Astron. Astrophys. 359, 447–456 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Off-center nuclei in dwarf elliptical galaxies

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Received 22 December 1999 / Accepted 16 May 2000

Abstract. We have searched for off-center nuclei in 78 "nucleated" dwarf elliptical (dE,N) galaxies, drawing on digitized photographic images from a previous study of Virgo cluster dwarfs. The search is based on a simple algorithm which compares the center coordinates of a series of outer elliptical isophotes with the position of the galaxy's nucleus. Monte Carlo simulations of the measuring procedure are used to assess random and systematic errors. Roughly 20% of all dwarf nuclei in the sample (neglecting uncertain cases) are found to be significantly off-centered. The typical displacement is $1''$, or 100 pc (assuming a Virgo cluster distance of 20 Mpc), corresponding to 0.5 to 1 effective radii of the dwarf galaxy. There is a tendency of the nuclear off-center displacement to increase with decreasing surface brightness of the underlying galaxy. A similar trend was found with normal elliptical galaxies before. If real, the effect could mean that a nucleus can oscillate about the galaxy center with larger amplitude in a shallower (less cuspy) gravitational potential.

In an appendix we present evidence for the existence of a strong, unambiguous relation between the nuclear *magnitude* and the ellipticity of dE,N galaxies. If a nucleus is comprising 4% or more of the total light of the underlying galaxy, that galaxy is nearly always round, i.e. ellipticity less than 0.15 (dE0, dE1). This effect was predicted qualitatively long ago as the result of box orbit disruption caused by a central massive compact object (black hole).

Key words: galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: nuclei – galaxies: structure

1. Introduction

Since many, if not most non-active galactic nuclei are suspected to harbour a black hole (e.g. Kormendy & Richstone 1995), interest in these nuclei is no longer peripheral. Aside from their black hole "attraction", the nuclei are likely telling us something about the star formation history and the dynamics of the innermost part of galaxies. Among the most intriguing nuclei are those in dwarf elliptical (dE) galaxies (for a review on dEs see Ferguson & Binggeli 1994). Due to the low surface brightness of the underlying galaxy, the dE nuclei are not only popping out most clearly, their very formation in a low-density environment is a riddle. The most nearby dE nucleus is that of the Andromeda satellite NGC 205, which is of course known at least since Baade (1944). The universality of the dwarf nucleus phenomenon became clear with the Las Campanas survey of the Virgo cluster (Binggeli et al. 1985, preceded by Reaves 1983) where $\approx$400 nucleated dEs (out of $\approx$800 dEs in total) were identified. The morphology of "dE,N" galaxies is illustrated in the dwarf galaxy atlas of Sandage & Binggeli (1984).

The nature of the dE nuclei is still unclear, but most likely they are massive compact star clusters (like the nuclei in M33 and other low-luminosity spirals; Kormendy & McClure 1993, Phillips et al. 1996, Matthews et al. 1999) constituting separate dynamical entities, but without being totally decoupled from the rest of the underlying galaxy. Their formation is still more speculative. One plausible scenario regards the dE nuclei as the fossils of the last bursts of star formation in the evolutionary transition from dwarf irregulars (or blue compact dwarfs, BCDs) to dwarf ellipticals (Davies & Phillipps 1988; however, see, e.g., Durrell 1997 and Miller et al. 1998 for the shortcomings of the Irr to dE scenario).

In this paper we address the question of *how central* the dwarf nuclei are. The nuclei have of course to be *fairly* central to be noticed as such, but still they could be significantly off-center relative to the radially symmetric, global light distribution of the parent galaxy. Why should this be interesting? Suppose the nuclei were formed secularly by the merging of globular clusters through dynamical friction, or evolved from non-central star burst regions in dwarf irregulars, as in the Davies & Phillipps scenario mentioned above. Depending on the age of the nucleus we might expect them to be off-center to various degrees. Miller & Smith (1992) have shown that even old nuclei would not patiently sit in the center of a galaxy. Such a state would be dynamically unstable; a nucleus is bound to oscillate in the potential of a galaxy. Taga & Iye (1998), performing N-body simulations of a rotating spherical galaxy with a central black hole, have found that the amplitude of oscillation depends on the mass of the black hole (or the nucleus) relative to the mass of the underlying galaxy. The simulations suggest that the amplitude will also depend on the central mass density of the underlying

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galaxy. These things have still to be worked out in detail by further numerical experiments.

In any case, there are enough hints from theory that off-center nuclei should be widespread, and that a quantification of the nuclear offsets might help us to put constraints on the formation, mass, and dynamics of the nuclei and the inner region of galaxies. Several off-center nuclei have been discovered by the *HST* survey of the centers of giant elliptical (E) galaxies (Lauer et al. 1995). However, part of these nuclear offsets in Es could be artifacts due to dust obscuration, or be caused by unresolved off-center sources. Spectacular cases of such off-center sources are the apparent double nuclei in the bulge of M31 and the compact elliptical NGC 4486B (Lauer et al. 1993, 1996), which are most plausibly modelled by an eccentric nuclear disk (Tremaine 1995).

The present paper is a first attempt to find off-center nuclei in dwarf elliptical galaxies, and to quantify the nuclear off-center distances, based on a homogeneous sample of 78 nucleated Virgo cluster dEs.

The rest of the paper is organized as follows. In Sect. 2 we define our sample of nucleated dwarfs, and in Sect. 3 we describe the procedures adopted to measure off-center positions. Some individual cases of off-center nuclei, illustrating the phenomenon and the measuring procedure, are shown and discussed in Sect. 4. To get reliable statistics for off-center nuclei we had to account for systematic and random errors of the measuring procedure, which we did by running Monte Carlo simulations with artificial galaxies, as described in Sect. 5. The statistical results are then presented in Sect. 6, showing the general trends for the whole sample. Our conclusions are given in Sect. 7.

In an appendix we address the relation between nuclear brightness and ellipticity. This feature is related to our main topic of off-center nuclei insofar as it may also have some bearing on the mass of the nuclei and the possibility that they harbour a black hole.

2. Sample

The present investigation draws on the photometric study of $\approx$ 200 Virgo cluster early-type dwarf galaxies by Binggeli & Cameron (1991, 1993, hereafter BC91 and BC93, respectively), which itself is based on digitized photographic plates from the Las Campanas survey of the Virgo cluster (Binggeli et al. 1985, hereafter VCC = Virgo Cluster Catalog). For our purpose of measuring nuclear dwarf positions digitized (deep & high-resolution) photographic images are as well suited as modern CCD images. We have selected a subsample from the BC91 sample by the following constraints: (1) the dwarf object had to be classified as nucleated, i.e. dE,N or dS0,N, and (2) the apparent magnitude was required to be brighter than $B_{\rm T}$ = 18 mag, corresponding to an absolute blue magnitude of -13.5 by assuming a distance to the Virgo cluster of 20 Mpc. Note that the dS0 type is a slight, and for the present purposes insignificant, variant of the dE class (see Sandage & Binggeli 1984, and BC91). – This sample amounted to 109 objects. Due to bright stars in the central areas of the galaxies and other technical difficulties we lost about 30 images. Without introducing strong biases, this left us with a final, representative sample of 78 nucleated dwarfs. The sample galaxies with some of their fundamental photometric parameters (all from BC93) are listed in Table 1. The **columns of Table 1** are as follows:

column (1): VCC number of the galaxy;
column (2): dwarf type classified in the system of Sandage & Binggeli (1984);
column (3): total apparent blue magnitude $B_{\rm T}$;
column (4): mean surface brightness within the effective radius $r_{\rm eff}$ that contains half of the total light, $\langle\mu\rangle_{\rm eff}$ (in B arcsec^{-2}).

