Astron. Astrophys. 150, 62–68 (1985)

ASTRONOMY AND ASTROPHYSICS

Photometry of NGC 6166

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Received January 22, accepted April 29, 1984

Summary. We present the 2-color photometry of the Cd galaxy NGC 6166, made at the CFH with the CEA/INAG CCD camera. For the main galaxy we derive the luminosity profiles, the characteristics of the isophotes as a function of the radius and color gradients. NGC 6166 behaves like a normal elliptical galaxy and does not exhibit any sign of cannibalism or merging. The same studies were applied to the bright spots usually referred to as the nuclei B and C. Calculation of dynamical parameters permits the reconstruction of the 3 dimensional shape of the system, which suggests that B and C are cluster galaxies seen in projection rather than additional nuclei.

Key words: galaxies: elliptical – galaxies: evolution – galaxies: individual: NGC 6166 – galaxies: nuclei of

1. Introduction

Supergiant galaxies known as cD galaxies are often found in the central regions of clusters of galaxies. About 1/3 to 1/2 of cD galaxies have multiple nuclei (Hoessel, 1980; Schneider et al., 1983). Projection effects in clusters of galaxies are barely able to explain such a high proportion of multiple nuclei. On the opposite side they are taken as evidence that galaxy merging play an important role in the cD formation. Dynamical friction (Ostriker and Tremaine, 1975) is the most likely phenomenon to dissipate the orbital energy of individual galaxies and to merge them in the monstruous central object. But recent calculations (Merrit, 1984) have shown that the time scale for dynamical friction is longer than the Hubble time. Dynamical friction then cannot explain the growth of cD galaxies during the ongoing cluster evolution.

Multicolor surface photometry can give some insights in the cD formation mechanism in several respects. First it allows to look for color gradients in a cD galaxy. A strong color gradient will be in favor of a common origin of normal elliptical and cD galaxies rather than formation by mergers (Kormendy, 1982; White, 1982). Secondly the surface brightness profile of each nucleus can be obtained and, together with the velocity dispersion, give the tridimensional shape of the system. The best candidate for such a program is the archetypal cD galaxy NGC 6166. This galaxy is the first ranked galaxy of the cluster A 2199; it is associated with the radio-source 3C338 (Jaffe and Perola, 1975) and contains 4 nuclei (Minkowski, 1961) within a 14″ circle. Assuming a distance of 93 Mpc derived from an average redshift of 0.031 (Noonan, 1978) and a Hubble constant of 100 km s^{-1} Mpc^{-1}, this corresponds to a projected separation of ~6 kpc. Its total luminosity is $M_v \sim -22.7$ (Hoessel, 1980). However this number is very uncertain and strongly depends on the assumed asymptotic behaviour of the luminosity profiles. The 26 mag/arcsec^2 R-isophote has a major axis diameter of ~700″ and the galaxy extends further. Errors as large as 2 magnitudes are not unlikely (Carter, 1977).

2. Observations and data reduction

To fit the huge size of NGC 6166 on the CCD we used two telescopes. It was first observed in 1982 at the Newton focus of the 193 cm of the Observatoire de Haute Provence behind a $f/1.5$ focal reducer. A thin and backside illuminated RCA CCD of 320*512 pixels of 30 μ length was set up in the CEA/INAG CCD camera. The pixel size size was 2″.2 and the total field was 690″*1100″. Although too small to determine the very faint extension of NGC 6166, this field, according to Carter's (1977) result, is enough to determine a sky level with an accuracy better than 1 %. The same CCD camera was then set up in 1983 at the Cassegrain focus of the Canada France Hawai telescope behind the CFH $f/2$ focal reducer. The pixel size was 0″.83 for a total field of 265″*424″ (see Table 1). For both observations we used a Gunn R filter (Thuan and Gunn, 1976) and a blue filter centered at 450 nm with a FWHM of 50 nm. Transformation into standard B and R were performed with the use of secondary $UBVR$ standard (Moffet and Barnes, 1979) and a

Table 1. Log of the observations

		Telescopes	
		OHP	CFH
Date		June 1982	May 1983
Pixel size (arcsec)		2.2 × 2.2	0.83 × 0.83
Total field (arcmin)		11.5 × 18.3	4.4 × 7.1
B filter	Exposure time (seconds)	1800	1200
	λ_0 (nm)	450	450
	FWHM (nm)	50	50
R filter	Exposure time (seconds)	1200	720
	λ_0 (nm)	660	660
	FWHM (nm)	50	80

