

A Dust Lane in the Radio galaxy 3C270

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ABSTRACT

We present broad band surface photometry of the radio galaxy 3C270 (NGC 4261). We find a distinct dust lane in the $V - R$ image of the galaxy, and determine its orientation and size. We use the major axis profile of the galaxy to estimate the optical depth of the dust lane, and discuss the significance of the lane to the shape of the galaxy.

Subject headings: Galaxies: active; Galaxies: radio; Galaxies: individual; Galaxies: interstellar medium; Galaxies: photometry; Galaxies: dust lane

1. Introduction

3C270 (NGC 4261) is a radio galaxy with a bright compact radio nucleus and prominent jets and lobes. While at first sight it appears to be a morphologically simple elliptical galaxy of type E2, closer examination reveals many interesting features. A dust lane roughly along the apparent major axis of the galaxy was reported by Möllenhoff & Bender (1987), while others have failed to confirm its presence (e.g. Kormendy & Stauffer 1987; Peletier 1990). On a much smaller angular scale, recent observations with the Planetary Camera on the Hubble Space Telescope (Jaffe et al. 1993) have led to the detection of an absorbing disk of radius $\sim 2 \times 10^{20}$ cm which is made up of cool dust and gas. The plane of the disk is nearly normal to the radio jets, which are oriented close to the apparent minor axis of the galaxy. Long slit spectra (Davies & Birkinshaw 1986) have shown that the galaxy rotates round an apparent axis which lies only $6^\circ \pm 4^\circ$ from the apparent major axis, which suggests that the galaxy is prolate or close to prolate.

In this paper we use V and R images of NGC 4261 to confirm the existence of the dust lane first noted by Möllenhoff & Bender (1987). We demonstrate the existence of the lane in the combined $V - R$ colour image of the galaxy, determine its size and orientation, and estimate its optical depth from the colour excess relative to the region immediately outside the dust lane. We then independently estimate the optical depth of the dust lane by examining the deviation of the surface brightness profile of the galaxy from de Vaucouleurs' law. We end with comments on the contribution of the dust lane to the observed boxiness of galaxy isophotes and the significance of the orientation of the lane to the radio structure and intrinsic shape of the galaxy.

2. Observation and Data Reduction

NGC 4261 was observed at the prime focus ($f/3.5$) of the 2.3 m *Vainu Bappu Telescope* at Kavalur on the night of March 3, 1992 as part of a programme of broad band imaging of radio galaxies. The detector used was a GEC CCD with 576×385 pixels, each of $22 \times 22 \mu\text{m}^2$ in size, corresponding to $0.56 \times 0.56 \text{ arcsec}^2$ at the prime focus. We obtained two 600 s exposure frames in V and two 200 s frames in R , a number of twilight sky flats and bias frames spread throughout the night. We observed standard stars in the *dipper asterism* region of the open cluster M 67 for calibration; the procedure adopted has been described in detail by Anupama et al. (1994).

We followed the standard procedure for bias subtraction and flat fielding, and performed sky subtraction for each frame using a mean sky value estimated from pixels in the four corners of the frame, all of which were unaffected by the galaxy. We combined the two frames in each filter into single V and R frames after performing translations and

rotations so that the images were aligned to better than 0.1 pixel. Since the night was not photometric, we did not apply any extinction corrections. Tasks from IRAF¹ and STSDAS² were used for all the data reduction and analysis.

Boxiness is clearly discernible in the isophotes of NGC 4261, which nevertheless can be very well approximated by smooth ellipses. We fitted ellipses to the isophotes using routines in STSDAS, which are based on the method outlined by Jedrzejewski (1987). The semi-major axes of successive fitted ellipses were larger by a factor of 1.1, and the fit extended from the centre to a semi-major axis length of 60'', where the error in the surface brightness reaches ~ 0.1 magnitude. The semi-major axis brightness profile, ellipticity and position angle of the fitted ellipses as functions of semi-major axis length a for the V filter are shown in Figure 1. These parameters show similar behaviour in R . The rather large error-bars in case of ellipticity and position angle could be due to genuine departure of isophots from true ellipses. The deviation of an isophote from a perfect ellipse is estimated by expanding the difference in intensity between the isophote and the corresponding fitted ellipse as a Fourier series in the eccentric anomaly along the isophote. When boxiness is present, the coefficient b_4 of the $\cos(4\phi)$ term is negative. We have shown in Figure 1 the ratio b_4/a as a function of a for images in the V filter. All the distributions in Figure 1 are in good agreement with the values obtained by Möllenhoff & Bender (1987).

3. Colour Image

The putative dust lane in NGC 4261 is too faint to be seen in a single direct image, and the best place to look for it is a 2-colour image of the galaxy. Since we do not have a B frame with good signal-to-noise ratio, we investigate the $V - R$ image. The difference in the full width at half maximum (FWHM) in the point spread function (PSF) for the V and R images is $\sim 0''.06$, compared to the FWHM of $\sim 2''.4$. We therefore ignore the difference in further analysis. A narrow elongated structure is clearly seen in the $V - R$ image (Plate 1), oriented close to the apparent major axis of the galaxy. We show below that the feature is redder than its surroundings, and interpret it as a dust lane. In order to improve the appearance of the lane, we have also constructed a modified colour image adopting the procedure recommended by Sparks et al. (1985), which uses a smooth version of the higher wavelength image. This enhances the higher spatial frequency structures without affecting large scale colour features, and reduces noise in the 2-colour image as one of the components is smoothed. For this purpose we first fitted ellipses to the R image following the procedure

¹IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities, Inc. (AURA) under cooperative agreement with the National Science Foundation.

²The Space Telescope Science Data Analysis System STSDAS is distributed by the Space Telescope Science Institute.

described in the previous section, then obtained a smooth image R_{smooth} by interpolating between the isophotes using the ellipse parameters, and finally the modified colour image, $V - R_{smooth}$, which is shown in Plate 2. The elongated structure in the $V - R$ image is now more obvious than in Plate 1. The feature is also seen if the smooth image is obtained with the inclusion of higher harmonics which account for the boxiness of the isophotes. We wish to emphasize that all calculations presented in this paper are based on the original, unsmoothed V , R and $V - R$ images.