The remaining columns (5)–(7) of Table 1 are defined in Sect. 3 further below.

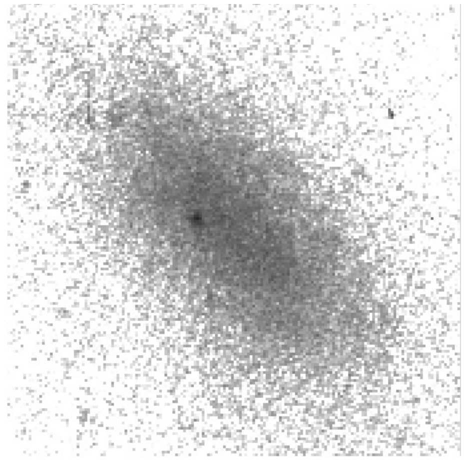

Fig. 1. The dwarf elliptical VCC1857 (=IC3647) classified as “dE,N?”. Note the very large off-center position of the bright quasi-stellar object, rendering its nuclear status uncertain. Compare with the more ordinary (only slightly off-centered) nuclei shown in Fig. 2. The image is 1.2 arcmin on a side.

Constraining the sample to objects explicitly classified as “nucleated” is of course not without problems. Besides a bias against very faint nuclei that simply went undetected in the photographic survey of Binggeli et al. (1985), a nucleus had to be sufficiently *central* to be considered and classified as such, to begin with. A “nucleus” very far off the center is indeed a contradiction in terms. Consider, e.g., VCC1857 depicted in Fig. 1 (also reproduced, as IC3647, in Sandage & Binggeli 1984, Fig. 2, Panel 5). There is a bright star-like object on top of the galaxy, but so much off-center that it might be a foreground star or a background galaxy rather than the type of nucleus seen in the center of “dE,Ns”; hence the classification “dE,N?”. This galaxy still happens to be included in our sample, albeit as “uncertain case” (see below).

A potential problem is the presence of globular clusters in the dwarfs. Deep *HST* images of Virgo dwarf ellipticals (dEs and dE,Ns) by Miller et al. (1998) show many globulars. The distinction between a faint nucleus and a globular may become impossible at this level of high resolution. However, our data do not go deep enough for this to be of any concern.

Table 1. Basic data and nuclear off-center displacements of 78 dE,N and dS0,N galaxies in the Virgo cluster

VCC	Type	B_T [mag]	$\langle\mu\rangle_{eff}$ $[B/\square'']$	δr_N $['']$	$\sigma_{\delta r}$ $['']$	$\frac{\delta r_N}{r_{eff}}$	VCC	Type	B_T [mag]	$\langle\mu\rangle_{eff}$ $[B/\square'']$	δr_N $['']$	$\sigma_{\delta r}$ $['']$	$\frac{\delta r_N}{r_{eff}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
0109	dE3,N	16.06	23.41	0.76	0.06	0.065	1122	dE7,N	14.60	22.42	0.90	0.18	0.062
0235	dE0:,N	16.87	24.81	2.56:	0.10:	0.165:	1164	dE6,N	16.66	24.94	0.88	0.29	0.048
0389	dS0(4),N	14.21	22.16	1.09	0.17	0.070	1167	dE0,N	15.91	23.53	0.96	0.34	0.073
0554	dE2,N:	17.11	24.90	1.19:	0.44:	0.082:	1172	dE5,N	16.23	22.85	0.54	0.12	0.065
0684	dE0,N	16.04	23.16	0.20	0.06	0.019	1185	dE1,N	15.68	22.93	0.23	0.06	0.020
0753	dE0,N	16.37	24.46	0.72	0.14	0.043	1207	dE0,N	17.55	24.72	0.50	0.06	0.047
0765	dE1,N	16.49	22.16	0.30	0.01	0.054	1210	dE0,N	17.65	24.24	0.54	0.06	0.065
0779	dE0,N	17.67	25.00	0.92:	0.34:	0.078:	1213	dE0,N	16.42	24.08	0.41	0.08	0.030
0781	dS03(5),N:	14.72	21.80	0.68:	0.09:	0.065:	1254	dE0,N	15.51	22.90	0.44	0.08	0.036
0810	dE0,N	16.95	23.67	0.26	0.06	0.030	1264	dE0,N	17.31	24.52	0.35	0.07	0.032
0812	dE1,N	17.03	24.43	0.34	0.10	0.028	1308	dE6,N	15.64	22.35	0.16	0.01	0.018
0815	dE2,N	16.10	23.48	0.69:	0.05:	0.057:	1348	dE0,N pec	15.87	22.29	0.33	0.02	0.042
0854	dE8,N	17.69	24.67	0.89:	0.20:	0.089:	1386	dE3,N	14.32	24.18	1.70	0.46	0.046
0856	dE1,N	14.25	22.36	0.41	0.21	0.025	1389	dE2:,N	15.91	22.84	0.27	0.04	0.028
0870	dS0(5),N	15.52	22.51	1.01	0.11	0.101	1399	dE5,N	16.49	24.16	0.68	0.14	0.049
0871	dE4,N	15.79	24.01	0.28	0.05	0.016	1407	dE2,N	15.49	22.46	0.37	0.07	0.037
0872	dE0,N	17.00	23.65	0.08	0.03	0.009	1420	dE4,N	16.41	23.19	0.22	0.04	0.024
0896	dE3,N	17.96	24.60	1.72	0.21	0.202	1444	dE8,N:	16.05	23.46	0.64	0.12	0.053
0916	d:E1,N:	16.04	21.41	0.28	0.02	0.060	1446	dE0,N	16.00	23.55	0.56:	0.06:	0.043:
0931	dE2,N	16.43	24.11	0.53	0.04	0.038	1451	dE5:,N	16.47	23.56	0.23	0.08	0.022
0933	dE2,N	17.00	23.14	0.64	0.10	0.056	1491	dE2,N	15.24	21.98	0.37	0.05	0.041
0936	dE1,N	15.81	23.34	0.31	0.05	0.024	1496	dE5,N:	17.92	24.21	0.36	0.02	0.050
0940	dE1,N	14.72	23.05	0.81	0.10	0.043	1509	dE0,N	16.42	24.05	1.05	0.11	0.078
0949	dE4,N	15.48	23.78	0.40	0.05	0.022	1523	dE0,N	17.64	24.19	0.70	0.12	0.086
0974	dE3:,N	16.11	22.62	0.19	0.06	0.024	1539	dE0,N	15.68	23.85	0.47:	0.10:	0.027:
0992	dE0,N	16.81	23.87	0.44	0.08	0.043	1561	dE0,N:	15.82	25.03	4.48:	0.57:	0.163:
1010	dS0(5),N	13.68	21.88	0.33:	0.08:	0.019:	1563	dE3,N	16.11	24.38	0.97	0.20	0.053
1036	dS0(6),N	13.68	21.94	0.19	0.04	0.011	1567	dS0(5),N	14.52	23.56	0.86	0.16	0.033
1044	dE5,N	16.98	23.71	0.16	0.05	0.018	1661	dE0,N	15.97	24.06	0.69	0.18	0.041
1075	dE4,N	15.08	23.32	0.37	0.09	0.021	1711	dE3,N	16.48	23.68	0.22	0.06	0.020
1076	dE0,N	17.36	24.85	0.63	0.29	0.050	1767	dE5,N	16.45	24.08	1.01	0.10	0.075
1079	dE2,N	16.95	25.14	1.11:	0.67:	0.064:	1773	dE5:,N:	16.16	24.18	0.22	0.05	0.014
1093	dE0,N	16.85	24.48	0.55	0.11	0.041	1796	dE5:,N:	16.52	24.15	1.41	0.08	0.104
1095	dE,N	17.93	24.65	0.51	0.03	0.058	1812	dE3,N	17.78	23.73	0.52	0.10	0.084
1099	dE4,N	17.71	23.99	0.20	0.06	0.028	1826	dE2,N	15.70	21.72	0.57	0.03	0.088
1101	dE6,N	15.78	24.12	1.18:	0.05:	0.063:	1857	dE4:,N?	15.07	23.89	6.92:	0.09:	0.295:
1104	dE5,N	15.22	22.67	0.53:	0.19:	0.043:	1886	dE5,N	15.49	23.09	0.69	0.07	0.052
1119	dE4:,N:	17.36	24.20	0.95	0.39	0.102	1896	dSB01(2),N	14.82	22.58	0.49	0.12	0.035
1120	dE2,N	17.17	24.18	0.70	0.08	0.070	2045	dE6:,N	16.33	23.27	1.68	0.15	0.172