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sequence in the globular cluster M 92. Both sets of images were flat-fielded with flat fields taken on twighlight sky. In each case a bias level was calculated for each column by extrapolating to zero the signal corresponding to several images taken with decreasing exposure times and using a highly stabilized lamp giving a roughly uniform illumination of the CCD. A complete description of the reduction procedure and the accuracy of the photometry can be found elsewhere (Souviron, 1984; Souviron and Vigroux, 1985).

As a standard galaxy we observed also at the CFH the galaxy NGC 3379. Comparison with de Vaucouleurs and Cappacioli results (1979) shows an rms difference of 0.02 mag except at the center where we found the galaxy 0.1 magnitude brighter. However this difference was also found by Nieto (1985). A careful analysis of the 20 galaxies observed during the CFH run has shown that the accuracy of the B–R colors is ~ 0.02 magnitude for a R surface brightness $\mu_r < 24\,\mathrm{mag/arcsec}^2$.

3. Surface photometry

For both colors we used the low resolution OHP images to derive a sky level which was scaled and used for the CFH observation by comparing the intensities of several galaxies contained in the two fields. Only the CFH results are presented here. Figure 6a shows the R image illustrated in False colors. Three nuclei, designed hereafter by A, B and C are clearly resolved. A careful inspection shows that B is also double, in agreement with the Minkowski picture (1961). But, due to the low resolution of the CFH focal reducer, they are barely resolved and we take the B nucleus as a single object. Clearly the isophotes of the galaxy are distorted below the A nucleus by the B component. Several trials were performed to separate the A, B and C components. The best results were achieved by an iterating symmetrisation procedure. First we have determined the center of the A nucleus; then in a zone including the B and C nuclei we have replaced each pixel intensity by the intensity of the pixel symmetric with respect to the center of A; we have then subtracted the resulting image from the original one to obtain the nuclei B and C alone (see plate). This separation gives a good result for that half part of B, most distant from A. In particular it shows that the B radius is larger than the A–B separation so that the points between A and B are not well determined. Then we symmetrize the B nucleus by replacing all the points up to a line passing through B by their symmetrics with respect to the center of B. This new file was subtracted from the original one to obtain the A component alone. This process was iterated twice and the last B symmetrisation allows to obtain the C component. Since the A nucleus is almost at the center of the outer isophote of the galaxy, we assume in the following that it is its true nucleus. Let us first discuss its photometric properties.

We have used a standard χ^2 procedure to fit the isophotes by ellipses. This procedure gives the variations of the center position, the inclination angle, the size of the major axis and the ellipticity. An interacting procedure was used to eliminate the stars and the contamination by other cluster galaxies to the isophotes. The results of this ellipse fitting are displayed in Figs. 1 to 6. Figure 1a displays the B profile along the major axis. Superposed is the B profile from Carter (1978). The agreement is far from good; several reasons can explain this disagreement. For the very center ($r < 10''$), Carter's results are affected by plate saturation. For $r < 20''$ the disagreement comes from the presence of the B nucleus in Carter's data. Some other problems due to plate calibration or to plate background subtraction can also affect