A cut across the dust lane in the $V - R$ image, averaged over ten rows around the galaxy centre, is shown in Figure 2. Even though the instrumental colour profile in the figure is noisy in the outer parts, it is clear that there is an overall shift to the blue as one moves towards the centre of the galaxy. A region obviously more red in colour than its immediate surroundings is seen straddling the centre. The red colour persists over the narrow feature, and we interpret it to be a thin disk of dust seen nearly edge on and appearing as a dust lane.

From inspection of Plate 1, the extent of the dust lane is found to be $\sim 21 \times 6 \text{ arcsec}^2$. We have taken several 5-pixel wide cuts across the dust lane, and assuming that the maximum in the $V - R$ profile in such a strip corresponds to the centre of the lane for that strip, obtained the coordinates of the centre along its length. A linear least square fit to these points then provides a straight line representation of the dust lane. This is shown in Figure 3, along with the direction of the major axis obtained from the ellipse fits, and the direction of the large scale radio jet as given by Birkinshaw & Davies (1985). The dust lane makes an angle of $9^\circ \pm 1^\circ$ with the major axis, and an angle of $97^\circ \pm 1^\circ$ with the radio jets.

We have estimated the colour excess in the dust lane by comparing the colour in it with that of the surroundings. For this purpose we used a circular aperture with radius $1''.68$ (3 pixels) on the V and R frames separately to extract magnitudes along the lane and a region along the minor axis $10''$ from the centre, which is free of dust. The mean of the colour excess obtained in this manner is

$$E(V - R) = (V - R)_{dust} - (V - R)_{galaxy} \simeq 0.05 \pm 0.01.$$

Assuming that the composition of the dust in the disk is similar to that of dust in our galaxy, and using standard relations from Savage & Mathius (1979), it follows that $E(B - V) = 0.06$, $\tau_V = 0.17$ and $\tau_R = 0.08$, where τ is the optical depth. Because these numbers are small the dust lane is not immediately apparent in the individual direct images. However, the dust does affect the luminosity profile, and we explore that aspect in the next section.

The optical depth obtained requires a correction since the dust disk obscures only those stars which are behind it, and not the ones that are between the disk and the observer. It can be shown (Brosch et al. 1990) that if the fraction of stars obscured is f , the relation

between the observed extinction A_{λ}^{obs} and the optical depth τ_{λ} is

$$A_{\lambda}^{obs} = -2.5 \log[1 + f(e^{-\tau_{\lambda}} - 1)].$$

For $\tau_{\lambda} \ll 1$, the extinction is given by $A_{\lambda}^{obs} \simeq 1.09f\tau_{\lambda}$, which may be compared to the usual relation $A_{\lambda} \simeq 1.09\tau_{\lambda}$ obtained by assuming that all the stars are obscured. The value of f depends on the geometry and orientation of the disk. When the disk is inclined to the line of sight, as in the present case, it is expected that the near side of the disk is darker than the far side³, and this could be used to fix the inclination when better data is available.

Following Burstein & Heiles (1978), the column density of neutral hydrogen and the total neutral hydrogen content in the dust disk can be obtained from

$$N(H) = 5.8 \times 10^{21} E(B - V) \text{atoms cm}^{-2}$$

and

$$N_{tot}^H = D^2 \int (dust) N(H) d\Omega.$$

Using $E(B - V) = 0.06$ and $D = 14.7 \text{ Mpc}$ we get $N_{tot}^H = 1.8 \times 10^{63}$, i.e. $M_{tot}^H = 1.7 \times 10^6 M_{\odot}$. H here refers to the neutral hydrogen. Assuming that the dust to gas mass ratio is $\sim 10^{-2}$ as in our galaxy, we get the dust mass $M_d = 1.5 \times 10^4 M_{\odot}$, which is a lower limit since a faint disk can extend beyond the confines presently detected. The factor f discussed above appears in the denominator of the integral defining N_{tot}^H . Therefore, since $f < 1$, the actual neutral hydrogen content is larger than the estimate.

4. Effect of Dust on the Luminosity Profile

It is known that de Vaucouleurs' $r^{1/4}$ law describes very well the observed brightness distribution for elliptical galaxies within $0.1r_e \leq a \leq 1.5r_e$ (e.g. Burkert 1993), where a and r_e are the semi-major axis distance and effective radius respectively. The lower limit is mainly due to seeing effects. Following an iterative fitting procedure, Burkert finds that for NGC 4261, $r_e = 34.5''$, so that de Vaucouleurs' law should hold at least upto $\sim 3''.5$. This procedure neglects the presence of the dust, which is expected to lead to departures from the law because of the absorption well above $0.1r_e$. The distribution of the surface brightness of NGC 4261 as a function of $r^{1/4}$, where a is in arcsecond is shown in Fig. 1. It

³We wish to thank an anonymous referee for pointing this out to us.

is clear from the linear part of the curve for $a > 11''$ that de Vaucouleurs' law provides an excellent fit in this region. The departure from a straight line towards the centre is due to seeing, absorption and any real departures from the law at small radii.

We have fit de Vaucouleurs' law to the V and R profiles after excluding the inner $11''$. For the fit, a model galaxy was generated with assumed values of the effective radius r_e and central surface brightness and using the observed distribution of ellipticity. The model was convolved with the point spread function (psf) obtained from stars in the frame, and the major axis profile was generated and compared with the observed profile. Parameters of the model were determined using the method of least squares. The effective radius obtained in this manner is $35''.8$. The best fit profile together with the observed surface brightness obtained from the ellipse fits described in Section 2 is shown in Figure 4, and the agreement between the two in the region used in the fit is seen to be excellent. If all points of the observed profile are used in the fit, the effective radius r_e obtained is $42''.6$, which is in agreement with the value obtained by Peletier et al. (1990), but is an overestimate because of the neglect of absorption.