3. Measurement of nuclear off-center positions

The procedure we adopted for the determination of the offset distance of a nucleus to the center of the galaxy is straightforward. Our basic tool was the image processing package MIDAS provided by ESO. Within the context SURFPHOT we used the algorithm FIT/ELL3 to fit a series of ellipses to the surface brightness distribution of a galaxy. The important point with the fitting procedure FIT/ELL3 is that the center coordinates of the fitted ellipse are kept as free parameters. Any difference between the calculated ellipse center and the actual position of the nucleus is then giving an off-center distance of the nucleus.

The galaxy images had already been background-subtracted, cleaned from disturbing foreground stars, and calibrated from BC93 (where also all details concerning the photometry can be found). The pixel size of the digitized images corresponds to 40 μ, or 0.43$''$, which has to be compared with the typical FWHM of 1.2$''$ for the stellar images on the photographic plates. The position of a nucleus was simply taken as the center of the brightest pixel, resulting in a geometrical mean error of the nuclear position of 0.16$''$. For the ellipse fitting the images were slightly smoothed with a running 5$\times$5 pixel mean. This degree of smoothing was found experimentally to be optimal for our purposes.

Ellipses were then fitted to five isophotes in the surface brightness range 24–25 B arcsec^{-2} with steps of $\Delta\mu$ = 0.25 mag, i.e. at the isophotal levels of 24, 24.25, 24.5, 24.75, and 25 B arcsec^{-2}. The fainter surface brightness boundary at 25 B arcsec^{-2} was arbitrarily chosen to avoid the noisy outer parts of the galaxy images. The brighter surface brightness boundary at 24 B arcsec^{-2}, on the other hand, was dictated by the inclusion of faint dEs that have a surface brightness of 24 B arcsec^{-2} already close to the center of the galaxy (underlying the nucleus). This simple and convenient procedure guarantees that all dwarfs are treated in a homogeneous way. We have also experimented with individually different surface brightness ranges within which to determine the nuclear position but found no difference, in the statistical results, to the present procedure.

For each isophotal level in the adopted surface brightness range we calculated the distance of the nucleus to the ellipse center as well as the position angle of the nuclear offset with respect to the major axis. Averaging over the five points in the surface brightness range we derived a mean off-center distance of the nucleus, δr_N, with a 1σ standard deviation, $\sigma_{\delta r}$. To account for the differing sizes of the dwarf galaxies we have also calculated *relative* nuclear off-center distances by dividing δr_N by the "effective" (half-light) radius r_{eff}. All of these data are given in **Table 1** as follows:

column (5): mean off-center distance of the nucleus, δr_N (in arcsec);
column (6): standard deviation of the nuclear displacement, $\sigma_{\delta r}$ (in arcsec);
column (7): relative nuclear off-center distance, $\frac{\delta r_N}{r_{eff}}$.
Columns (1)–(4) of Table 1 are defined in Sect. 2 above.

The δr_N values in arcsecs can be transformed to linear distances by adopting a Virgo cluster distance. A convenient scaling is provided by $D_{Virgo} \approx 20$ Mpc, where an angle of $1''$ just corresponds to 100 pc at the Virgo cluster.

In a number of cases the strong scatter, or generally inconsistent behaviour of the nuclear off-center distance in the surface brightness range 24–25 B arcsec^{-2} was found to cast strong doubt on the calculated mean δr_N. A clear sign of an unreliable mean nuclear offset was also the inconsistency of the offset *position angles* for the different isophotal levels. A significant off-center distance is accompanied by a robust value for the position angle. Uncertain cases in this sense are flagged with a colon in columns (5) to (7) of Table 1 and they are shown with open symbols in Figs. 5–7 below.

4. Illustration of individual cases

The large uncertainties involved call for a statistical treatment of the subject, which is carried out below. First we show, in Fig. 2, a few cases with significant nuclear off-center displacements, to illustrate the phenomenon as such and to show how the procedure to determine a mean nuclear offset in the isophotal range 24–25 B arcsec^{-2} works. All six dwarfs have an average nuclear offset of $1''$ or more (for the exact values see Table 1), which is larger than what could be explained by systematic and random errors alone (as explained below), i.e. the displacements are very likely real. In fact, in all cases but one (VCC1386) the displacements are easily recognized by eye.