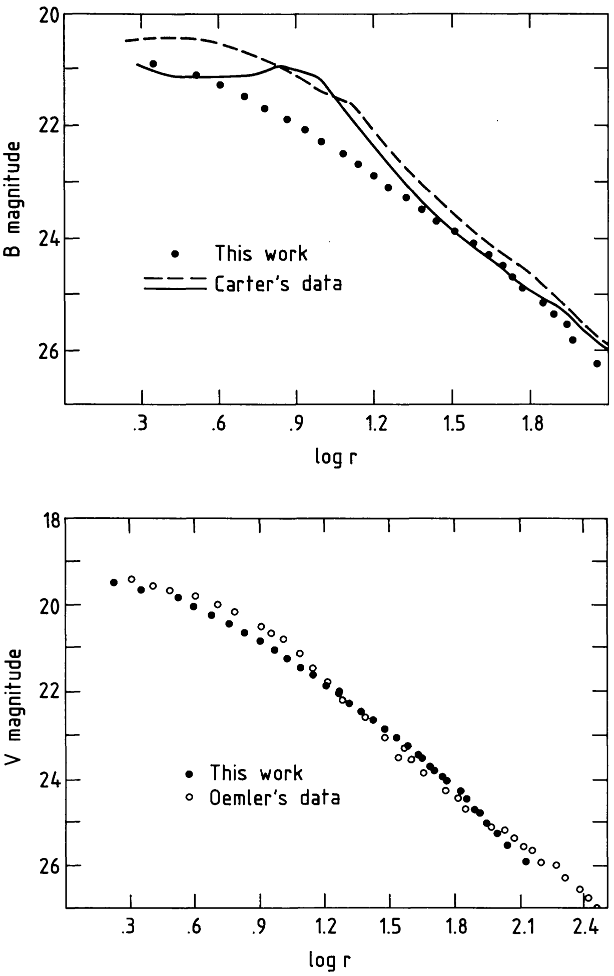


Fig. 1. **a** B profile of NGC 6166, resulting from our photometric data, which appears to follow a de Vaucouleurs law. It has been calculated for the galaxy after elimination of the contributions of other nuclei or galaxies, as indicated in the text. For comparison are also plotted Carter's data. The strong difference near the center results from the contribution of other nuclei (or galaxies) in Carter's data. The discrepancies are discussed in the text. Coordinates are the logarithm of the galactocentric radius in arcseconds and the B surface brightness in magnitudes. **b** V profile of NGC 6166, resulting from a composition of our R and B data; Oemler's data are also plotted for comparison. The coordinates are identical to Fig. 1a

Carter's results, in particular for the B plate for which the disagreement is the worst.

We have also calculated, from our B and R images, a V image. Figure 1b shows the comparison of our V profile with the one obtained by Oemler (1976). With the exception of the inner 20″ where Oemler profile is affected by the three nuclei, the agreement is much better than with the Carter result.

Our data show that, at least down to $\mu_R = 25\,\mathrm{arcsec}^{-2}$ the profile is almost a $r^{1/4}$ de Vaucouleurs law and neither a change of slope nor the presence of other components are detectable. The best fit is achieved with an effective radius $r_e = 100''$ and a central R magnitude of 15.3. Figure 2 exhibits the variation of the ellipticity with the R surface brightness. The most surprising result is the continuous increase of the ellipticity from the center to the external part of the galaxy. This result may be discussed: it is not present in Carter's data; however, for $r < 20''$ his results are affected by the presence of the B nucleus. A bad seeing leads to almost round

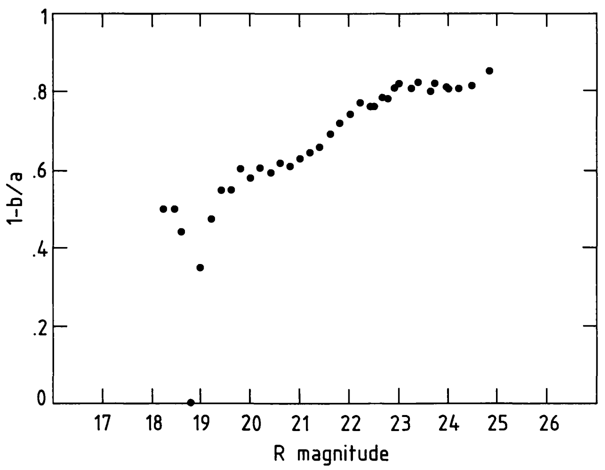


Fig. 2. This figure shows the variation of ellipticity of the isophotes for NGC 6166, with respect to the R magnitude. Ellipticity is calculated from an ellipse least-square fitting of the isophotes. Contributions of the B and C nuclei have been eliminated as indicated in the text. Ellipticity is increasing from the center to the edge

