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Multicolor surface photometry of brightest cluster galaxies ★

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Abstract. Two color ($B-V$ and $V-i$) CCD photometry of the dominant galaxy (BCG) in five Bautz-Morgan type I clusters has been obtained at the 1.5 m Danish telescope at La Silla. In this paper we analyze their surface brightness and color profiles. All galaxies but one have surface brightness profiles that can be described by a de Vaucouleurs' law with similar effective surface brightness $\mu_e \sim 23.2$ V mag arcsec^{-2} and effective radius r_e between 30 and 40 kpc. Average colors are alike in all the five galaxies and color gradients are small or absent.

Key words: galaxies: elliptical – galaxies: evolution – photometry

1. Introduction

Several authors, beginning with Oemler (1976) and continuing with Hoessel et al. (1980), Thuan & Romanishin (1981), Schneider et al. (1983), Malumuth & Kirshner (1985), and Schombert (1986), have studied samples of nearby Brightest Cluster Galaxies (BCG). The main aim of many of these studies has been that of understanding the processes leading to the formation of these giant galaxies, their evolution and relation with the environment in which they are found. At present the structure of BCGs is generally explained by two classes of models. One possible scenario is that tidal interactions affect the structure of galaxies in clusters, and that mergers are held responsible for the large radius and the low central surface brightness of D and cD BCGs (Ostriker & Hausmann 1977, but as for the low central surface brightness see also Schweizer 1979). The excess of multiple nuclei in BCGs (Hoessel 1980; Schneider et al. 1983) and the high percentage of BCGs with close neighboring galaxies showing morphological disturbances (Lauer 1988) should be taken as evidence that BCGs are interacting with the environment. Moreover, there is strong evidence for cooling flows from X-ray imaging and spectral observations of clusters of galaxies (for a recent review, see Fabian et al. 1991). As much as 10^{12} $M_\odot$ can be deposited along the radius of a BCG over a Hubble time thus altering the stellar mass distribution.

A second possibility is that BCGs are formed during the collapse and virialization of clusters and that little is happening afterwards (Merritt 1985). The lack of correlation between cluster properties and BCG morphology (correlation which would be expected if BCGs have been interacting with the environment) can be considered as indirect evidence that tidal interactions and merging are not frequent phenomena. Furthermore, there is no correlation between the presence of a D or cD galaxy and the low value of the cluster velocity dispersion (Merritt 1984; Zabludoff et al. 1991), BCG luminosities increase with cluster velocity dispersion (Schombert 1986), cD and D galaxies are not bluer than gE galaxies (Lugger 1983).

Because of their absolute brightness, these galaxies hold a large potential as distance indicators since they show an important photometric property: their effective radius and effective surface brightness are strongly correlated, independently of luminosity and perhaps cluster richness or concentration. Oegerle & Hoessel (1991) have found that the dispersion in the $r_e - \langle\mu\rangle_e$ relation is such that the distance errors are only of $\sim 25\%$ per galaxy (without requiring the knowledge of the galaxy velocity dispersion as in the fundamental plane solution for normal ellipticals). The use of BCGs as cosmological tools, however, needs a knowledge of the modifications of their surface brightness with redshift induced by the evolution of their stellar population and by the interactions with the environment. In this paper we present our contribution to these problems through the analysis of multicolor observations of a small sample of BCGs having redshifts up to $z \sim 0.2$. We adopt $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

2. Observations

We selected a sample of BCGs in clusters of Bautz-Morgan type I catalogued in Abell et al. (1989) (A 1644, A 1996, A 2328 from Table 6 and A 3429, A 3670 from Table 4). The main characteristics of the five objects studied in this paper are given in Table 1.

Table 1. The sample

Cluster (1)	$B-M$ type (2)	R (3)	z (4)
Abell 1644	I	2	0.047 [a]
Abell 1996	I	0	0.13 [b]
Abell 2328	I	0	0.147 [c]
Abell 3429	I	0	0.06 [b]
Abell 3670	I	2	0.175 [b]

[a] Dressler & Schectman (1988).
[b] Estimated following Scaramella et al. (1991).
[c] Struble & Rood (1987).

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★ Based on observations collected at the European Southern Observatory, La Silla, Chile

Table 2. Summary of CCD observations

(1)	Start time h m s U.T. (2)	Object (3)	$t_{\rm exp}$ (s) (4)	Filter (5)	Seeing (FWHM) (arcsec) (6)
8/5/1989	04 31 36	E8–18P	2	B	
	04 37 14	E8–18P	1	V	
	04 42 48	E8–18P	1	i	
	04 56 54	Abell 1996	720	i	1.43
	05 19 56	Abell 1996	900	V	1.28
	05 43 28	Abell 1996	1800	B	1.08
	06 59 01	Abell 3670	900	V	1.50
	07 20 34	Abell 3670	1800	B	1.32
	08 01 08	Abell 3670	720	i	1.10
9/5/1989	00 43 03	Abell 3429	600	V	1.26
	01 00 08	Abell 3429	1200	B	1.50
	01 23 38	Abell 3429	600	i	1.41
	01 57 01	Abell 1644	480	i	1.00
	02 09 13	Abell 1644	600	V	1.14
	02 20 48	Abell 1644	900	B	1.10
	05 12 51	1439 + 00	30	i	
	05 19 10	1439 + 00	40	B	
	05 22 30	1439 + 00	40	V	
	07 05 59	Abell 2328	900	V	1.42
	07 23 39	Abell 2328	1800	B	1.42
	08 00 03	Abell 2328	720	i	1.30
	08 20 35	E8–18P	1	i	
	08 24 30	E8–18P	1	V	
	08 27 10	E8–18P	2	B	

As can be seen, for 3 clusters we were obliged to estimate the redshift from Scaramella et al. (1991). This means that their redshifts have an uncertainty $\Delta z/z = 0.2$, which reflects into the determination of some photometric parameters, as discussed later.

The observations were carried out in May 1989 at the Cassegrain focus (f/8.46) of the 1.5 m Danish Telescope at La Silla equipped with CCD No. 5, which is a thinned back-illuminated RCA type SID 501 EX chip with 320×512 pixels. The angular scale is 0.47 arcsec pixel^{-1}, resulting in a field of view of $2\overset{\prime}{.}5 \times 4\overset{\prime}{.}0$. The images were taken through the Bessell B, V (Bessell 1976) and the Gunn i (Wade et al. 1979) filters. The reason for using such a mixed photometric system lies in the possibility of comparing both the $B-V$ color profiles of our BCGs with the published color profiles of BCGs and elliptical galaxies which were available at the time of the observations and the Gunn i profile of our BCGs with the one of GREG (Maccagni et al. 1968), the brightest galaxy in an X-ray selected poor cluster showing a huge cD-type envelope in the i filter, which Johnstone & Fabian (1989) interpreted as evidence of a cooling flow.

Table 2 is the journal of the observations: columns (1) and (2) give the date and UT time of the observation; columns (3) and (4) the object observed and the exposure time; column (5) gives the filter used and column (6) the image seeing (FWHM).

3. Data reduction and analysis

The bulk of the data reduction was carried out with the IHAP image analysis package, but also IRAF and MIDAS were used at different stages of the reduction and analysis procedure. Each frame was dark subtracted and flat-fielded.