Notes on individual galaxies (see Fig. 2):
VCC389: This is a bright dwarf S0 galaxy, classified as such because of a distinct and clearly visible two-component structure: there is an inner, lens-like feature of high surface brightness, with a fairly sharp edge, on top of a more extended low-surface brightness part (for the morphology of dS0s, see Sandage & Binggeli (1984) and BC91). If we look how the nuclear distance to the center correlates with the surface brightness level at which the center was determined from fitting an ellipse, we see that the nucleus is quite central (only insignificantly displaced) in the inner part, but then jumps to $\delta r_N \approx 1''$ beyond $\mu \approx 24$ B arcsec^{-2}. Obviously, the nucleus is central with respect to the inner "lens", while the whole lens seems to be displaced with respect to the rest of the galaxy.
VCC870: Again a bright dS0,N with a lens-like structure in the inner part. In contrast to VCC389, however, the nucleus is clearly displaced already within the lens and it remains so, albeit with a strange bump in the $\delta r_N - \mu$ relation, with respect to the outer part. Such cases, where the nucleus is shifted against the *whole* galaxy, including the inner part, seem to be rare.
VCC1386: This is an ordinary, bright dE,N. A nuclear displacement sets in at $\mu \approx 24$ B arcsec^{-2} and rapidly increases towards fainter surface brightness. Nevertheless, the effect is very hard to see by eye.
VCC1563: A fainter dE,N with a "well-behaved" and easily visible off-center nucleus.
VCC1767: Similar to VCC1563. However, the nucleus is clearly peculiar, being irregular in shape. The whole galaxy appears somewhat lumpy.
VCC1796: This dwarf is again slightly peculiar as dE, having explicitly been classified as "dE5:, N:" (the colon means uncertainty). Yet the nuclear offset is obvious.

5. Error estimation

The standard deviation $\sigma_{\delta r}$ of the mean off-center distance within the adopted surface brightness range, of the order of $0.1''$, is of course only a lower limit to the true uncertainty of any measured δr_N value. The adopted procedure, when applied to a noisy galaxy image, is likely producing large systematic and random errors in δr_N. To get a handle on these errors, we have run Monte Carlo simulations of the measuring procedure with artificial galaxies. We have chosen a typical dE with B_T = 16 mag and ellipticity 0.25 (between E2 and E3) and formed a purely exponential model galaxy from its measured exponential scale-length and central surface brightness as given in BC93. Having added a suitable sky background and Gaussian nucleus at a certain off-center distance (to be varied), a Poissonian pixel-to-pixel noise was mimicked by a Gaussian sigma weighted with the square root of the local total intensity, and then again added to the artificial image.

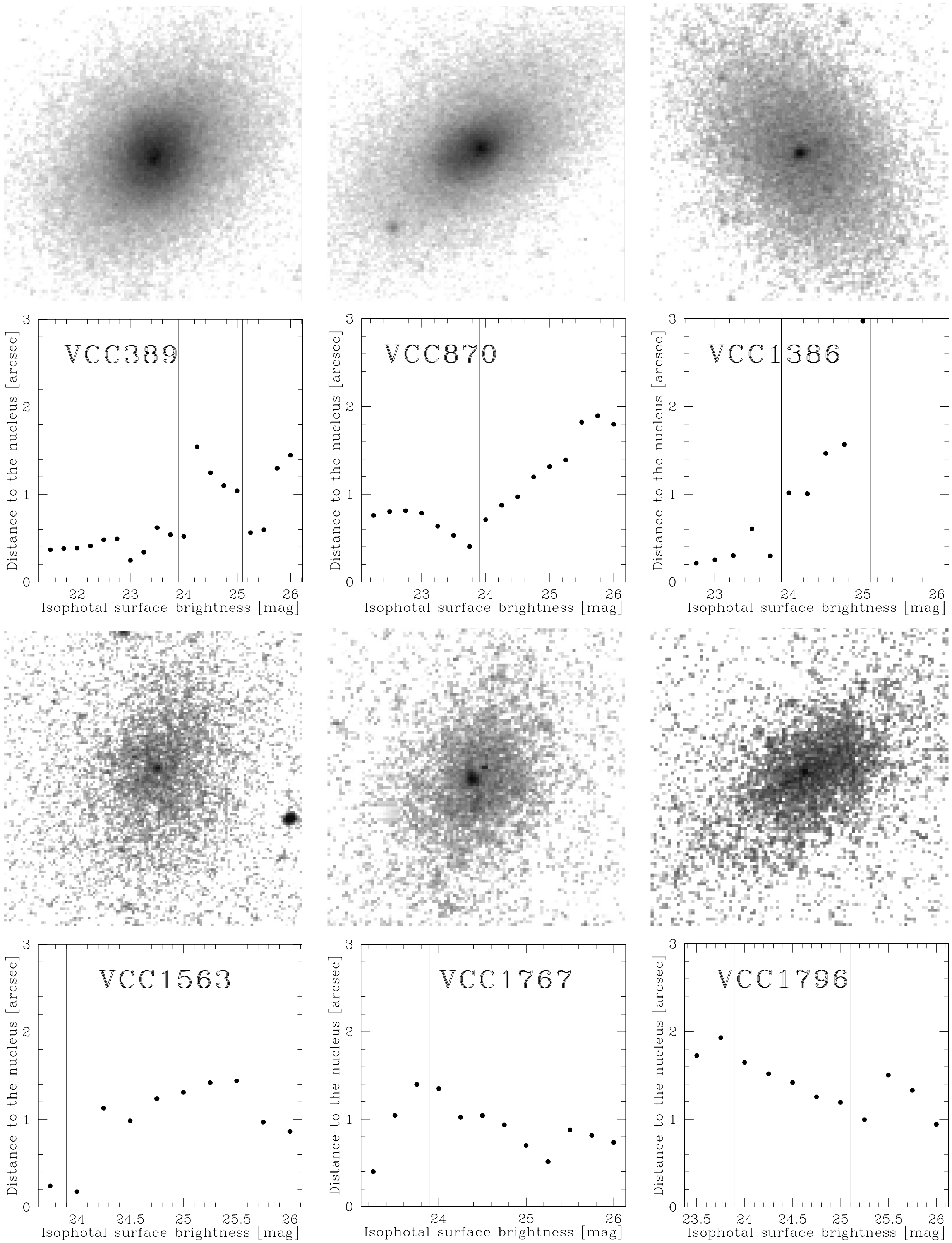

Fig. 2. Six individual cases of dwarfs with off-center nuclei. For each galaxy we display a direct image on top of a plot showing the nuclear off-center displacement (in arcsecs) as function of the surface brightness level (in B arcsec^{-2}) at which an ellipse was fitted and a center defined. The thin vertical lines are indicating the boundaries of the surface brightness range 24–25 B arcsec^{-2} within which an average nuclear offset was determined. The objects can be identified from the VCC numbers given in the plots. Each image is 45 arcsecs on a side, except VCC1563 which is 1 arcmin. A detailed description is given in the text (Sect. 4).