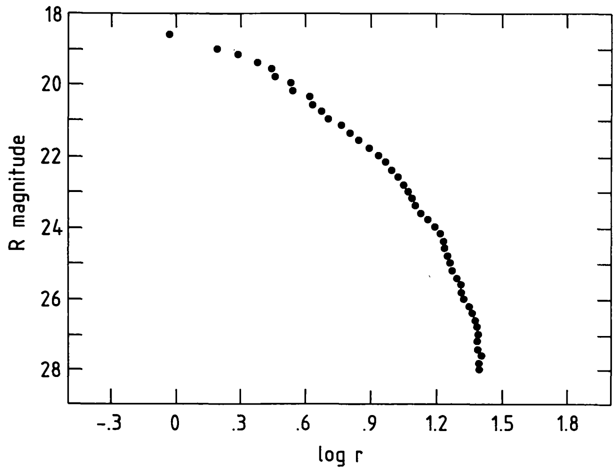


Fig. 4. The photometric R profile of the B nucleus is presented, with respect to the distance to its center, in arcsec. A cut off is apparent at $r = 26''$

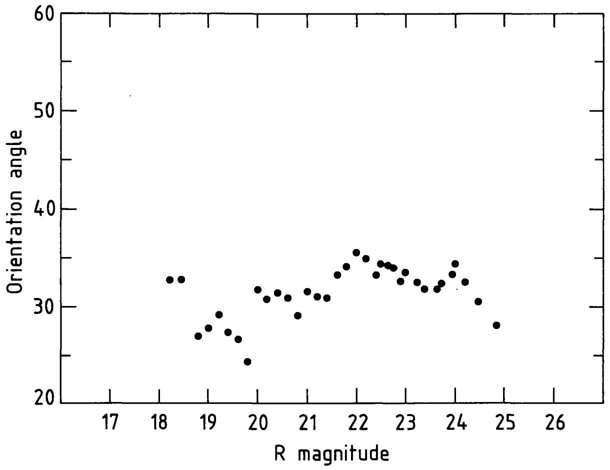


Fig. 3. This figure shows the variation of orientation angles of the isophotes for NGC 6166. These angles are obtained like in Fig 2. No variation with magnitude (or with radius) is apparent

