mu_B = 24$, 0.027 at $\mu_B = 25$ and 0.025 at $\mu_B = 26$. Note that fainter isophotes were computed from more pixels and $\sigma_{\mu_B}(\mathrm{fit})$ does not always increase with μ_B. Based on these sources of uncertainty, the 1σ confidence limits on the extrapolated apparent magnitude values were found to be of the order of 0.04 mag (with a strong correlation between σ_n and σ_{M_B} such that an increase in n was accompanied by an increase in magnitude). We therefore estimate the net observational uncertainty to be 0.23 mag and the intrinsic scatter on the correlation to be 0.41 mag.

Furthermore, we expect the intrinsic dispersion on the correlation to decrease with increasing n, as nucleation, star formation and internal absorption (within the cores) become less significant. Also, due to observational considerations, Caldwell & Bothun's galaxy sample was understandably biased towards brighter (lower n) objects, and they did not present the profiles of most of their more typical ($n \sim 1$) objects. At $n \gtrsim 0.9$, the true observational and intrinsic dispersions may thus be smaller than those inferred from our galaxy sample.

The estimated errors on the parameters derived for the LG dEs were larger than those for the FC dEs, and are listed in Table 3. Uncertainties in $(m-M)$ were taken from Buonanno et al. (1985), Freedman (1992) and Lee et al. (1993a); those in $E(B-V)$ are probably about 0.03 mag (whence $\sigma_{A_B} \sim 0.13$ mag) for all objects (see e.g. Buonanno et al. 1985; Lee et al. 1993a). Zero-point uncertainties of 0.1 mag have been assumed throughout, as have $r_{\rm TG}$- to B-band transformation errors of 0.04 mag. Errors due to extrapolating the profiles of NGC 205, 185 and 147 beyond the limiting isophotes have been taken to be one-quarter of the size of the extrapolation between the limiting and $\mu_B = 26.0$ (A_B-corrected in both cases) isophotes, in magnitudes with respect to the derived total magnitude. The strong interdependence between σ_n and those components of σ_{M_B} based on the confidence with which the profiles could be fitted and extrapolated $[\sigma_{n({\rm fit})} \sim \sigma_{M_B({\rm fit})}/4$ and $\sigma_{n({\rm ex})} \sim \sigma_{M_B({\rm ex})}/4]$ meant that the FC locus could be fitted to the LG data points in Fig. 2 by minimizing the residuals in magnitude only. Our best estimate of the correlation is

$$M_B = 3.940(\pm 0.313)n - 17.79(\pm 0.30), \qquad (4)$$

with the error on the constant having been determined from the LG locus. This yields a FC distance modulus of $30.70(\pm 0.30) + \overline{A_B}$(FC), and a distance of $13.8^{+2.2}_{-1.8}$ Mpc assuming $\overline{A_B}$(FC) $= 0.00^{+0.13}_{-0.00}$ mag.

Table 3. Estimated error budget for the n- and M_B-values derived for LG galaxies. $\sigma_{n({\rm fit})}$ represents 1σ confidence limits on n based on the relevant observers' photometric errors. '*ex*' denotes the size of the extrapolation between the limiting $+ A_B$ and $\mu_B = 26 + A_B$ mag arcsec^{-2} isophotes, in magnitudes. '*zero point*' denotes photometric zero-point, whilst '*transformation*' denotes transformations between the $r_{\rm TG}$ and B bands. Uncertainties flagged * are mutually correlated, as are those flagged †.

Source of error	N205	N185	N147	Fornax
OVERALL σ_n:	±0.05	±0.02	±0.06	±0.04
* $\sigma_{n(fit)}$	±0.01	±0.02	±0.06	±0.04
† $\sigma_{n(ex)}$	±0.05	±0.01	±0.01	±0.00
OVERALL σ_{M_B}:	±0.29	±0.28	±0.31	±0.31
$\sigma_{(m-M)}$	±0.20	±0.21	±0.15	±0.22
σ_{A_B}	±0.13	±0.13	±0.13	±0.13
$\sigma_{zero\ point}$	±0.10	±0.10	±0.10	±0.10
$\sigma_{transformation}$	±0.00	±0.04	±0.04	±0.00
* $\sigma_{M_B(fit)}$	±0.04	±0.06	±0.22	±0.14
† $\sigma_{M_B(ex)} = ex/4$	±0.12	±0.05	±0.03	±0.00

5 DISCUSSION

Dwarf ellipticals are thought to be unmerged systems and amongst the simplest galaxies dynamically. Apart from the cores of some of the brighter systems, dEs are essentially optically thin (which makes orientation and internal absorption corrections unnecessary for most purposes), and the absence of detectable colour gradients in most systems (except within the cores of some of the brighter objects) suggests that the constituent stars are well mixed. There are thus many reasons to believe that the surface profiles of dEs could make excellent distance indicators.

We hypothesize that the n-value of a dE is a strong function of the gravitational potential well constraining its constituent stars, which is itself a strong function of mass, and hence luminosity in an optically thin system. The more massive the system, the more centrally concentrated it is (and the more likely a nucleus is to condense within it) and the lower its n-value. The more concentrated the system, the higher its stellar number density and hence surface brightness at any r, and therefore the larger and more luminous it is. In this picture, the exponential model is only appropriate for dEs with $n \sim 1.0$, even though portions of the profiles of some other dEs may be approximately exponential.

In order to avoid differences in M/L, we suggest that the new indicator is only applied to galaxy samples within restricted colour or surface brightness ranges (a possible surface brightness parameter might be mean surface brightness within an isophote), or, if samples are sufficiently large, that one of these additional parameters defines a third axis orthogonal to luminosity and n. In the case of this work, there is good reason to believe that the stellar populations within our LG and FC dE samples are very similar, with a few exceptions: Fornax, G 14 and NG 63. The mean $(B-V)$ colour of Caldwell & Bothun's FC dEs is 0.72 (Caldwell & Bothun 1987), whilst the corresponding intrinsic integrated colours for NGC 205, 185 and 147 are 0.71, 0.72 and 0.74 respectively, based on the sources of photometry and $E(B-V)$ values already cited. De Vaucouleurs & Ables (1968) observed $(B-V)$ to be 0.63 for Fornax, which corresponds to an intrinsic colour of 0.60 (although CCD observations would be useful to confirm this). Environmental factors may also be relevant, but these are beyond the scope of this paper.

Another difference between dEs is that some of the brighter systems, such as NGC 205, appear to be undergoing nuclear star formation. By excluding the area of nuclear star formation ($r<20$ arcsec) but including the rest of the core containing bright youngish stars formed during previous epochs of star formation, the extrapolated magnitude that we have derived for this galaxy is not of course a rigorous total integrated magnitude, but a systemic magnitude more appropriate to our correlation. Note that by including the $20<r<60$ arcsec region for NGC 205, which contains stars more luminous per unit mass than in the rest of the galaxy, there has also been a departure from the $M \propto L$ assumption. This, however, need not be a problem, as the more massive the system the greater the deviation should be, and this deviation is such that it can improve the resolution in n for the lower end of the n-range. As suggested by Binggeli & Cameron (1991), the surface brightness profiles of the brighter dwarfs may therefore be described by a King (1966) model (describing the mass distribution) plus a central luminosity excess.

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