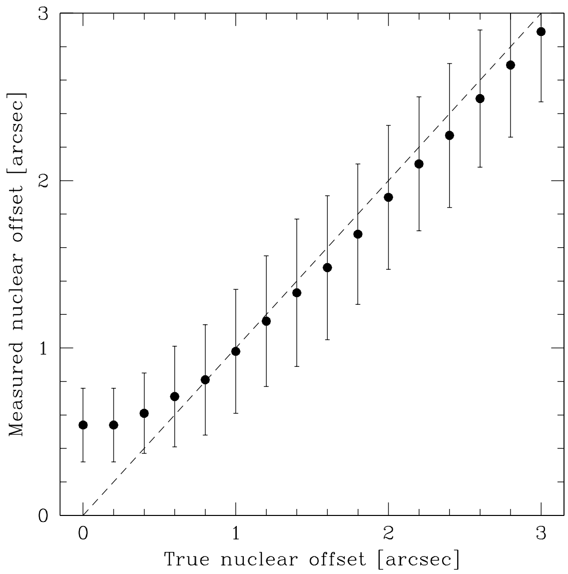

Fig. 3. Measured nuclear offset δr_N as a function of the true nuclear offset given as input parameter for an artificial dE,N galaxy with B_T=16 mag and an exponential light profile. Each point is the mean from 500 random (Monte Carlo) representations of the same galaxy. The error bars give the uncertainty for a single case. The broken line is the locus of identity between true and measured nuclear offset.

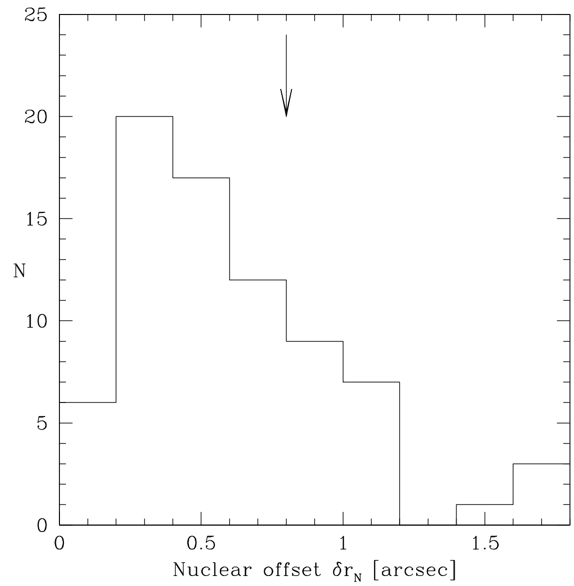

Fig. 4. The frequency distribution of measured nuclear offsets δr_N. There are three very large (however uncertain) nuclear offsets beyond the bounds of the figure. The arrow at δr_N = 0.8″ is indicating a critical line above which a nuclear offset can be regarded as real (see text).

Using that Gaussian sigma as a probability distribution, a single artificial galaxy was produced, pixel by pixel, with a random number generator. Then, we determined its nuclear off-center distance δr_N exactly in the same way as with a real galaxy, i.e. according to the procedures described in Sect. 3 (including a convolution of the model galaxy with a Gaussian seeing function and 5×5 smoothing). For a given (true, input) displacement of the nucleus from the center of the underlying (exponential) galaxy, this application was repeated for 500 representations of the galaxy, and a mean (output) δr_N and its associated standard deviation were calculated. The results of such a Monte Carlo run are shown in Fig. 3, where we have varied the input nuclear offset – along the major axis in this case – in steps of 0.2″.

The main characteristics of this simulation are as follows. Exactly central and nearly central (up to about $\delta \approx 0.5''$) *true* nuclear positions, when measured with our procedure, appear *systematically* larger, i.e. displaced from the center. The more central a nucleus truly is, the more displaced it appears. There is a minimal apparent displacement of $\approx 0.5''$. This result of image noise had to be expected. In the process truly displaced nuclei can get more *or* less displaced, but truly *central* nuclei can get *only* more displaced. On the other hand, large true nuclear displacements ($\delta \geq 1''$) get systematically, but insignificantly too small. The *random* errors for a given single case, shown as error bars in Fig. 3, are quite large – again as expected –: from 0.22″ at δ = 0″ up to $\approx 0.4''$ at larger displacements (note that the errors of the means would be $\sqrt{500}$ times smaller).

We have of course also varied the total magnitude, and hence surface brightness and exponential scale length (see BC91) of the artificial galaxy, but found rather little variance in the Monte Carlo results, except that for bright dwarfs with B_T = 14 mag (which are in the minority, however), both random and systematic errors are significantly smaller. Also, displacing the nucleus along the minor, rather than the major axis, as well as altering the ellipticity of the galaxy made little difference. As there is a degeneracy of δr_N for small true nuclear displacements, and in view of the generally large random errors, any correction of the measured δr_N for an *individual* galaxy is infeasible. We therefore, in the following, take resort to a very rough and global, statistical accounting for the uncertainties in δr_N, drawing on the results for an artificial typical dE,N (B_T = 16 mag, ellipticity E2.5) shown in Fig. 3.

6. Statistical trends

From Fig. 3 it is clear that, if most nuclei are truly central, we should expect to see, in the frequency distribution of measured nuclear offsets, a strong peak around $\delta r_N \approx 0.5''$. This is indeed what is observed, as shown in Fig. 4. However, what is also quite evident from this distribution is the existence of a tail of large δr_N-values; the distribution is strongly skewed towards large measured offsets, and this is clearly hinting at a population of dwarfs with *true* nuclear offsets. How can we quantify this? First, we note that the peak is centered on δr_N = 0.4″, rather than 0.5″(or 0.54″, as is the precise value from Fig. 3). This means that we have apparently slightly overestimated the systematic errors with our Monte Carlo simulation. It should be noted that the observed peak, at $\delta < 0.5''$, must almost certainly stems from a population of dwarfs with central nuclei; at least we see no other explanation for it. Judged from the width of this peak towards smaller offsets (to the left), we estimate a Gaussian

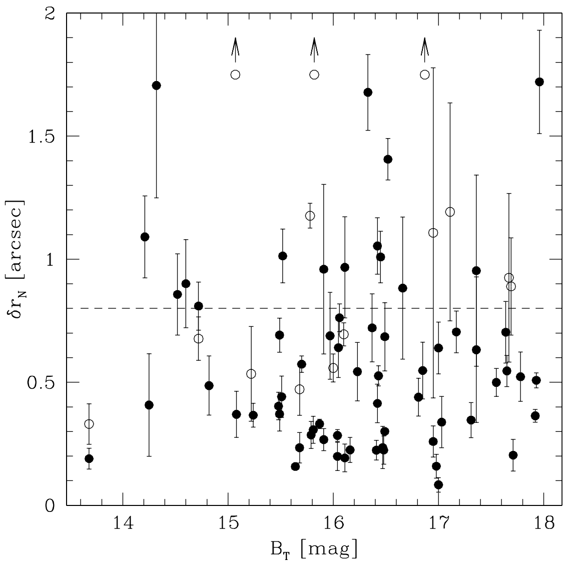

Fig. 5. Nuclear off-center distance δr_N versus total galaxy magnitude B_T. Open symbols indicate uncertain offset distances, three of which are larger than 2″(arrows). The error bars are standard deviations of the mean δr_N-values. The broken line at δr_N is the fiducial division line between dwarfs with central and non-central nuclei.