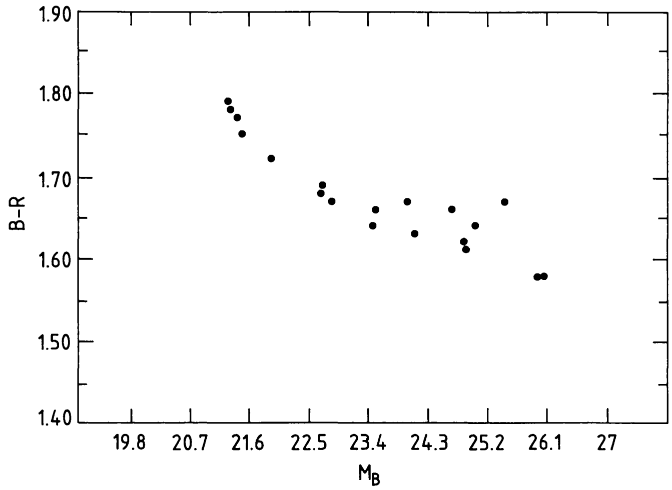


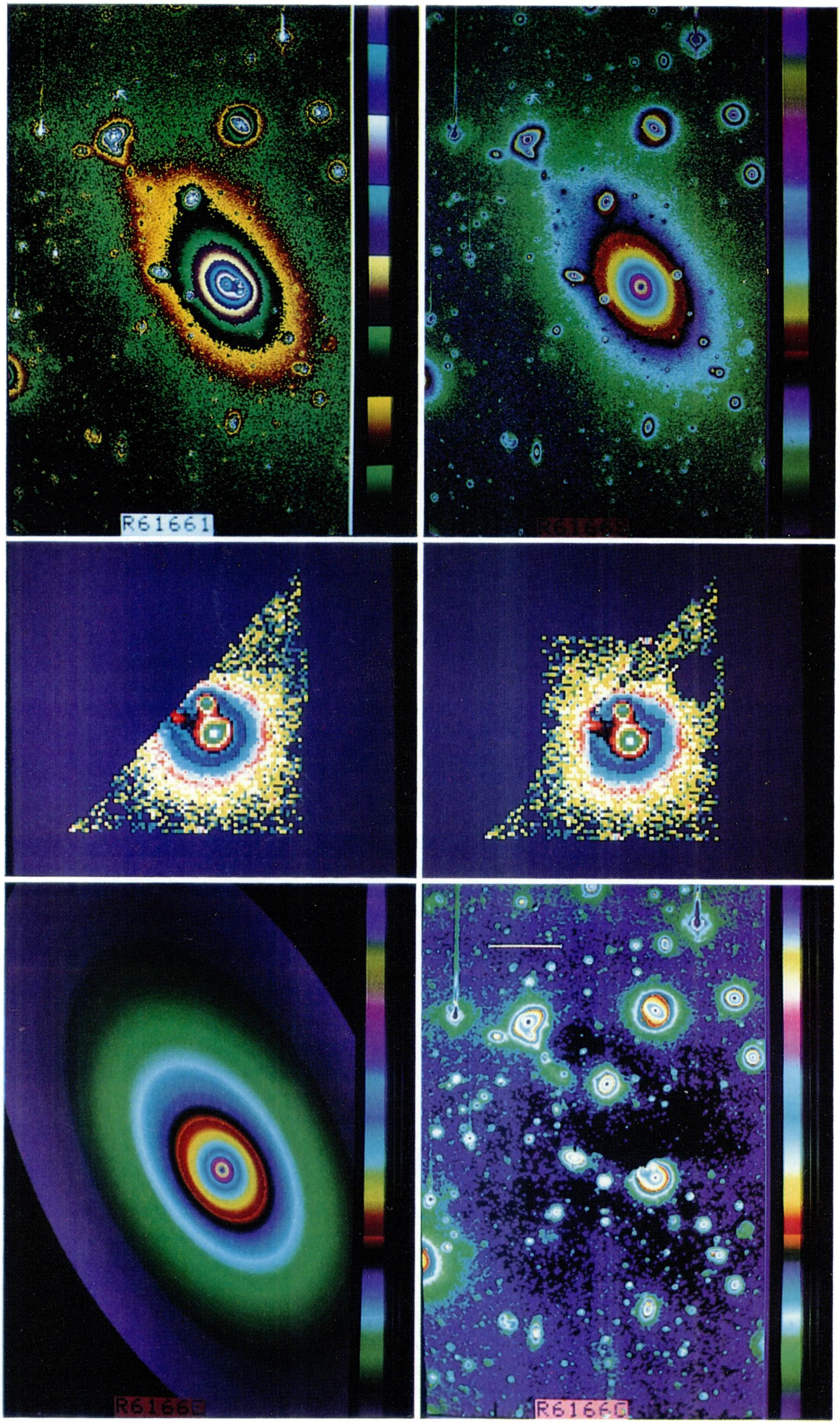
Fig. 5. Color profiles of the galaxy NGC 6166 along the main axis. B and R magnitudes are evaluated in areas of the image free from contamination by other galaxies

isophotes in the central part. However, as usual at the CFH, the seeing was very good ($\leq 1''$) and we do not expect seeing contamination to extend beyond $5''$, which corresponds to the limit derived from the observations of flatter elliptical galaxies in the same conditions.

On the other hand out symmetrisation procedure may induce some spurious results despite the fact that symmetry with respect to a point conserves ellipticity. We have checked this possible influence by fitting ellipses only in the half part of the galaxy which is not affected by the B nucleus. While less steep, the increase of ellipticity toward the external part is still present. If real, such an important variation is very unusual. On the opposite the position angle of the major axis (Fig. 3) does not exhibit any strong variation.

Figure 4 shows the profiles of the B component in R color. This profile is very smooth but presents a very sharp cut off at $r \sim 26''$.

Fig. 6a–f. This plate illustrates the various stages of the iterative procedure used for separating in our data the contribution of the galaxy NGC 6166 and of the two nuclei labelled B and C. **a** Shows the initial picture, after pretreatment. **b** Shows the galaxy NGC 6166, reconstructed by symmetry with respect to its center, from its upper left half (see text). **c** Presents the difference between pictures **a** and **b**. It shows the features of the two nuclei B and C alone (in first approximation). As the upper left part is contaminated by the bad subtraction near the center of NGC 6166, this picture is then symmetrized again, with respect to a line passing through the center of B. **d** Gives the B and C nuclei at the end of the procedure. **e** Shows a reconstruction of the galaxy NGC 6166 with parameters resulting from the ellipse fitting procedure. **f** Gives the original field from which the galaxy NGC 6166, reconstructed as in picture e, has been subtracted