The extrapolation of the best fit profile to the region of the dust disk lies above the observed points. If this is attributed to the absorption due to dust, which is certainly valid for $a \geq 3''.5$, the difference ΔV in magnitude between the fit and the observed surface brightness directly provides a measure of the extinction, with optical depth $\tau_V = \Delta V/1.086$. The optical depth obtained in this manner for the V as well as the R filter is shown in Figure 5. There are two points to be noted here : (1) The optical depth is independent of any assumptions regarding the properties of the dust, and therefore can be used to examine the validity of the assumptions made in Section 3 in estimating optical depth from the colour excess . (2) The observed surface brightness used in the determination of the extinction is obtained as a result of averaging over the best fit ellipses, which improves the signal-to-noise ratio and provides a smooth representation of the dependence of the optical depth on the semi-major axis length.

For $8'' \leq a \leq 11''$ some points along the fitted ellipses lie outside the region covered by dust, and extinction obtained from the mean intensity as described above could be an underestimate. To check the magnitude of this effect, we have taken intensity cuts through the centre which extended only through the region covered by dust. These were then averaged and an intensity profile obtained. We found that this profile differed at most by 0.01 magnitude from the profile obtained using the fitted ellipses. We therefore use the latter over the entire dust region.

The mean value of the optical depth over the dust region obtained using the above method separately for the two filters is $\tau_v = 0.19 \pm 0.01$ and $\tau_r = 0.10 \pm 0.01$, with the indicated error being primarily due to the uncertainty in deciding the extent of the dust obscured region. The optical depth here agrees within errors with the value in Section 3, which justifies the assumption made there that the dust in the disk is similar to the dust in

our galaxy.

It is possible to look for departures from de Vaucouleurs' law in the image rather than in the radial surface brightness profiles. For this purpose, using the best fit de Vaucouleurs' profile outside the putative dust region in the V filter, we have generated a 2-D model, extrapolated it to the region covered by the dust and convolved the whole with the point spread function. This provides a dust free representation V_{df} of the galaxy. The residual image $V - V_{df}$ shows features similar to $V - R_{smooth}$, with some variations which arise because of the differences in model generation and smoothing used in the two cases. The similarity in the residual and colour images makes it reasonable to assume that de Vaucouleurs' law modified by dust absorption provides a reasonable description of the inner region of NGC 4261.

It is expected that the optical depth in V is higher than that in R . However in Figure 5 it is seen that $\tau_V \simeq \tau_R$ for $a \geq 4''$ and for $a < 4''$ there is decrease in optical depth τ_R while τ_V continues to rise. Literally taken, this would mean increased red light towards the center. Some ellipticals are known to have red nuclei (e.g. Sparks et al. 1985) and red cores (e.g. Carter et al. 1983), but good spectroscopic data and observations in the B band under better seeing conditions will be necessary to confirm these trends here, as well as the similarity of the dust in NGC 4261 and in our galaxy. Dust in the two galaxies could have significantly different properties because of different origin and environment. The active galactic nucleus in the radio galaxy could also have some effect on the dust (Begelman 1985; Shanbhag & Kembhavi 1988). The results at small radii would of course be affected by any colour dependent departures from de Vaucouleurs' law.

5. Dust and Isophote Boxiness

The dust lane reduces the surface brightness at every point along its extent, which results in the isophotes appearing to be pulled inwards. When the dust lane is oriented along the major axis, this produces the appearance of boxiness, with the coefficient b_4 of the $\cos(4\phi)$ term in the angular dependence of the differential intensity along the best fit ellipses becoming negative. To examine the magnitude of this effect, we have generated an elliptical galaxy with the central surface brightness and effective radius obtained for the best fit model in Section 3, using tasks from IRAF that allow the introduction of Poisson shot noise and characteristics of the CCD. After convolving the model with the observed psf, we have placed in it a dust lane which has the extent and optical depth observed in NGC 4261 in the V band. We have then fitted ellipses to the isophotes, and obtained b_4/a , which is shown in Figure 6. The magnitude of b_4/a is seen to be similar to the observed value where dust is present, and the circularizing effect of the seeing is not dominant. However the boxiness is colour dependent, unlike in the observed case, and reduces to insignificant values as soon as the dust is left behind. Nevertheless it is clear that observed isophotal boxiness

could have a contribution from dust and could in fact be used as a diagnostic of major axis dust lanes which are too faint to be seen directly. In the same manner, dust lanes oriented in directions other than the apparent major axis will produce changes in isophotal shape which can be traced in the various Fourier coefficients.

6. Discussion

The shape and orientation of a dust disk in an elliptical galaxy is determined by the allowed trajectories of the dust particles, which depend on the shape and the overall rotation of the galaxy. NGC 4261 shows rotation around the apparent major axis (Davies & Birkinshaw 1986) and therefore it cannot be an oblate spheroid (Binney 1985). Davies and Birkinshaw have argued from the kinematical data and modelling that the galaxy is prolate or triaxial and nearly prolate. In such a configuration, orbits in the equatorial plane (which is normal to the long axis) are stable, but these are not appropriate to describe the dust disk in NGC 4261, because the dust lane is observed to be aligned close to the major axis. However there is another class of orbits which is stable (see Kormendy & Djorgovski (1989) and de Zeeuw & Franx (1991) for a review of the possibilities and references) and has different orientations at different radii which may be more appropriate to the present case. At small radii these orbits are polar, i.e. they lie in a plane containing the long and short axes; at larger radii the orbits are equatorial and skew at intermediate radii. The small scale absorption disk discovered using the Hubble Space Telescope (Jaffe et al. 1993) is inclined at an angle of $\sim 64^\circ$ to the plane of the sky, while the inclination of the larger disk is $\sim 75^\circ$. The two disks are to be viewed as the warped parts of a single disk, with the warping being due to the complex nature of the orbits, and the possible change in the shape of the galaxy from prolate to oblate towards the inner region, which will change the plane of stable orbits. The relative orientation of the different parts of the disk are also dependent on the extent to which the parts have settled in their final orbits, and projection effects which again depend on the shape of the galaxy and the direction of the line of sight. Higher signal-to-noise observations under better seeing conditions as well as spectroscopic data will be able to provide further information about the extent and shape of the dust disk which can be used in modelling the galaxy.