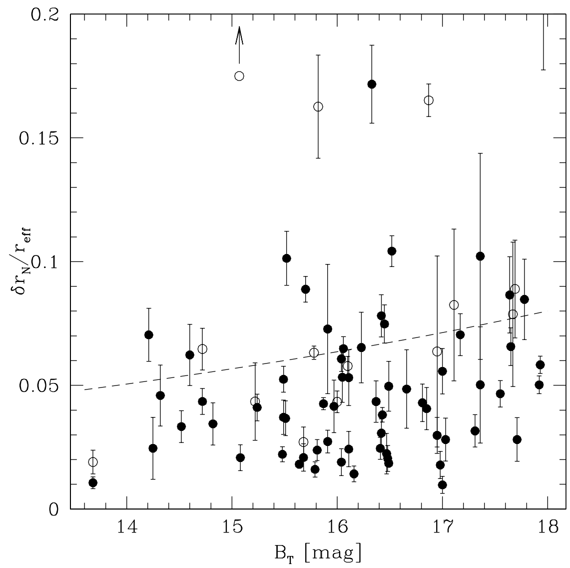

Fig. 6. Same as Fig. 5 but now plotting the dimensionless ratio $\delta r_N/r_{eff}$ (nuclear offset divided by effective radius) versus total magnitude B_T. The broken line is the mean locus of δr_N = 0.8″(see text).

sigma of $\approx$ 0.2″ (as compared to 0.22″ from our simulation; Fig. 3). Assuming, then, a Gaussian distribution with mean and sigma as 0.4″±0.2″ for a population of perfectly central nuclei, any measured nuclear offset larger than 2σ = 0.8″ is very likely real (with a probability of 95%). There will be some true nuclear offsets among those with $\delta r_N <$ 0.8″, but for an individual case we cannot tell. Above 0.8″ we should be on the safe side and be allowed to take the measured δr_N for granted, albeit with a large random error of $\approx$ 0.4″. We therefore adopt a very rough division line at δr_N = 0.8″ (the arrow in Fig. 4) in the sense that most dwarf nuclei with $\delta r_N <$ 0.8″ are regarded as central, while those with $\delta r_N >$ 0.8″ are regarded as truly displaced from the galaxy center.

In Fig. 5 we have plotted the nuclear offset δr_N versus the total galaxy magnitude B_T. The nuclear offset distances are shown with their formal r.m.s. errors from averaging the five offsets determined at five isophotal levels. As discussed above, the true uncertainties are usually much larger, of order 0.4″, without considering the systematic errors (see Fig. 3). However, it is evident that even these formal errors can be considerably large for dwarfs with $\delta r_N >$ 0.8″. Truly "uncertain" or inconsistent cases (cf. Sect. 3) – indicated by colons in Table 1 and flagged with open symbols in Figs. 5–7 – are also more common above the division line of δr_N = 0.8″.

No systematic trend of δr_N with B_T is obvious from Fig. 5. A few bright dwarfs with off-center nuclei are popping out, but this is caused by the large size of the parent galaxies (see below). The fraction of dwarfs above the chosen division line at δr_N = 0.8″ compared to the total, given as percentage of dwarfs with off-center nuclei, is 29% (23 out of 78) if uncertain cases are included, or 23% (15 out of 64) if uncertain cases are excluded. Overall, it seems fair (and conservative) to state that *roughly 20% of all nucleated dwarf ellipticals have off-center nuclei*.

So far we have given the nuclear off-center distances in absolute units of arcsecs. However, as the size of the dwarf galaxies varies, one might suspect that a *relative* measure of nuclear off-center distance, i.e. relative to some characteristic radius of the parent galaxy, is physically more meaningful. We have therefore plotted, in Fig. 6, the ratio $\delta r_N/r_{eff}$ versus B_T, to see whether we get a different picture.

One obvious change is that the large nuclear offsets in some bright dwarfs (see Fig. 5) are strongly reduced in relative units, i.e. the nuclear offsets in those dwarfs are large in distance but are *relatively* small as the dwarfs themselves are large in size. Less luminous dwarfs tend to have larger relative nuclear offsets. But where do we now have to draw the critical line between significant and non-significant nuclear offsets?

It turns out that this line does not strongly depend on B_T, simply because the metric (effective) radius of dE galaxies does not. This is also expressed by the basic $\mu - L$ relation of dEs, where the surface brightness is systematically decreasing with decreasing luminosity. To show this, we use the formula for the observed scaling law of Virgo cluster dEs given in BC91:

$$\langle\mu\rangle_{eff} \approx 0.75\, B_T + 11.5\,, \tag{1}$$

where $\langle\mu\rangle_{eff}$ is in B mag arcsec^{-2}, and the identity:

$$\langle\mu\rangle_{eff} = B_T + 5\,\log\, r_{eff} + 2\,, \tag{2}$$

to derive the equation (r_{eff} always in arcsecs):

$$r_{eff} = 10^{1.9 - B_T/20}\,. \tag{3}$$

Eq. (3) and δr_N = 0.8″ now define a critical *relative* nuclear offset $\delta r_N/r_{eff}$, which is shown as broken line in Fig. 6. Obiously, using $\delta r_N/r_{eff}$ instead of δr_N does not make much difference,

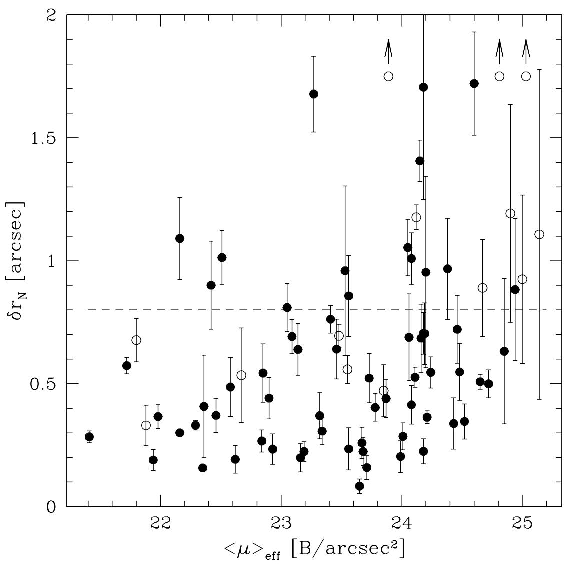

Fig. 7. The nuclear off-center distance δr_N (in arcsecs) versus the effective mean surface brightness $\langle\mu\rangle_{eff}$ (in B mag arcsec^{-2}) of the parent galaxy. Otherwise as Fig. 5.

justifying *a posteriori* that we have worked with absolute nuclear offsets (in arcsecs or parsecs) from the beginning. Still, there is a hint that the offsets become more common in fainter dwarfs when they are measured in a relative way.