a b c d e f

Table 2. Photometric properties of the 3 main components of NGC 6166

	A Component (main galaxy)	B Component	C Component
Central surface brightness (B mag/arcsec^2)	20.20	19.77	20.52
Mean velocity	9350 ± 15[a]	8024 ± 15[a]	10,114 ± 15[a]
Velocity dispersion (km s^{-1})	299[a]	197[a]	
Core radius			
arcsec	7.5 (4.32[a])	< 0.6	
1/h pc	3403 (1960[a])	280	
I_0 ($L_\odot$ pc^{-2})	550 (1000[a])	2450	
$I_0 r_c$ (10^6 h^{-1} $L_\odot$ pc^{-1})	1.87 (2[a])	< 0.70 (1.2[a])	
M/L ($M_\odot/L_\odot$)	15.9 (15.3[a])	< 17.0	
L_B ($10^9 h^{-2} L_\odot$)	6.63	5.17	1.0
m_B (mag)	14.22	16.05	17.9

[a] Denotes the values used by Tonry (1983)

The identification of this cut off with a tidal radius allows the reconstruction of the tridimensional shape of the system. This is discussed in the next section.

4. Dynamical properties

4.1. Tidal radius

As shown on Fig. 4 the profile of the B nucleus obeys a classical form for an elliptical galaxy but with a strong cut off. The reality of this cut off is questionable since a bad estimation of the background level could lead to an artificial decrease which mimicks such a behaviour. However the fact that the B and R images, which were processed independently, give similar profiles and the same estimates for this cut off radius is in favor of the reality of the latter. Anyway a conservative approach would be to take the observed value as a minimal one.

The shape of the profile permits us to determine dynamical parameters for this B nucleus. Interpretation of the cut off as a tidal radius in the gravitational field of NGC 6166 seems very natural and gives $r_{\text{tidal}} = 26''$ (this is from the R image which is less noisy; the B image would give $r_{\text{tidal}} = 24''$).

4.2. Core radius

We can easily fit a Hubble profile $I = I_0/(1 + r/a)^2$ to the galaxy NGC 6166. This gives I_0, the surface brightness of the central pixel, and the core radius a; both are given in Table 2. Our values differ substantially from the ones found by Hoessel (1980) and used by Tonry (1984), which we mention in the table for comparison. Our value for the core radius may be overestimated by the low sampling of the CCD. The convolution of the best fit de Vaucouleur's law by a gaussian of FWHM $\sim 1\overset{''}{.}65$, i.e. 2 times the pixel size, reproduces quite well our observed profile. However we are only interested by the product $I_t = I_0 \times a$ and the simulations of Schweitzer (1979) have shown that this quantity is quite independent of the seeing conditions: Then it is not surprising that our I_t value differs only by ~ 0.1 from Hoessel's results.

For the nucleus B we do not have enough resolution for a direct determination of these parameters. We can only be sure that $a < 2$ pixels $= 1\overset{''}{.}6$. On the other hand we may estimate a using the mean relation between core radius a and effective radius O, $a = 9*O/100$ (Kormendy, 1982), where O is defined as containing half of the total luminosity of the source. Measuring $O \sim 8\overset{''}{.}87$ gives $a \sim 0\overset{''}{.}62$. It should be mentioned that this estimate may give only a lower limit: if the external part of the galaxy has been stripped by tidal forces without modifying the internal profile, the effective radius O is then underestimated and our derived value for a is only a lower limit. We are now able to derive I_0 from the mean surface luminosity in the central pixel

$$I = \left(\int_0^p 2\pi r\, dr\, I_0 (1 + r/a)^{-2}\right) \Big/ \left(\int_0^p 2\pi r\, dr\right) \sim I_0/3,$$

where p is the size of the pixel. The value obtained is given in Table 2.

4.3. M/L ratio

Our photometry, combined with the spectroscopic results of Tonry (1984) permits to estimate the M/L ratios and masses by the relation:

$$\frac{M}{L} = \frac{9\sigma^2 a}{2\pi G I_0 a^2} = 330 \left(\frac{M}{L}\right)_\odot \left(\frac{\sigma}{\text{km s}^{-1}}\right)^2 \left(\frac{a}{\text{pc}}\right) \left(\frac{I_0 a^2}{L_\odot}\right)^{-1},$$

where σ is the one dimensional central velocity dispersion, a the core radius and I_0 the central surface luminosity. We then use our photometric data, calibrated with multiaperture standard photometry, to derive M/L for the central galaxy and the B nucleus.