The radio jet in NGC 4261 is oriented almost normal to the dust disk, which hints at a possible connection between the two. The direction of the angular momentum of the disk changes somewhat from region to region as the disk is warped. It would be reasonable for the direction of the base of the jet to be determined by the innermost parts of the disk, and precession of the disk would lead to a change in the direction of the jet. However the large scale jet may overall appear to be normal to the large scale disk. Based on the statistical analysis of radio jet directions (e.g. Palimaka et al. 1979; Kapahi & Saikia 1982), it has been argued that the jets are oriented along the apparent minor axis of ellipticals.

When the galaxy is an oblate spheroid, the apparent minor axis always coincides with the projection of the short axis. The observation then means that jets are preferentially emitted close to the short axis. This coincidence could be related to the fact that in non-rotating or slowly rotating oblate spheroids the equatorial plane has stable orbits, so that the accretion disk is situated in this plane or close to it. When the galaxy is prolate, triaxial or rotating, the situation is more complex, and as mentioned above a variety of stable orbits is possible. If the jet direction is again taken to be determined by a disk, the relation between the jet direction and the apparent minor axis will depend on the the shape of the galaxy, the initial conditions of dust formation and the viewing direction. One should also expect to find a disk at least in those ellipticals which are powerful radio galaxies with well collimated jets. As in the case of NGC 4261, these disks may be too faint to be observed directly, but it would not be difficult to spot them using the techniques we have discussed above. If ellipticals are the results of mergers or cannibalism, one may well find dust disks in all of them.

7. Conclusions

The main conclusions of the present paper are the following :

1. The radio galaxy NGC 4261 contains a dust lane with dimensions $\sim 21 \times 6 \text{ arcsec}^2$, oriented close to the apparent major axis of the galaxy. The dust lane can be interpreted as the projection of a dust disk with inclination angle $\sim 75^\circ$ to the plane of the sky. The observed colour excess is $E(V - R) = 0.05$. Assuming dust properties similar to those in our galaxy, the optical depth obtained from $A_\lambda \simeq 1.09\tau_\lambda$ is $\tau_V = 0.17$ and $\tau_R = 0.08$. The actual optical depth could be a factor ~ 2 higher than this value.
2. The optical depth can be estimated directly from departures of the surface brightness profile from de Vaucouleurs' law, and has values close to those obtained from the colour excess, confirming that the dust is similar to that in our galaxy.
3. Absorption due to a major axis dust lane can produce boxiness which is colour dependent.

8. Acknowledgements

The authors wish to thank the staff of the Vainu Bappu Observatory, Kavalur for help with the observations, and Professor D. Lynden-Bell, Dr. G. C. Anupama, Dr. S. K. Pandey for many enlightening discussions.

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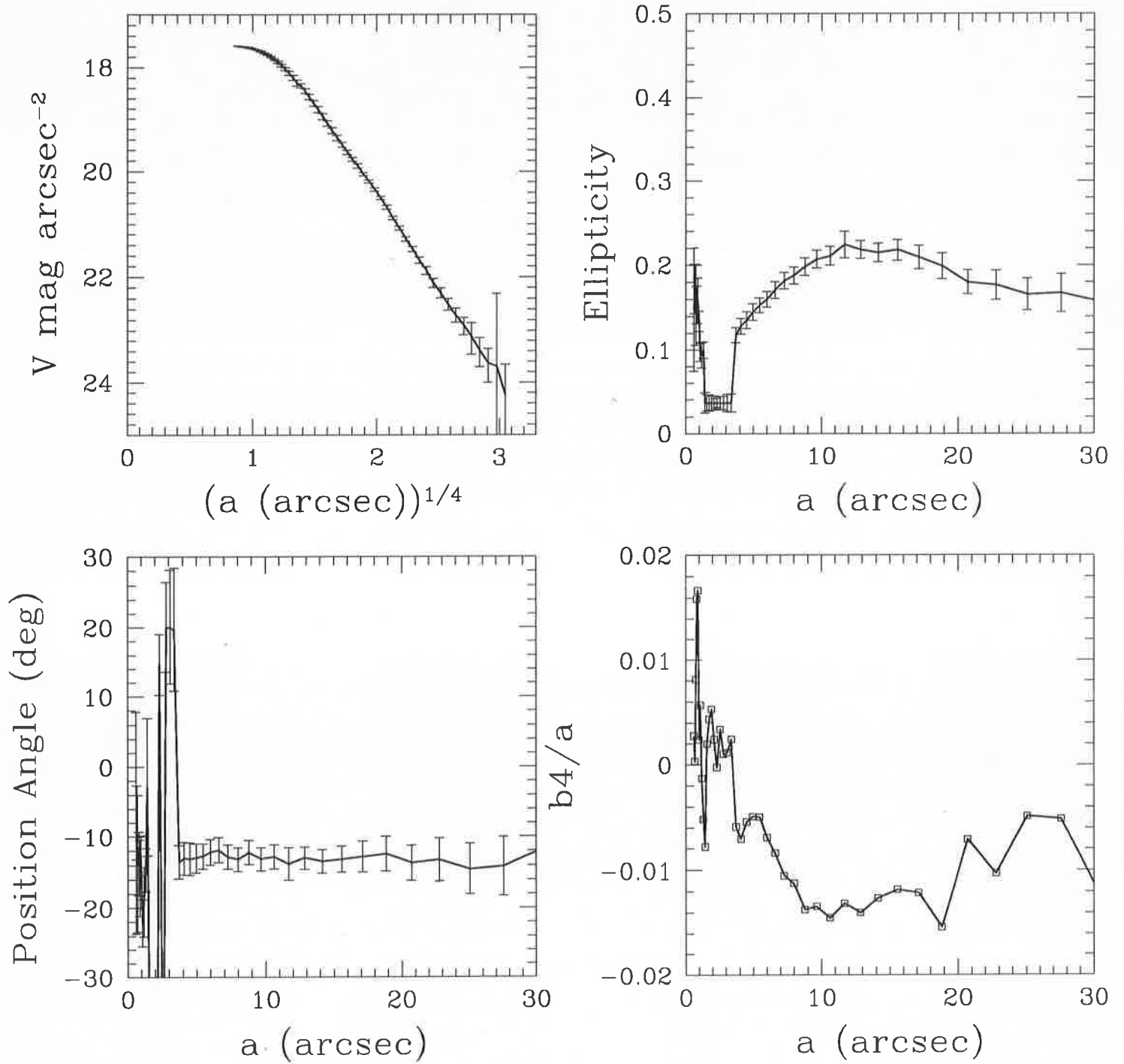


Figure 1 : Semi-major axis profiles in the V band of surface brightness, ellipticity, position angle and the *boxiness coefficient* b_4/a . The surface brightness is shown as a function of $a^{1/4}$, where a is the semi-major axis length, of the isophotes.