A most interesting and possibly real statistical trend of the nuclear offset distance with the mean effective surface brightness of the parent galaxy is shown in Fig. 7. There is a clear tendency of δr_N to increase with decreasing surface brightness. Again, given the small sample and large errors, we cannot claim significance of the effect, but Fig. 7 is certainly very suggestive. What is most striking, of course, is the apparent lack of high-surface brightness dwarfs with large nuclear offsets (the void region in the upper left of Fig. 7). Remember that the *relative* offsets ($\delta r_N/r_{eff}$) for bright dwarfs, which on average also have higher surface brightness, would be even further reduced.

On the other hand, the apparent lack of very low-surface brightness dwarfs with small nuclear offsets (the void in the lower right in Fig. 7) is probably an observational bias (incompleteness of the sample), or an artifact from unaccounted-for errors which grossly increase at such faint surface brightness levels. In this case the trend might be better described as an *increasing spread in the range of observed offsets with decreasing surface brightness*.

This spread might result from the nuclear oscillations seen in the simulations of Miller & Smith (1992) and Taga & Iye (1998). Its increase towards fainter surface brightness, *if real*, would then simply mean an increase in the amplitude of oscillations. Although this was not explicitly explored by the simulations just mentioned, it appears quite plausible that a nucleus can oscillate more easily, i.e. with larger amplitude, in a galaxy of low surface brightness and hence shallow gravitational potential than in a deep, cuspy potential (high-surface brightness central part). Interestingly, the few normal elliptical galaxies with known nuclear displacements in the study of Lauer et al. (1995) all have *cores*, as noted by the authors themselves. *Core* ellipticals have lower central surface brightness than *cuspy* ellipticals, so this would be the same effect.

We have also looked for a trend with the "exponential" *central* surface brightness, μ_0^{exp}, which is one of the parameters of the exponential law that was fitted to the dwarf profiles by BC91/93, but found this relation to be much weaker than that with the mean effective surface brightness. This is actually not too surprising, as μ_0^{exp} is nearly constant (although with very large scatter) in the magnitude range B_T = 14–17 mag (see Fig. 9a of BC91). The reason for this is that the exponential law was fitted to the outer part of the dE profiles. As there is often an extended brightness excess above the fitted exponential, μ_0^{exp} does not represent the "true" central surface brightness of the parent galaxy underlying the quasi-stellar nucleus (see BC91/93). A better measure for this would be the central surface brightness from the best-fitting King model (King 1966), but many dwarf profiles could not be fitted by a King model. Ironically, these are often those dwarfs that are found here to have an off-center nucleus. One reason for this could be that all dE,N profiles were automatically centered on their "central" nucleus. On the other hand, there are hints that a significant fraction of bright early-type dwarfs are rotating disk galaxies rather than King spheroids (e.g., Jerjen et al. 2000, and references therein). Rotation might, in fact, be the driving mechanism for the nuclear oscillations (see Taga & Iye 1998)!

We have looked for possible trends of δr_N with many other parameters, among them are –: (1) the flattening of the parent galaxy (with a slight hint that apparently flatter dEs have higher nuclear offsets; but see the appendix for a significant nucleus-ellipticity relation); (2) the angular distance of the parent galaxy from M87 (as the nuclear displacement might be influenced from the environment within the Virgo cluster); (3) the isophotal shape a_4/a of the parent galaxy (diskyness $\leftrightarrow$ boxyness, as given by Ryden et al. 1999); (4) the strength of the nucleus itself (as given by BC91/93 from their King profile fitting, but unfortunately, as mentioned above, only available for a subsample).

No clear trends were found with these parameters. But this is no proof of their absence, as our qualitative analysis of a very limited data set is necessarily blind for any subtle effects, if present. The most interesting, or most expected trend would be a relation between nuclear displacement and nuclear strength. Such a relation, in the sense that stronger nuclei should be less displaced from the center (oscillate with smaller amplitude), is in fact predicted (Taga & Iye 1998).

Finally, we have looked for any systematic trend of the nuclear offset position angle with respect to the galaxy major axis, and found none.

7. Summary and conclusions

With very simple means, by fitting ellipses to the outer galaxy part and measuring the distance of the nucleus to the ellipse centers, we have searched for the existence of off-center nuclei in a sample of 78 nucleated dwarf elliptical galaxies of the Virgo cluster. Simulating the measuring procedure with artificial galaxies showed that nuclear displacements of more than 0.8″ can safely be regarded as real. Taking this into account, we found that roughly 20% of all nucleated dEs have off-center nuclei.

In search for a relation between the nuclear displacement and any kind of structural and environmental parameter of the underlying galaxy, we found a possible tendency of the nuclear displacement (or its spread) to increase with decreasing surface brightness of the underlying galaxy. A similar trend (but even less significant, given the small number of objects involved) appeared in Lauer et al.'s (1995) study of the centers of normal elliptical galaxies. If confirmed to be real, the trend could simply mean that the nuclei are less strongly bound in a shallow gravitational potential, moving more easily away from, or oscillating with larger amplitude about, the center of the underlying galaxy (see Miller & Smith 1992, and Taga & Iye 1998), whatever the excitation or driving mechanism for this motion may be.

A typical off-center distance in a Virgo dE,N is 1″, or 100 pc with D_{Virgo}=20 Mpc. With respect to the size of the dwarfs, this corresponds to 0.5 to 1 effective radii. But it has to be borne in mind that dwarfs with nuclei more displaced from the galaxy center than $\approx 2''$ are strongly selected against in our sample, because such objects, if they really exist, would not always have been recognized and classified as "nucleated" (dE,N).

We have used a fairly large and homogeneous data set of digitized photographic images of dE,N galaxies. Future studies of the subject, based on higher-resolution images, will undoubtedly allow much more precise measurements of the nuclear displacements. However, as exemplified beautifully by the *HST* imaging of Miller et al. (1998), high resolution also opens up *Pandora's box*, in that all bright globular clusters become detected as well, rendering the distinction, or even definition, of a fairly faint "central" nucleus non-trivial. But this kind of entanglement is quite natural, as globular clusters and "central" nuclei are related phenomena and may well have a common origin. Nevertheless, even with superior imaging, a large sample ($N \approx 100$) of dE,Ns will be needed to search for statistically significant trends of any nuclear property with the structure of the underlying galaxy, as has been attempted with archive data in the present paper.

Finally, the nuclear displacements, as well as the nuclear magnitudes in relation to galaxy shape (see appendix), will likely tell us something about, or at least allow us to put constraints on, the masses of the nuclei and the galaxy potentials in which they sit. But this is only possible based on quantitative models. Aside from the simulations of Miller & Smith (1992) and Taga & Iye (1998), we completely lack an adequate, realistic and quantitative modelling of off-center nuclei in galaxies.

Acknowledgements. The idea for this investigation came up in a discussion by one of us (H.J.) with Dr. John Kormendy. We are grateful to an anonymous referee whose comments helped to improve the paper considerably. Financial support by the Swiss National Science Foundation is gratefully acknowledged.