4.4. Position of B

We now come to the most exciting part which is an estimate of the physical distance between B and the true nucleus A of the galaxy. As the dimension of B ($r_t \sim 26''$) is greater than the apparent separation $d_{AB} = 12\overset{''}{.}1$ it seems unlikely that d_{AB} is the true separation: it probably is only its projection perpendicular to the line of sight. This is reinforced by the fact that the profile of B is typical of an E galaxy (with a tidal cut off imposed) rather than of a nucleus. In order to check this idea we used the well known formula to estimate the tidal radius (Van Hoerner, 1957):

$$r_{\rm tidal} = d\left(\frac{M_{\rm gal}}{3M_{\rm B}}\right)^{1/3} = d\left[\frac{(M/L)_{\rm gal}\,L_{\rm gal}}{3\,(M/L)_{\rm B}\,L_{\rm B}}\right]^{1/3}$$

where d is the true distance, which can therefore be estimated only from observable parameters. It is interesting that this relation depends only on the ratio of the two M/L and not on their absolute value, and at a low power, which reduces considerably the effects of possible errors.

The equation is in fact not so simple because $L_{\rm gal}$ has to be taken inside a sphere of radius d, which is precisely the unknown quantity. However we started from the lowest value $d_{\rm AB} = 12''.1$ and iterated the procedure. The first value obtained is $41''.4$ and then the procedure converges quickly toward the value 75″ which is independent of the starting value; we should remember that this is only a lower limit.

The Van Hoerner formula may be too crude an approximation for this particular problem. It assumes in particular that the two galaxies are spherical and in circular orbits, which is obviously not the case. A more correct approach can use the Monnet and Simien results (1977) which give the gravitational potential for the $r^{1/4}$ law and allows to take the ellipticity into account. However this more accurate approach gives the same result (Monnet, private communication). The uncertainties on the photometric parameters of the B component do not require the use of a more sophisticated analysis.

4.5. Dynamical implications

We have shown that the B nucleus is situated at more than $34\,h^{-1}$ kpc from the center of the galaxy: it can hardly be considered as a nucleus but is more probably a companion galaxy. This is in accordance with the observed profile and the strong radial velocity relative to the galaxy (see Table 2). The question remains as to the orbit of this galaxy B in the potential of NGC 6166.

The possibility of a circular orbit can be rapidly excluded: in this case $d \geqq 75''$ would imply $v = 8300\,{\rm km\,s^{-1}}$ which would require a central mass $\geqq 2.8\ 10^{14}\,M_\odot$ and is clearly contradictory with the observed M/L. If M/L had such a large value (due for instance to a very massive central component) our preceding estimate would no longer be valid but become $x \geqq (M/L)/15.9$, where we define $x = d/70''$. Circularity would then require that $v = x\ 8300\,{\rm km\,s^{-1}}$, $m_A \sim 2.3x^3\ 10^4 M_\odot$ and $M/L \sim 2.3x^3\ 10^4$. All things together give $x < 0.026$ or $d < 1''.8$, which is clearly excluded by the observations. The orbit of B can therefore in no way be circular. It is in fact not difficult to show that any bound orbit around NGC 6166 is excluded, as was mentioned by Tonry (1984). B appears to be necessarily a galaxy falling toward A.

It should be mentioned that this analysis does not take any time scale into account: it assumes for instance that the galaxy B adjusts instantaneously its profile to the potential of NGC 6166. This is of course not true and the time scale for this adjustment could be estimated as being of the order of a characteristic length for B (say about 20″) divided by a characteristic velocity for the potential of NGC 6166 (say $1000\,{\rm km\,s^{-1}}$): This gives a time of about $8\ 10^6$ yr. So the tidal radius measured for B is in fact related to its position at this time. The consequence is only that the whole analysis made here is valid not for today but for some $8\ 10^6$ yr in the past. As we expect no major modification of the system on such a time scale, our conclusions remain valid.