3.1. Calibrations

As Table 2 shows, the photometric calibration was obtained through the observation of Graham's star E8–18P (Graham 1982) for A 1996, A 3670 and A 2328 and of Stobie's star 1439 + 00 (Stobie et al. 1985a) for A 3429 and A 1644. We note that 1439 + 00 was observed more than two hours after the observation of the program objects.

The magnitudes and colors of star 1439 + 00 are known in the Kron-Cousin photometric system and have been transformed into Bessell BV and Johnson VRI following Stobie et al. (1985b), and Bessell (1979) respectively, and then into Gunn i magnitudes by using Wade et al. (1979) equations. Magnitudes and colors of star E8–18P are known in the Kron-Cousin (Graham 1982) and in the Gunn-La Silla photometric system (Pedersen 1988) and have been converted into the Bessell and Gunn systems by using the transformations given by Stobie et al. (1985b) and Garilli et al. (1991).

The small number of standard stars observed prevents to derive the atmospheric extinction values during the 2 observing nights. Therefore standard site coefficients have been used. This may introduce a zero-point error especially during the first part of the second night when the photometric quality of the sky was not excellent. An estimate of the photometric accuracy was obtained by plotting the $B-V$ vs. $B-i$ color diagram for all the stars in the A 3429 and A 1644 fields (see Fig. 1) and for a sample of stars from

Stobie et al. (1985b) and Graham (1982). While the transformations from one photometric system to another do not introduce an appreciable inaccuracy (Graham's and Stobie's stars overlap well in the diagram), the stars in our frames are systematically offsetted, as a result of a 0.1 mag uncertainty in the calibration of the first part of the second night, whilst for the remaining observing time the agreement is excellent. The zero-point derived from E8−18P is affected by a different source of inaccuracy, that is the jitter in the shutter speed which can be of the order of 0.1 s. This produces an uncertainty of up to 0.1 mag because of the short exposure time used. These inaccuracies affect the absolute color profiles, but not the shape of the surface brightness and color profiles as well as the effective radii of the BCGs.

3.2. *Sky determination*

In each frame the sky levels were sampled by measuring the counts in a series of 20 × 20 pixels boxes in areas away from the BCG and free from contaminating objects or chip defects. The mean, the mode and the median of the counts in each box were generally very close one to the other and we adopted the mode of the modes in the boxes as the sky level to be subtracted from the images before proceeding further with the analysis. In the single boxes the dispersion of the values is less than 0.5%. The dispersion of the mode of the modes in each frame is of the order of 0.2%, and therefore, at the intensity level of 1% of the sky background, the error in the surface brightness is 0.2 mag arsec^{-2}. For the two nearest BCGs in the sample, A 1644 and A 3429, for which the apparent dimensions of the galaxies are large with respect to those of the CCD frame, it is necessary to carefully measure the sky level in a region outside the BCG halo. A general criterion to avoid sky overestimate is given by the flattening off of the pixel intensities with radius. For A 3429 the region used to measure the sky level is more than ten times flatter than the flattest and largest halo belonging to a BCG (i.e. A 1413 and A 2670, Oemler 1976)[1]. Therefore our sky estimate should not be contaminated by the galaxy halo unless the galaxy brightness distribution is peculiar with respect to usual cD's. Anyway, we measure the sky level at about four times $D(0)$, the radius at which the B surface brightness of the galaxy is 25.0 mag arcsec^{-2}, for all BCGs but A 1644 for which we can sample the sky at $2D(0)$. Consequently, the surface brightness and color profiles of A 1644 have been terminated at a radius of 2.5% and 6.3%, respectively, of the sky brightness, in order to minimize effects due to the possible overestimate of the sky level. For all other BCGs we derive the surface brightness profiles to radii where the surface brightness reaches 1% of the sky level and color profiles to radii where the surface brightness in the filter with the brightest background reaches 2.5% of the sky level.

4. Results

Figures 2a to e show the V isophotes of the five BCGs. Fitting of the isophotes has been performed using the STSDAS (Space Telescope Scientific Data Analysis System) isophote package (version 1.2). Details on the algorithm can be found in Jedrzejewski (1987). The isophotes are well fitted by ellipses (Fig. 6a to e). Position angles are measured from N through E.

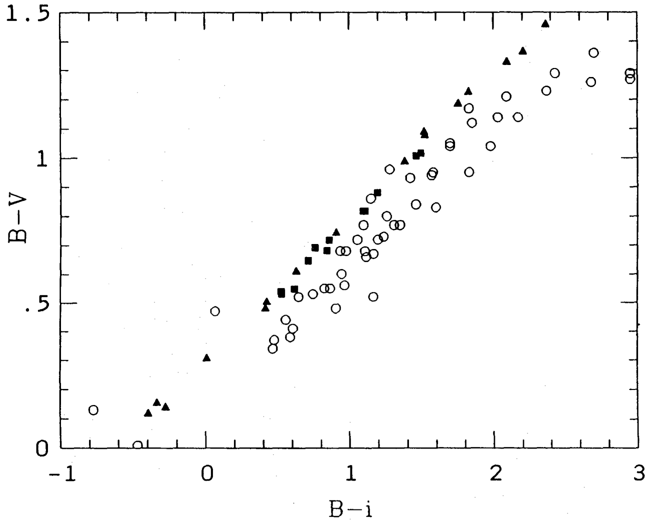


Fig. 1. $B-V$ vs $B-i$ color diagram for all the stars in the A 3429 and A 1644 fields (circles) and for a sample of stars from Stobie (1985b) and Graham (1982) (filled triangles and squares respectively)

A 1644. The position angle of the semimajor axis of this galaxy is constant around 50°. The ellipticity increases from 0.1 to 0.3 (Fig. 6a).