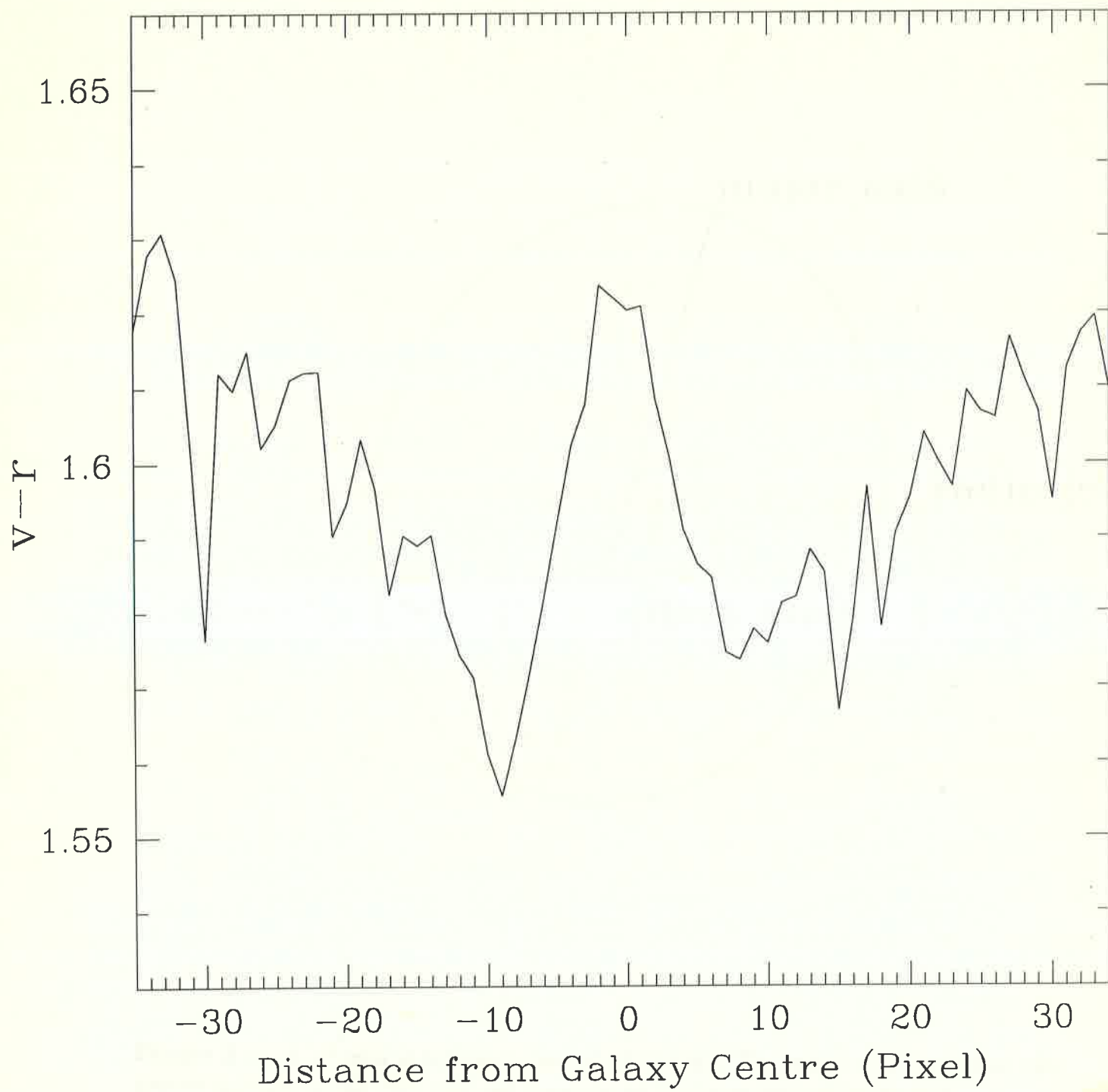


Figure 2 : A cut across the dust lane, averaged over 10 rows around the galaxy centre. The instrumental colour $v - r$ is shown.