5. Colors of NGC 6166

The same algorithms were used to separate the nuclei on the B and the R images. We have determined the central colors and the integrated colors for nuclei B and C. To avoid seeing and sampling errors, central colors were computed from the mean intensities in a 3*3 pixels square ($2''.5*2''.5$ square) in the 2 images. These colors are not very dependent on the separation procedure. Direct calculation on the original image, subtracting to each nucleus the appropriate background level, leads to about the same results. Nuclei B and C have the same central colors (B–$R \sim 2.0$) and are slightly redder than the main galaxy. Colors of B and C are typical of the normal E galaxies found in the same CCD field and more generally of the elliptical galaxies that we have observed during this CFH run.

The integrated color of nucleus B is identical to its central color. However the integrated color of nucleus C is bluer [$\Delta(B$–$R) \sim 0.4$]. If real, the integrated color of C would be typical of a Sb galaxy: But such a late type is incompatible with its high surface brightness. The total intensity of the C component is in fact very dependent on the symmetrization of the B nucleus during the separation procedure and the C integrated color may reflect errors introduced by this latter procedure more than the true color. Assuming that C has no color gradient, its total red intensity may have been underestimated by 40%. This difference is small enough to give confidence in the previous dynamical discussion.

Previous searches for color gradients in cD galaxies have been inconclusive: photographic photometry has failed to detect any color gradient in NGC 6166 (Carter, 1979) and NGC 6160 (Dressler, 1979), but a bluer external envelope has been suspected for NGC 6166, from aperture photoelectric photometry (Gallagher et al., 1980). The search for a color gradient in the main galaxy has been performed in several ways. Ellipses have been fitted to the isophotes in both images with a 0.2 magnitude step. Then, by interpolation between the two sets of ellipses we have reconstructed a color profile along the main axis. We found a pronounced gradient of $\delta(B$–$R) \sim -0.4$ from the center down to a surface brightness $\mu_B \sim 26\,{\rm arcsec^{-2}}$. Direct integration along blue and red isophotes is not possible due to the large fraction of the galaxy contaminated by light from other galaxies. To check the previous result we have simulated aperture photometry and determined the blue and red fluxes in several selected clean areas aligned with the main axis. This procedure gives about the same result as the ellipse fitting procedure (see Fig. 5). Our measurement is consistent with the B–V external colors of Gallagher et al. (1980). But we also found a color gradient in the central region of NGC 6166. It is not only, as claimed by Gallagher et al. (1980) an outer blue envelope but a general gradient covering the whole galaxy. It is very similar to the color gradients found in normal elliptical galaxies of the same eccentricity (Vigroux et al., 1984). The presence of this color gradient is hardly compatible with a merger origin for the galaxy. N body simulations have shown that merging would smear out preexistent color gradients in the merger (White, 1982) and that it cannot build a gradient by itself unless one invokes a non-linear star formation rate induced by shock in the gas during the merging process (Larson et al., 1979).

6. Conclusion

The two color CCD surface photometry that we have performed has led to several results: first 3 of the 4 nuclei are due to projection effects of cluster galaxies. Secondly the color distribution of NGC 6166 is very similar to the one found in other elliptical galaxies of the same eccentricity. Therefore, in spite of its 10 times larger mass, NGC 6166 behaves like a normal elliptical and is not built by a cannibalism mechanism.

The same analysis has to be performed in other cD galaxies to draw firm conclusions concerning their origin. But since NGC 6166 is the archetype of this class we may have some confidence for a standard formation for cD galaxies. The main evidence for cannibalism is the high proportion of multiple nuclei in these galaxies. However the estimate of chance projection effects are very crude. They must take into account several factors such as cluster richness and distance. An argument in favor of projection effects is the difference in multiple nuclei proportion between the sample of near and poor clusters of Hoessel (1980) and the sample of richer and more distant clusters of Schneider et al. (1983). There is no systematic trend of the multiple nuclei proportion with cluster richness only. Detailed studies combining surface photometry and velocity analysis, such as the one presented here, can help to resolve this issue.

Acknowledgements. We thank the CFH staff for its help during the observation, Dr. Georgelin who helped us for the installation of the CCD camera on the focal reducer, and Dr. A. Oemler for communication of unpublished results. We are grateful to Dr. G. Monnet for enlightning comments on an earlier version of this article.

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