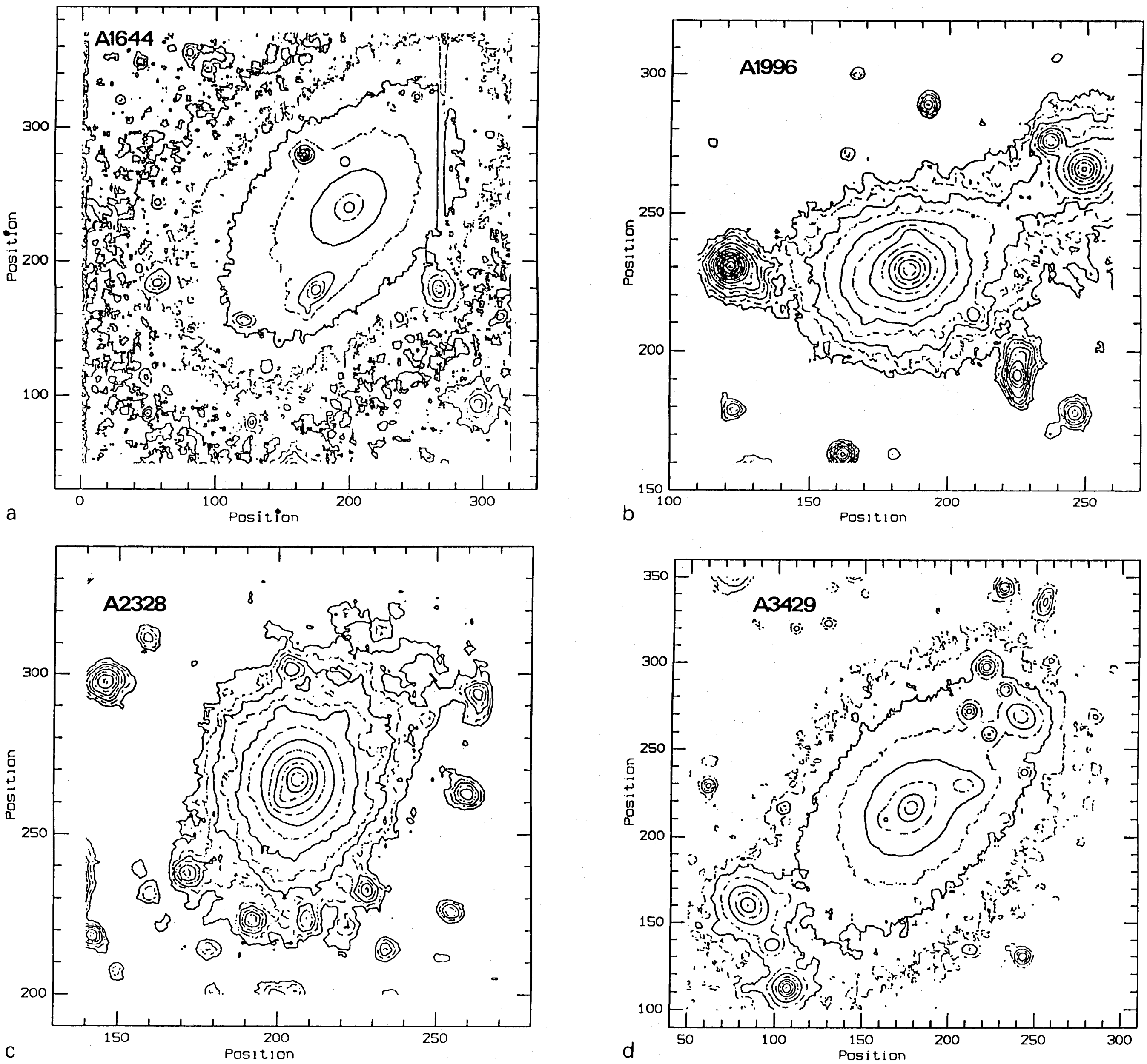
A 1996. The position angle is constant around 65°, but beyond 14 kpc shows a decrease of $\sim 15°$ (Fig. 6b). The ellipticity monotonically increases from 0.1 to 0.2.

A 2328. As Hoessel (1980) had already noticed, this BCG has a double nucleus (see Fig. 3). However the line joining the two nuclei differs by $\sim 30°$ from the position angle of the galaxy, which is stable at $\sim 20°$, but at radii where the second nucleus is located (Fig. 6c). The ellipticity of the outer parts of A 2328 is 0.12, the same as that of the brighter nucleus. Moreover there are no signs of isophote deviations from perfect ellipticity in the amplitude of the third and fourth harmonics of the Fourier analysis, with the obvious exception of the isophotes passing right through the second nucleus (at $\log a \sim 0.55$). In our opinion, this suggests that the second nucleus is only a chance superposition of a galaxy in the cluster center.

A 3429. According to Hoessel (1980), A 3429 also qualifies as possessing a multiple nucleus. However, the analysis of the profile of the object to the SW shows it is a star and the object to the NE looks very much a superposed galaxy, since the line joining the main nucleus and this second object have a different alignment from the whole galaxy (see Fig. 4) and there are no signs of isophote deviations from perfect ellipticity in the amplitude of the third and fourth harmonics (Fig. 6d), but, again, at radii where the two objects are located. The position angle of A 3429 is constant around 40°, and the ellipticity increases from 0.2 to 0.3.

A 3670. Ellipticity and position angle seem to be constant at 0.2 and 20° respectively, for the high surface brightness region (Fig. 6e). These parameters become poorly determined for isophotes fainter than 23 mag arcsec^{-2}, where numerous objects appear superimposed on the outer envelope of the BCG. Before

[1] A halo similar to the one of A 2670 would produce in our image of A 3429 a surface brightness gradient of about 4 count pixel^{-1} from 100 (72″) to 200 kpc (145″) radius. The observed radial gradient in the same range is, at worst, less than 0.3 ct pxl^{-1}



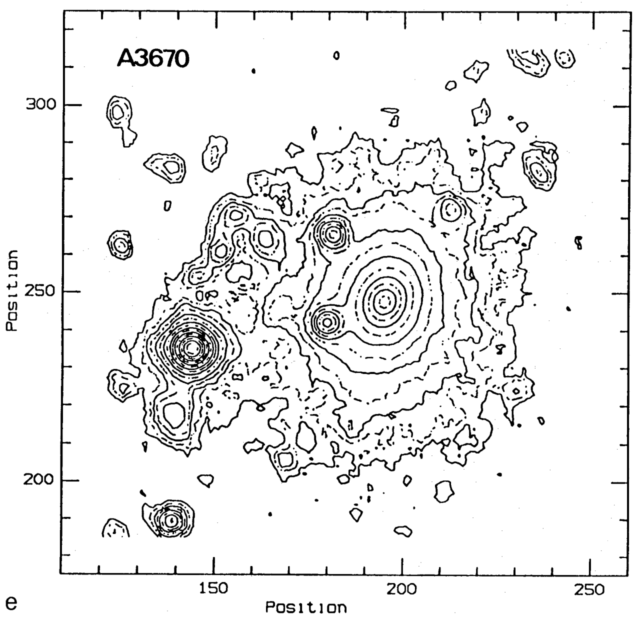


Fig. 2a–e. *V* isophotal contours of the 5 BCGs after applying a smoothing filter in a 3 × 3 pixels box. N is at the top and E to the right. The faintest contour corresponds to 26 mag arcsec^{-2}. The contour spacing is 1 mag arcsec^{-2} for A 1644 and A 3429 and 0.5 mag arcsec^{-2} for the other BCGs. The axis units are pixels (1 pxl = 0″.47). The vertical feature on the right of Fig. 2a is a defective CCD column