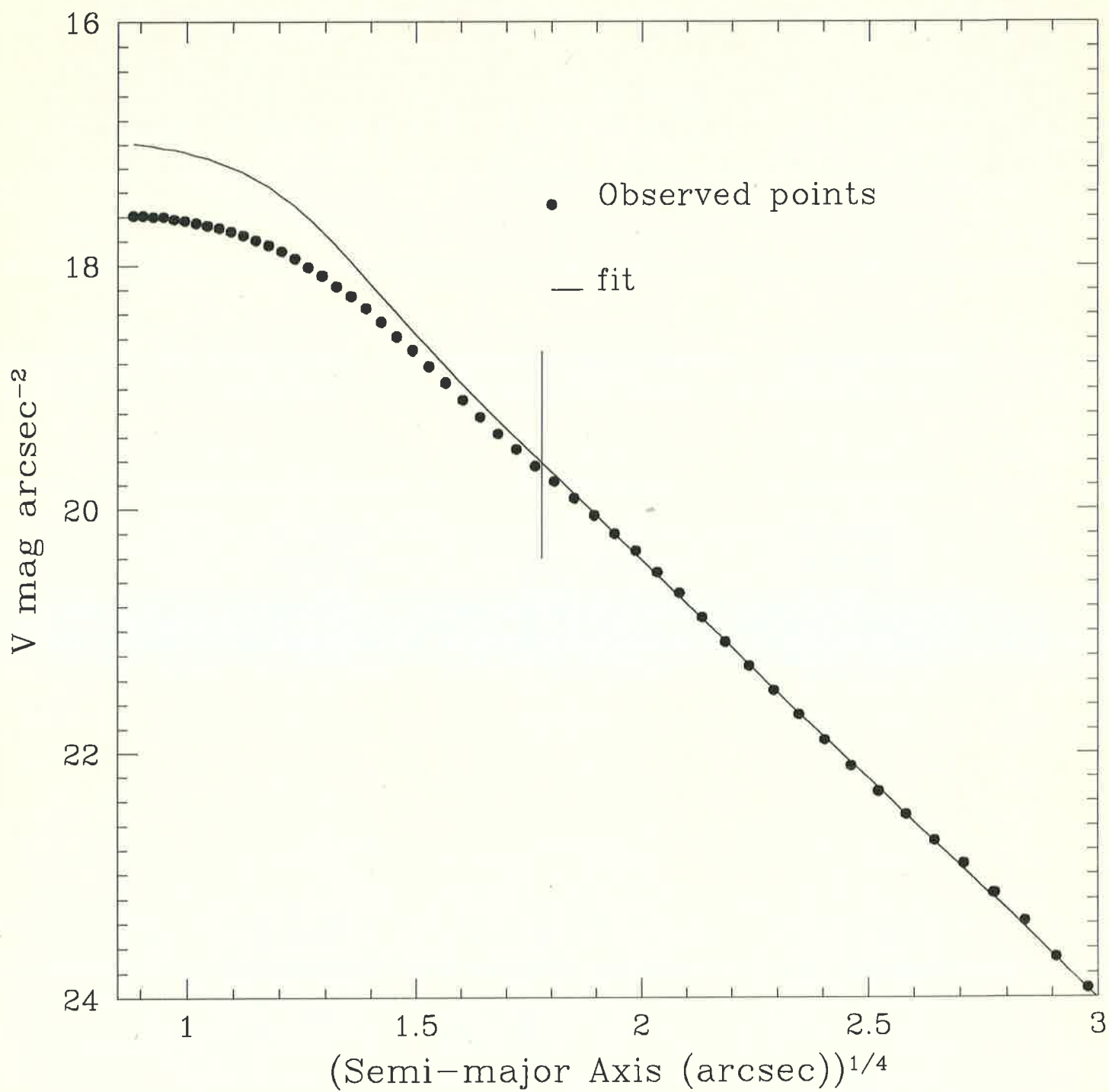


Figure 4 : Observed brightness profile along the semi-major axis, and a de Vaucouleurs' law fit made using points beyond the small vertical bar shown at $a = 11''$. The fit is extrapolated to the region inward of the bar. Deviation of the fit from the observed points in the inner region is indicative of the extinction due to dust.

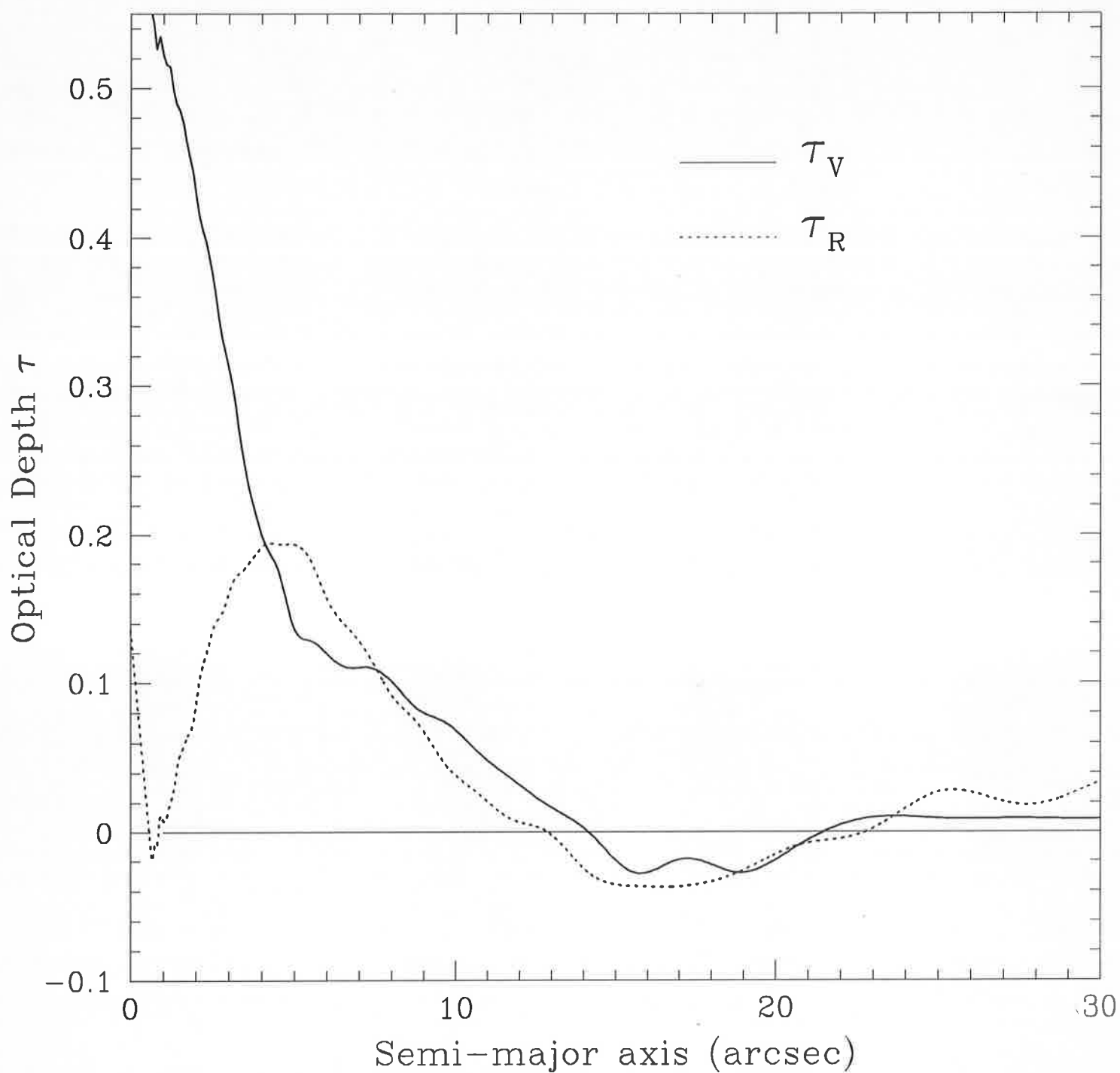


Figure 5 : Optical depth τ_V and τ_R as function of a . The value at a given a is the mean over the best fit ellipse with that semi-major axis.