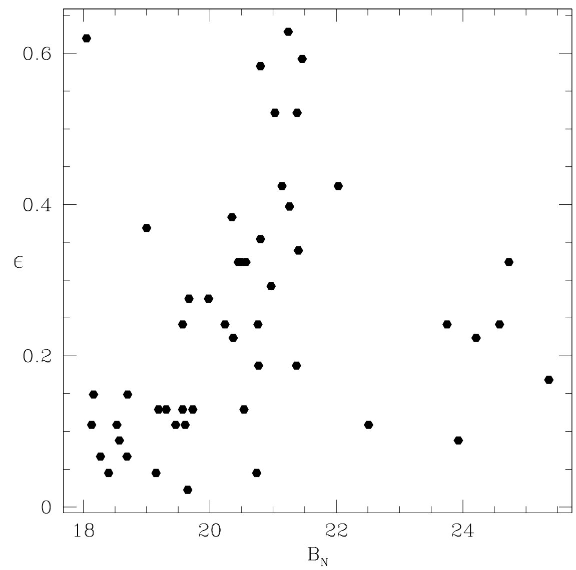

Fig. 8. Magnitude of the nucleus B_N, calculated as central light excess above a King model profile fitted to the underlying dE galaxy, versus the ellipticity ϵ of the underlying galaxy. Data taken from BC93.

Appendix A: nuclear strength versus ellipticity

Although there is apparently no correlation between the nuclear offset distance and the ellipticity of the underlying galaxy (see above), there is clearly such a correlation between nuclear *strength* and ellipticity. The data are available since years, but the correlation has never been shown in the literature. As the nuclear strengths, just as the nuclear offsets, must have a bearing on the mass of the nuclei and the structure of the host galaxies, we show this in the present appendix.

By nuclear strength we mean the magnitude of the central luminosity excess of a nucleated dE above a suitable luminosity profile fitted to the underlying galaxy. Such nuclear magnitudes are provided by BC91/93 for a subsample of their dENs, where the galaxy luminosity profile was represented by a King model profile (King 1966). In Fig. 8 we have plotted the ellipticity of the underlying galaxy (also taken from BC93) versus the nuclear magnitude, B_N, from the King model fitting of B93. B93 do not give a mean uncertainty for their nuclear magnitudes, but we estimate it to be as large as 0.5 mag. Recall first the absolute magnitude scale: with $(m - M)_{\rm Virgo}$ = 31.5 (D=20 Mpc) an apparent magnitude of B_N=20 corresponds to $M^{B_N} = -11.5$, which is roughly met by the very brightest globular clusters of M87 (however, being several magnitudes brighter than an ordinary globular cluster of the Milky Way galaxy; see BC91).

There is a rapid decline in the number of nuclei beyond B_N=21, which is most likely due to incompleteness: fainter nuclei are obviously much harder to detect. The interesting part of Fig. 8 is the bright end. We notice a pronounced tendency of the brightest nuclei (B_N <19.5) to live in *round* (ϵ <0.2) galaxies. In Fig. 9 we show the same for the *relative* nuclear strength, i.e. the luminosity ratio L_N/L_T, which in magnitudes is simply $B_N - B_T$. A value of $B_N - B_T$=2.5 means that the nucleus comprises 10% of the total light of the galaxy; a value

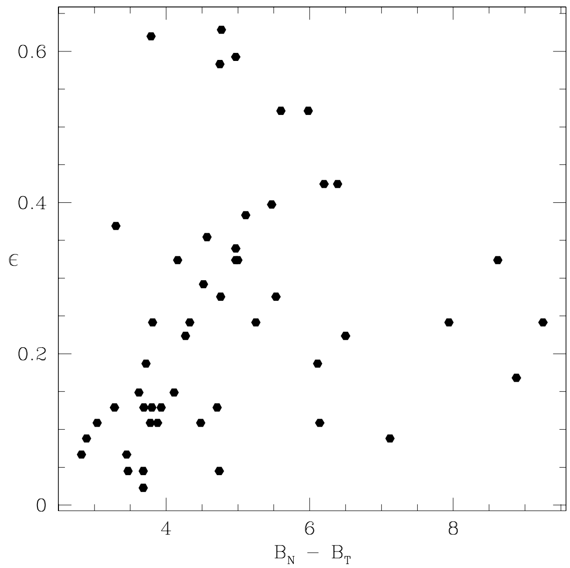

Fig. 9. Nuclear magnitude relative to the total galaxy magnitude (including the nucleus), $B_N - B_T$, versus the ellipticity ϵ of the underlying galaxy. Data taken from BC93.

of 5 corresponds to 1% of the total galaxy, etc. There is clearly the same effect here in Fig. 9: the relatively brightest nuclei are found in round galaxies. Nuclei that are brighter than 4% of the total galaxy light ($B_N - B_T$ <3.75) are found in galaxies with ellipticities $\epsilon < 0.15$ (there is only one outlier in Fig. 9, VCC1826).

Nucleated dEs are known to be rounder than the non-nucleated dEs on average by about half an ellipticity class (Binggeli & Popescu 1995). What we have shown here is that this is probably due to the distinct roundness of the host galaxies of the very brightest nuclei. There are at least three possible explanations for this effect. (1) The more elongated dwarfs might have higher internal extinction towards the nucleus due to our viewing angle. This is rather unlikely, as there is no evidence for a great amount of dust in dwarf ellipticals. (2) The built-up of the nucleus could be linked to gas infall which, in turn, is likely governed by angular momentum and, if dEs are rotation supported, by ellipticity (e.g., Davies & Phillipps 1988). However, the very sparse kinematic data for dEs available so far seem to indicate that dEs are *not* rotationally supported (see Ferguson & Binggeli 1994; however, Jerjen et al. 2000). (3) the most plausible explanation is that the presence of the nucleus, if it is massive enough, has changed the orbital structure of the galaxy over a Hubble time. Norman et al. (1985) have calculated and simulated the effect of a black hole put in the center of a triaxial elliptical, with a mass of a few tenths of the core mass of the galaxy, and found a significant roundening of the underlying galaxy out to at least five core radii. The physical cause for this is the disruption of box orbits by scattering of stars off the central density cusp. A similar result, with a less massive and less effective central compact object, was obtained by Gerhard & Binney (1985).

Based on the work of Norman et al. (1985), Norman (1986) actually predicted that nucleated dEs should be rounder than non-nucleated ones. This is certainly confirmed by our observations. Indeed, the effect that a nucleus of only a few percent of the total galaxy *light* should cause a nearly perfect roundness of the underlying galaxy out to a faint surface brightness of 26 B arcsec^{-2} (the level at which the ellipticities were determined in BC93) may appear even stronger than expected. Could it be that some of these nuclei harbour a black hole, thus comprising a more significant fraction of the total *mass* of the galaxy? Without further, detailed work on the dynamics of nucleated dEs, including the effects of dark matter, it is impossible to draw any quantitative conclusions.

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