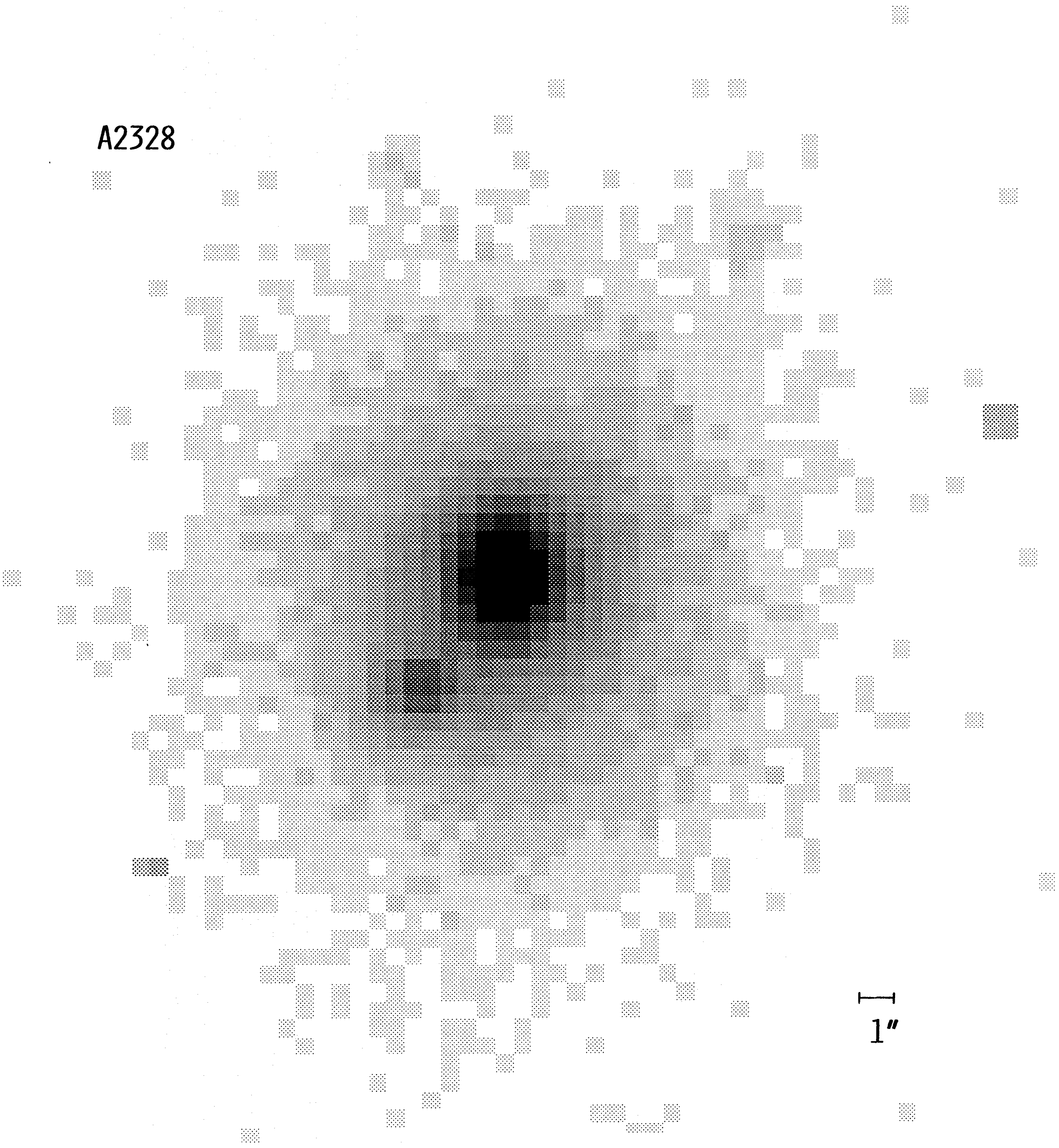


Fig. 3. *V* band image of the central part of A 2328 showing the possible double nucleus. N is at the top and E to the right