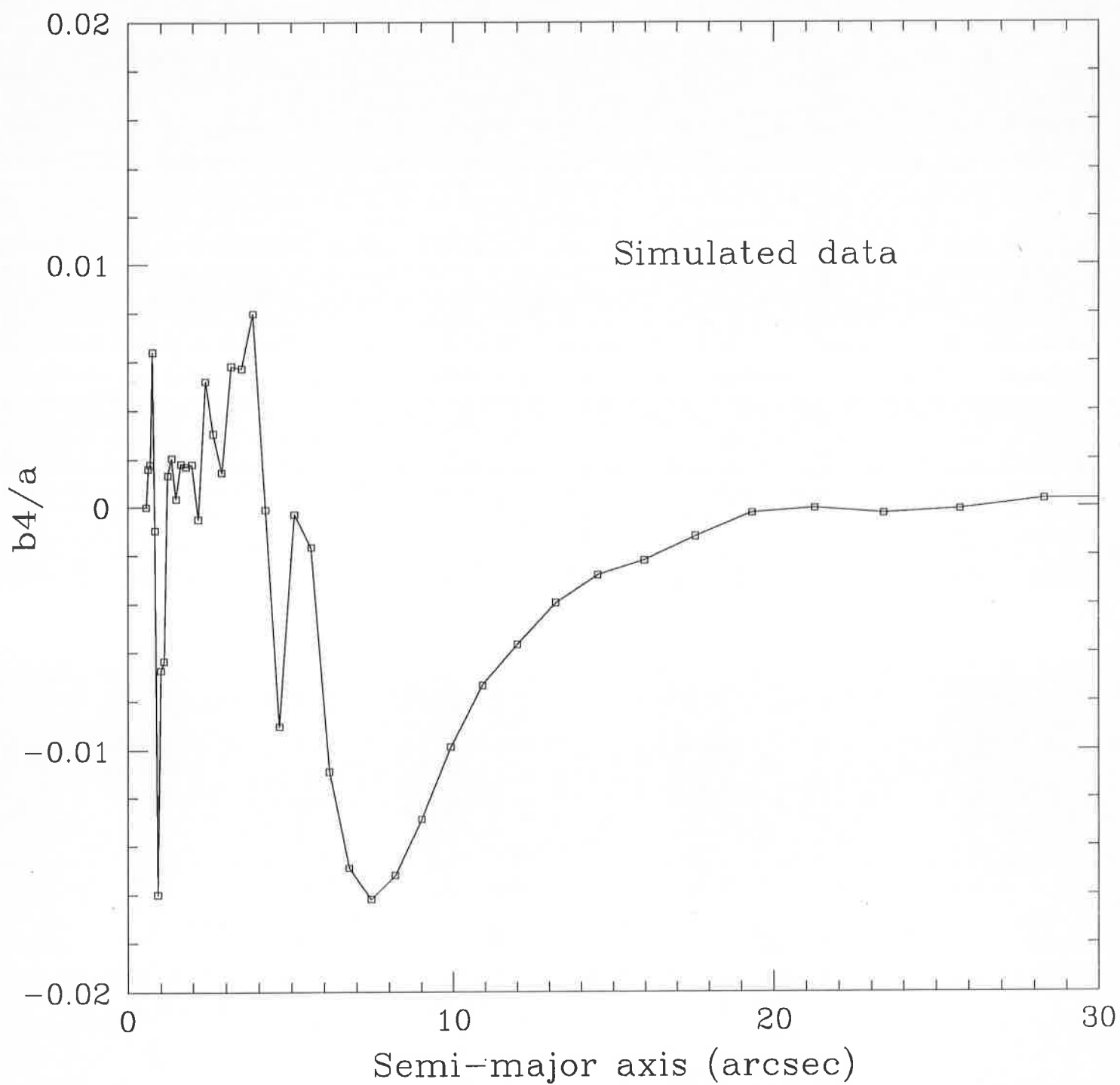


Figure 6 : The *boxiness coefficient* for a simulated elliptical galaxy generated using the parameters obtained for NGC 4261.