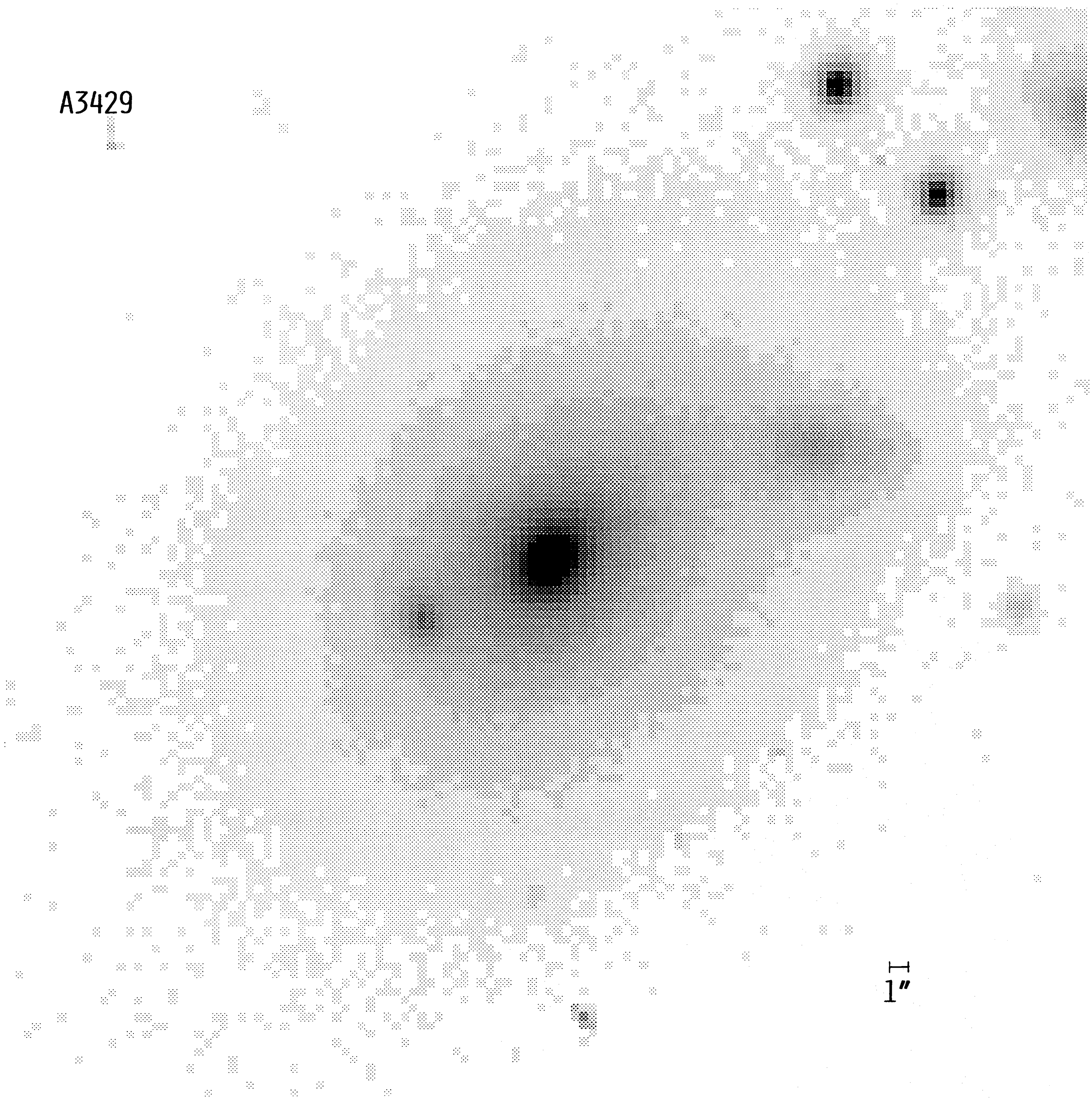


Fig. 4. V band image of A 3429. N is at the top and E to the right

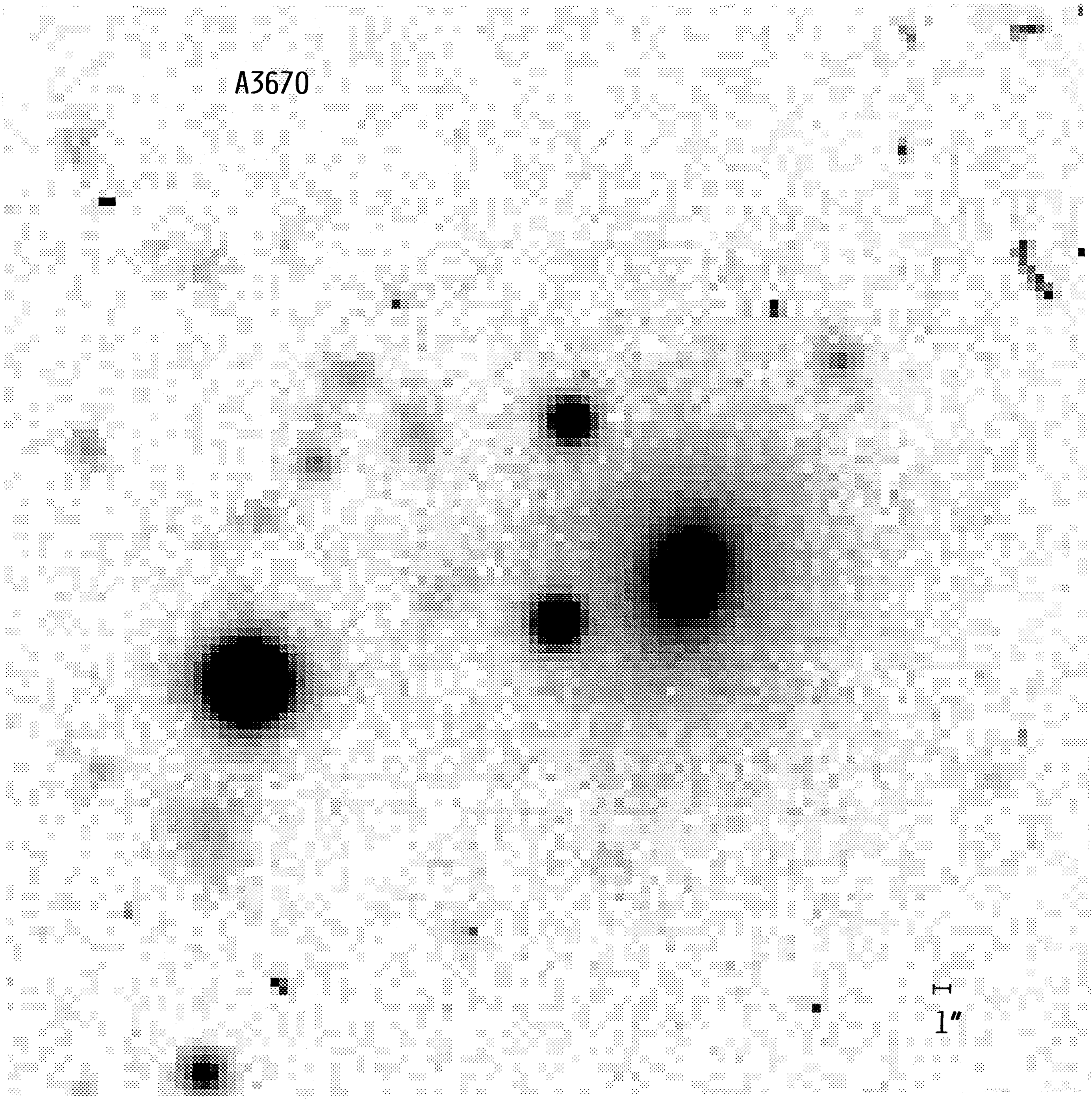


Fig. 5. *V* band image of A 3670. N is at the top and E to the right

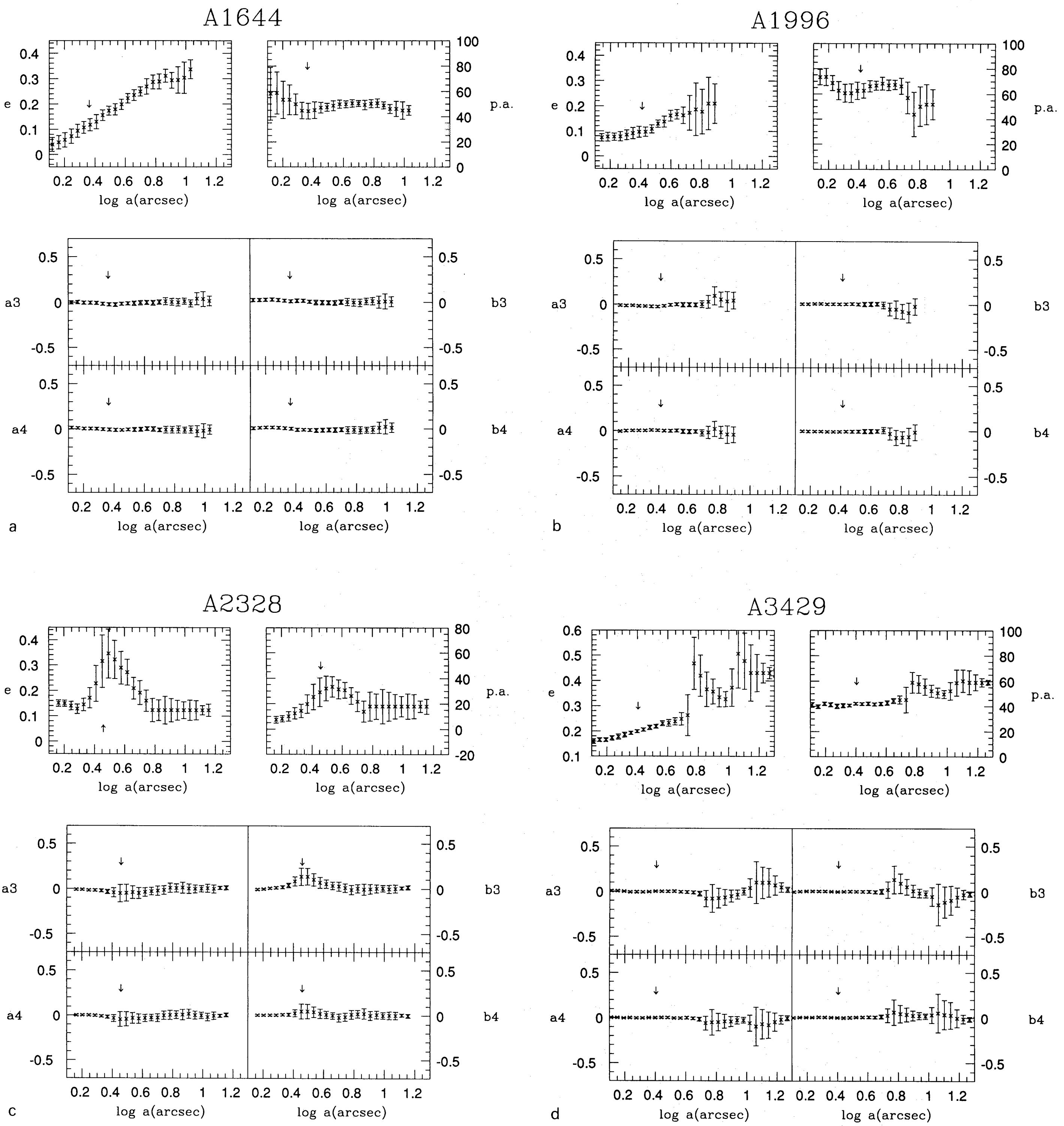


Fig. 6a–e. Ellipticity, position angle, and sine (a 3 and a 4) and cosine (b 3 and b 4) terms of the fitting function (Jedrzejewski 1987) in the *V* filter of the 5 BCGs in our sample as a function of the logarithm of the semi-major axis *a*. Arrows indicate twice the FWHM of the image seeing

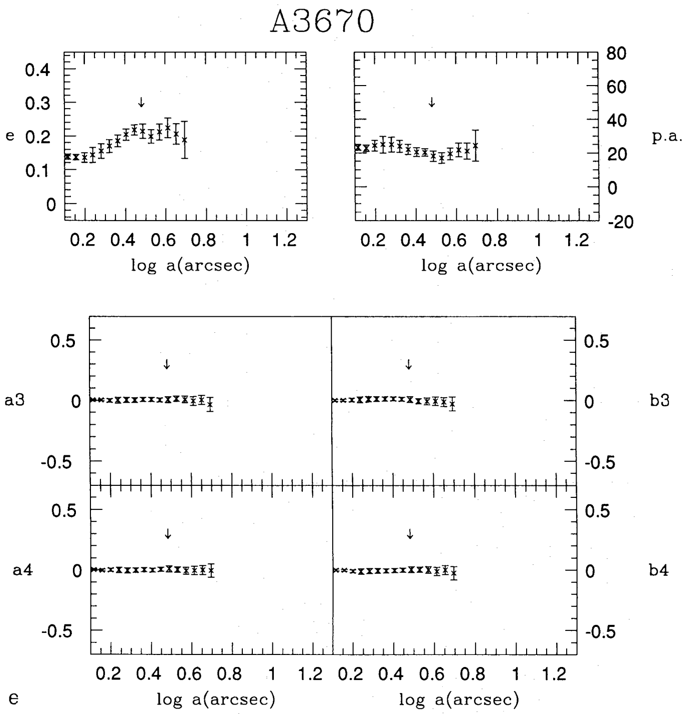


Fig. 6e

the observing run, we classified this galaxy as a dumb-bell upon plate inspection. On the contrary, the bright object to the WSW which lies inside a common envelope in Fig. 2e is a bright superposed star and the common envelope is due to an intervening series of faint objects (see also Fig. 5).

Table 3 gives the apparent V magnitudes of the 5 galaxies computed within 16 and 32 kpc radii, where $r=(ab)^{1/2}$, the V magnitude obtained by integrating pixel intensities inside the 25 mag arcsec^{-2} isophote and the absolute V magnitude within 32 kpc radius.

The surface brightness profiles of the BCGs were obtained in each filter by integrating the counts within concentric ellipses of the same position angle and ellipticity. An iterative sigma-clipping procedure was used to remove superposed stars, galaxies and chip defects from the integration. Figures 7a to e show the surface brightness and color profiles of the 5 BCGs as a function of the logarithm of the semi-major axis. The profiles have been plotted only beyond the radius where seeing induced effects [mainly a brightening of the surface brightness at intermediate radii due to the faint tails of the PSF, see Schweizer (1981) and Lauer (1985)] are less than 0.1 mag arcsec^{-2}. This value has been estimated by convolving a de Vaucouleurs' (1948) law with an effective radius similar to the one that can be estimated from the outer parts of the profiles of our BCGs with a measured PSF. We found that surface brightness profiles are unaffected (within the photometric accuracy) beyond a radius equal to 3.2 times the FWHM of the measured PSFs. For this same reason, color profiles are affected out to the same radii whenever there are seeing differences between the exposures.

The first point to note is that in the inner parts A 1644 is flatter than the other BCGs. Secondly, A 1644 shows a turnover at $\sim 25''$ radius. This can be brought about by an overestimate of the sky background of the order of 6%; however it would imply that the surface brightness of the envelope is ~ 24 V mag arcsec^{-2} at radii of the order of 150 kpc. In any case the turnover begins further in ($\sim 30-50$ kpc), where the effect of a possible overestimation of the sky level is negligible. We note that the shape of the profile of A 1644 is similar to the one of A 2063 (Porter et al. 1991).

V magnitude surface brightness profiles have been fitted to an $r^{1/4}$ law. The results are shown in Fig. 8a to d and reported in Table 4. We do not show A 1644, which could not be fitted by a de Vaucouleurs' law. A 3429 and A 3670 yield fits which are not particularly satisfactory ($\chi^2_{\rm red} > 3$), mainly because the profiles are not smooth enough with respect to the model law. However, the effective surface brightness [corrected for k dimming (Coleman et al. 1980), galactic extinction and $(1+z)^{-4}$ cosmological surface brightness dimming] are all within 0.5 mag. A 1996, A 2328 and A 3429 all have effective radii of ~ 30 kpc, while A 3670 has a significantly larger effective radius, i.e. ~ 44 kpc (this radius is outside the 90% confidence contour ($\sim 2\sigma$) for A 2328 and A 3429 and the 99% confidence contour ($\sim 2.5\sigma$) for A 3429).

We must note that none of the galaxies we studied shows a red halo in the i filter. The detection of such a halo in GREG (Maccagni et al. 1988) therefore still remains unique.

The colors of the 5 BCGs within a 64 kpc aperture are the same in the rest-frame, the color dispersion being equal to the photometric accuracy (see Table 5). Color profiles are generally quite flat (see Fig. 7a to e): three BCGs (A 1644, A 1996 and A 3429) have color gradients compatible with zero as well as with the small color gradient typical of ellipticals (Sandage & Visvanathan 1978) and BCGs (Mackie et al. 1990). We define as positive a gradient so that galaxies become redder with increasing radius. For A 2328 and A 3670 we can measure the trend to changing $B-V$ and $V-i$ with log a: the gradient found from the linear regression is -0.11 ($B-V$) and 0.10 ($V-i$) for A 2328 and -0.16 (both for $B-V$ and $V-i$) for A 3670 respectively. However statistical tests like the t-test give marginal evidence for the trend in the data being real

Table 3. BCG magnitudes integrated within metric and isophotal radii

Cluster (1)	m_V $r<16$ kpc (2)	m_V $r<32$ kpc (3)	m_V $V<25$ mag arcsec^{-2} (4)	M_V $r<32$ kpc (5)
Abell 1644	14.52	13.80	12.60	−23.6
Abell 1996	16.70	16.20	16.12	−23.6
Abell 2328	16.93	16.46	16.06	−23.7
Abell 3429	14.95	14.50	14.18	−23.5
Abell 3670	17.27	16.79	16.56	−23.8