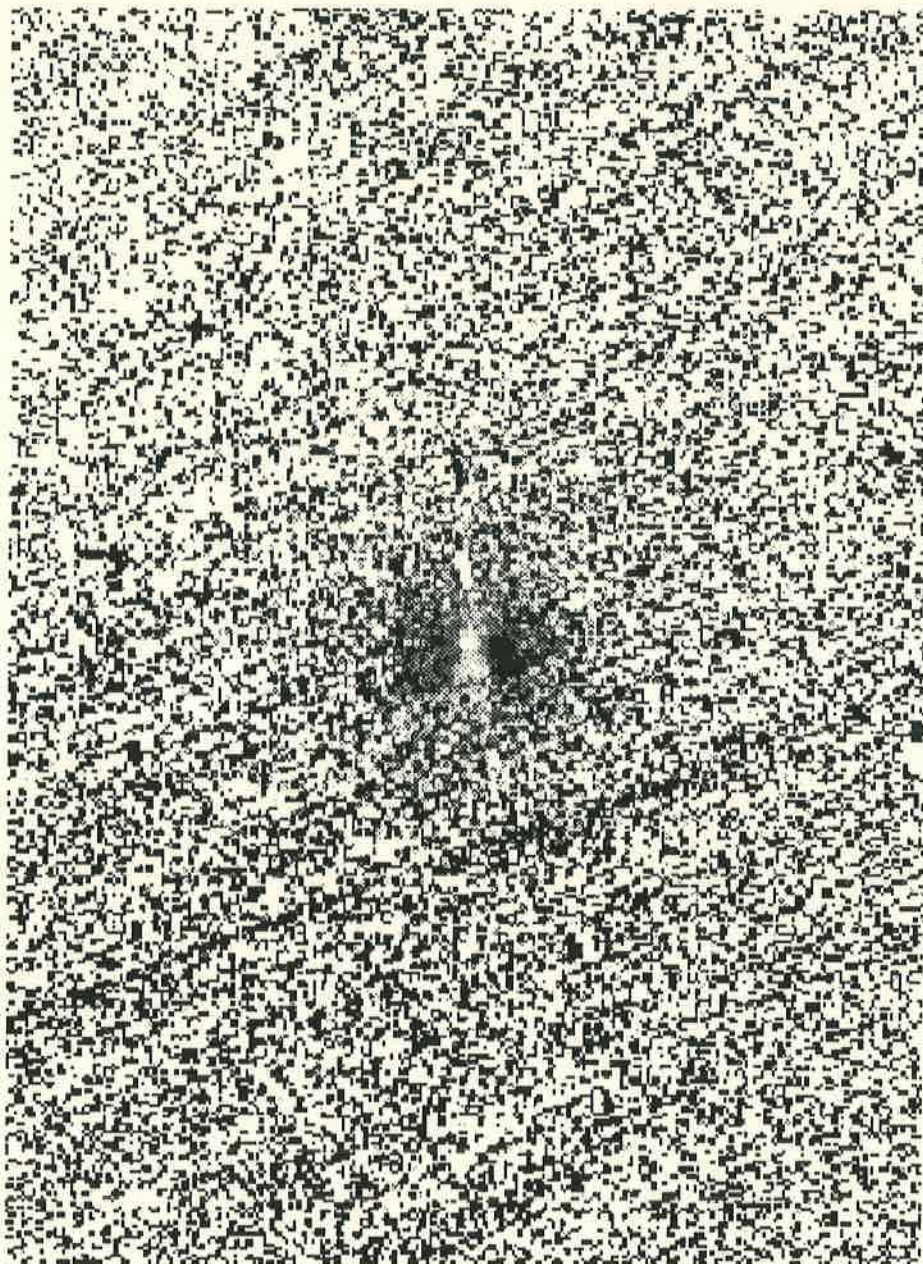


Plate 1 : $V - R$ image of NGC 4261 in false colour. Each pixel is $0''.56$.

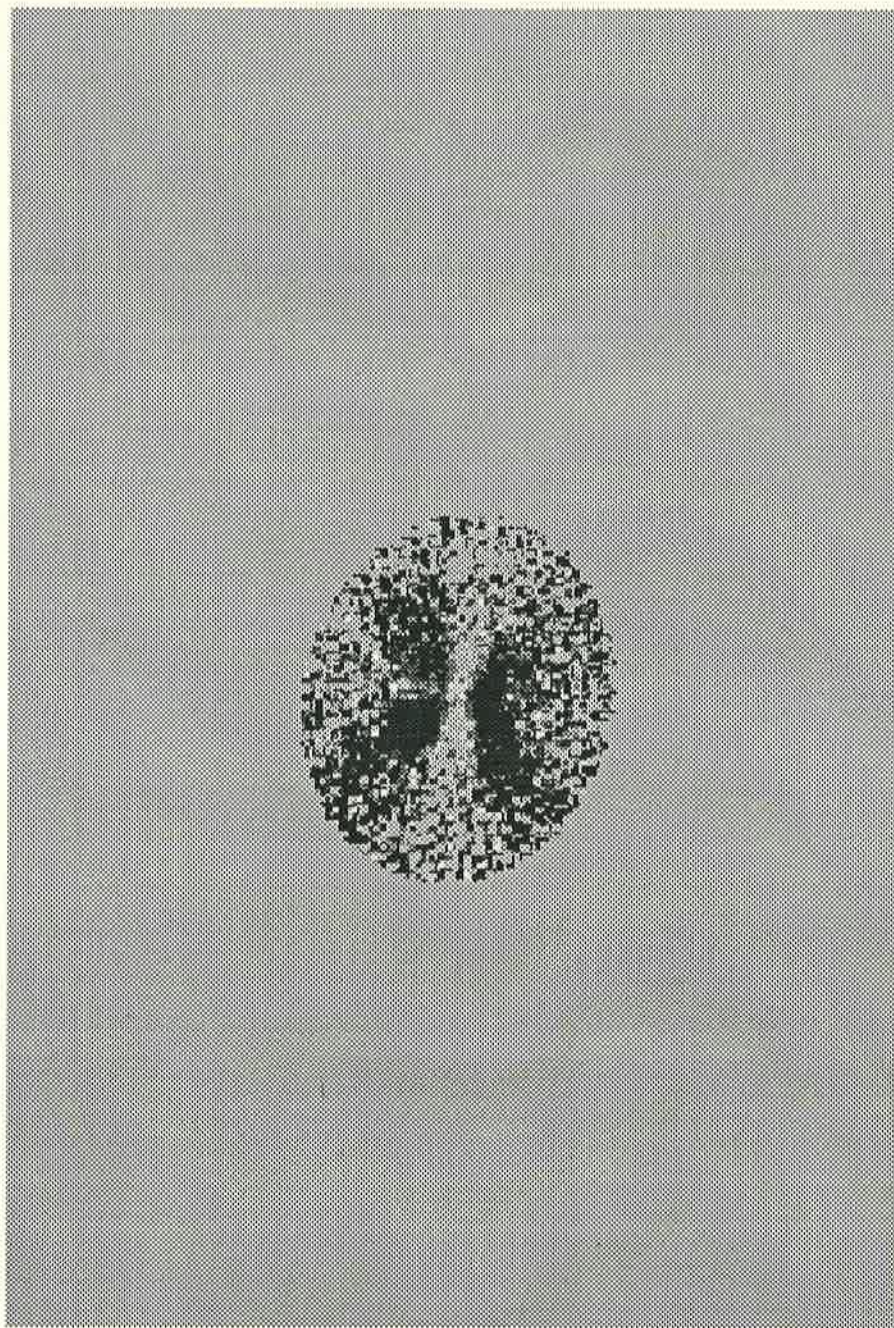


Plate 2 : $V - R_{smooth}$ image of NGC 4261 in false colour. Each pixel is $0''.56$.