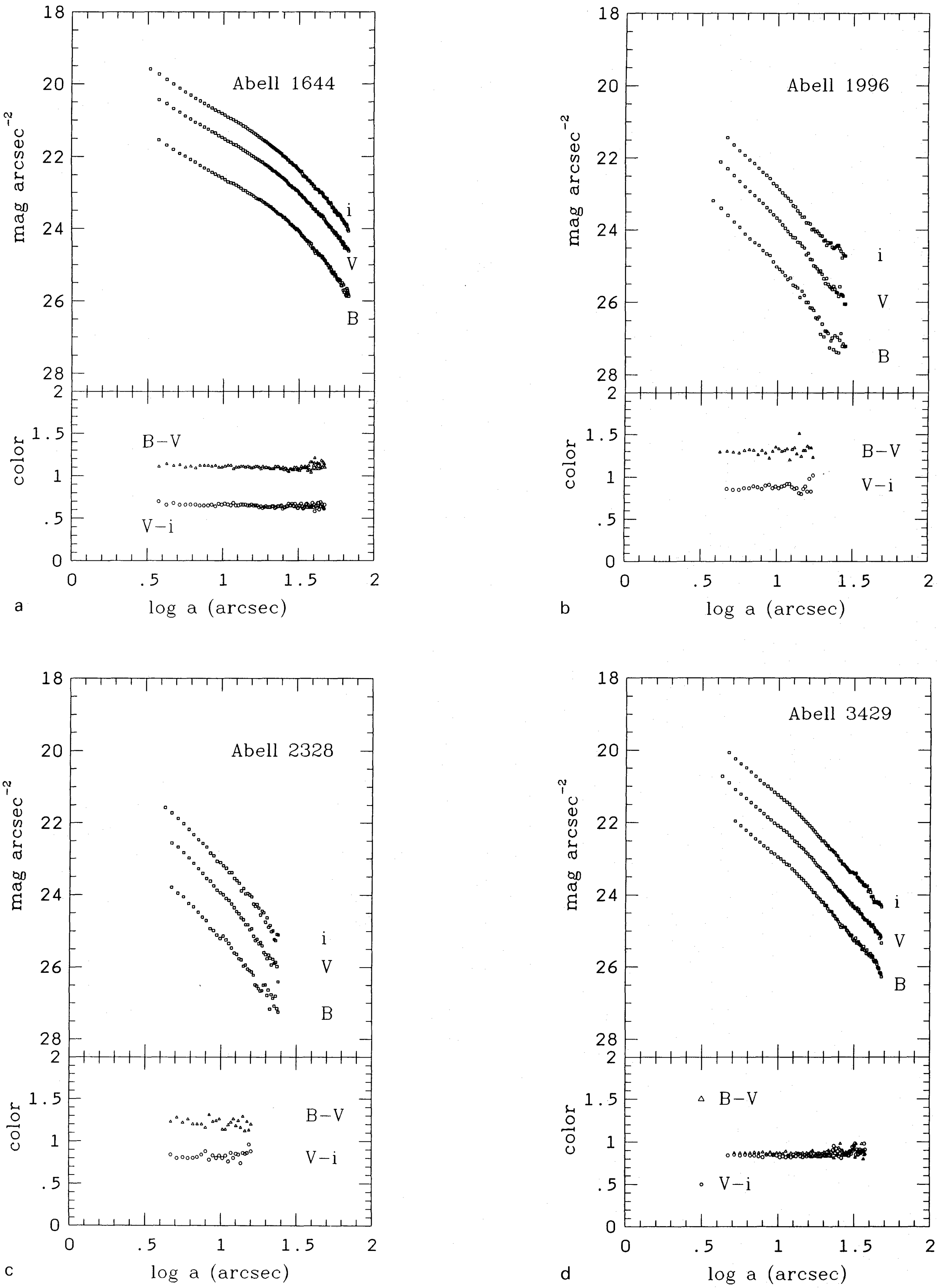


Fig. 7a–e. Surface brightness and color profiles for the 5 BCGs of our sample as a function of the logarithm of the semi-major axis *a*

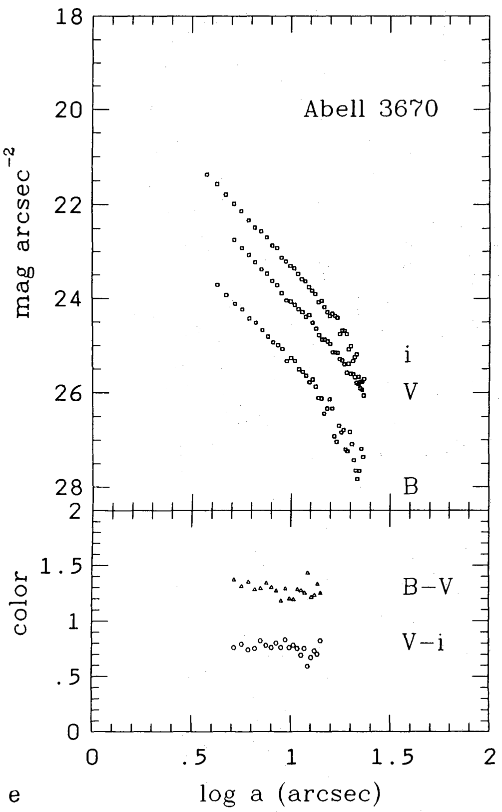


Fig. 7e

Table 4. de Vaucouleurs' parameters of BCGs

Cluster (1)	r_e (kpc) (2)	μ_e (m_V arcsec^{-2}) (3)	χ^2_{red} (4)	d.o.f. (5)
Abell 1996	30.3	23.2	1.7	49
Abell 2328	29.2	22.9	1.1	38
Abell 3429	30.1	23.3	4.7	140
Abell 3670	44.2	23.4	3.1	37

Table 5. BCG colors[a] in the rest-frame within a 64 kpc aperture

BCG (1)	$B-V$ (2)	$V-i$ (3)	$E(B-V)$[b] (3)
Abell 1644	0.95	0.62	0.026
Abell 1996	0.84	0.80	0.066
Abell 2328	0.74	0.71	0.025
Abell 3429	0.66	0.81	0.025
Abell 3670	0.74	0.56	0.050
Mean color	0.79±0.11	0.70±0.11	

[a] The correction for extinction in our Galaxy has not been applied since it is negligible with respect to the photometric error.
[b] The $E(B-V)$ has been calculated following Schneider et al. (1983) from the N_H column density of Stark et al. (distributed data).

(since the probability that the null hypothesis of no color gradient is verified is of the order of 10^{-3}). It should be noted that these color gradients (of the order of 3.3 10^{-3} and 4.7 10^{-3} mag kpc^{-1}, respectively) are observed in the two most distant galaxies, for which the errors of the color profile points are almost of the same order of the gradient found. If errors are taken into account, the significance of the gradient is much reduced. Furthermore, in these two cases we are studying a bluer region of the spectrum, where we would expect even larger gradients (Sandage & Visvanathan 1978).

5. Discussion

Since the size of the sample we studied is small, we will only discuss a few points which could be useful in future works.

The Bautz-Morgan type I classification of clusters of galaxies (as revised by Abell et al. (1989)) includes clusters with BCGs of different morphologies: A 1996, A 2328 and A 3429 are all very similar, with effective radii of ~30 kpc; A 1644 and A 3670 are larger galaxies with similar and brighter profiles beyond ~25 kpc (see Fig. 9). However A 1644 has a lower surface brightness in the inner parts. There seems to be an indication of a relation between outer brightness and size of the BCG and cluster richness, since both A 1644 and A 3670 are richness 2 clusters, while the others are richness 0. This independently of the presence of a large envelope like the one characterizing cD galaxies. Nevertheless, we must caution that the larger size attributed to A 3670 depends on a redshift which is only estimated and not measured: its profile would become similar to the other three and nullify the hint of a correlation between size and richness in this sample if A 3670 were at a redshift 40% lower. Of course, in this case its total absolute magnitude would become 1 mag fainter, making it quite different from the other BCGs of the same size. We remind, however, that the redshift of two of the three galaxies having similar morphology is only estimated ($\Delta z/z = 22\%$) producing in the effective radius an error of 18% when $z = 0.1$. Probably, the best parameter to correlate with effective radius would be the local galaxy density, rather than a global parameter like Abell richness, which also suffers from large uncertainties, though being statistically corrected for field density.

The second point is the question of multiple nuclei. Two of the galaxies in this sample qualified as multiple nuclei objects. However, both the ellipticity and position angle trends with radius as well as the undisturbed isophotes are what one would expect from superposed objects. If dynamical simulation of mergers could show that the situation we found cannot be reproduced during the merging process, i.e. that the relaxation time of the outer parts of a galaxy cannot be shorter than the merging times of the nuclei, then this type of photometric analysis can be a useful tool to assess the statistics of true multiple nuclei BCGs.

Finally, the average colors within 64 kpc of all those BCGs are the same and, if any, the color gradients they show are compatible with previous measurements of high luminosity ellipticals and BCGs. Our data seem to suggest that if the different morphologies of our BCGs are tied to the environment of the clusters, the

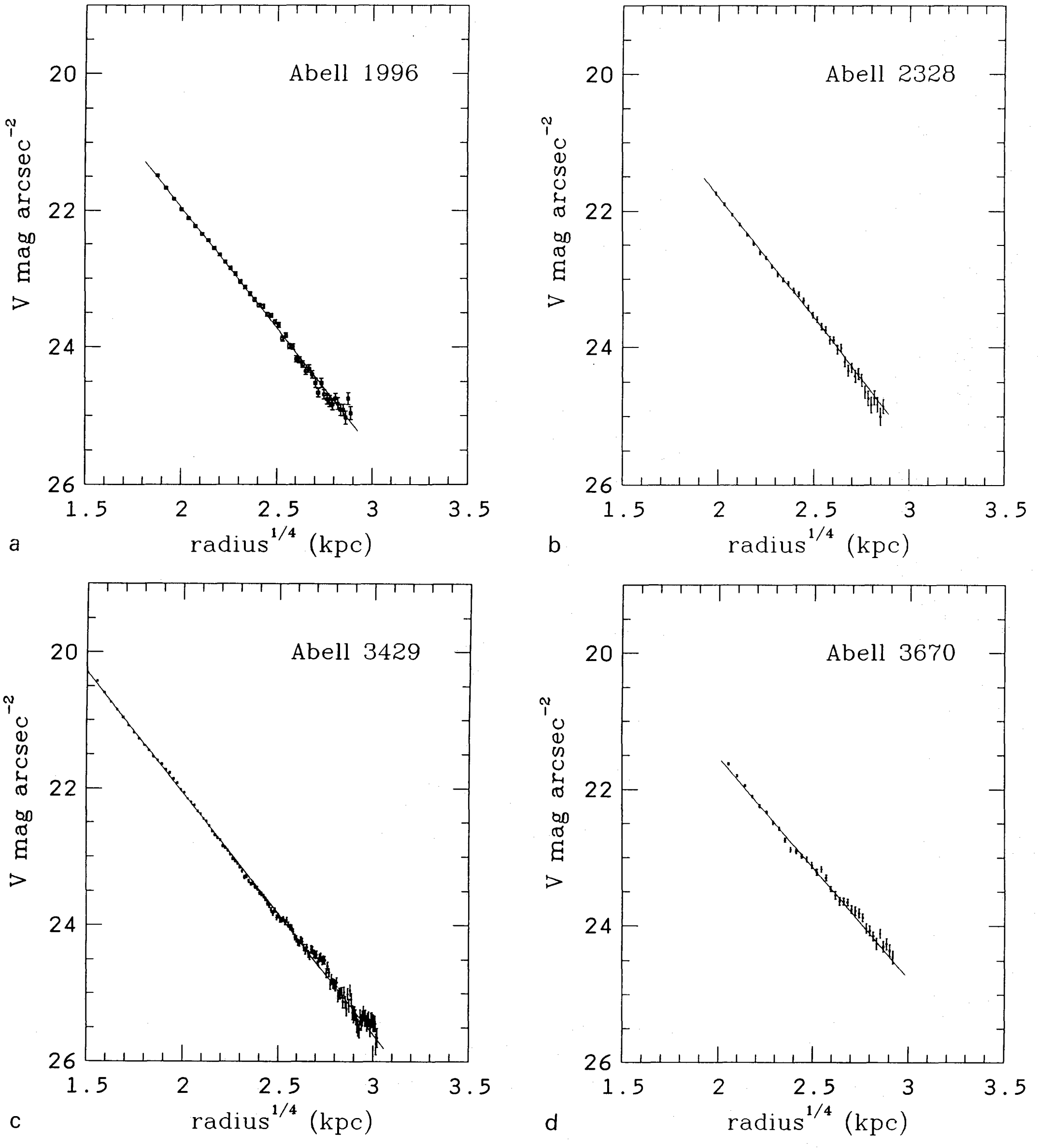


Fig. 8a–d. *V* surface brightness profiles of A1996, A2328, A3429 and A3670 plotted as a function of $r = (\sqrt{ab})^{1/4}$. The errors shown are the combination of counting statistics and systematic errors. The solid lines are the best fitting de Vaucouleurs' laws

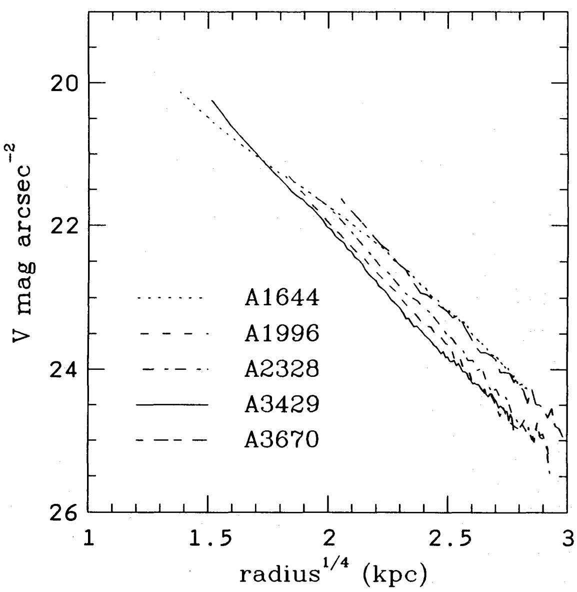


Fig. 9. Comparison of the *V* surface brightness profiles of the BCGs in our sample. Surface brightnesses have been computed in the galaxy rest frames

mechanisms governing their formation and evolution, be they merging, tidal interactions, or cooling flows, cannot modify the stellar population and its radial distribution. On the other hand there are suggestions that at least merging can modify the stellar populations (Vader et al. 1988; Mackie et al. 1990). Clearly no firm conclusions can be reached from such a small sample and we are presently enlarging it to further investigate the results hinted in the present paper.

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